

# PDG

particle data group

2024

# PARTICLE PHYSICS BOOKLET

Extracted from the *Review of Particle Physics*  
S. Navas et al. (Particle Data Group),  
Phys. Rev. D 110, 030001 (2024).

See <http://pdg.lbl.gov/> for Particle Listings,  
complete reviews and pdgLive.

Available from PDG at LBNL and CERN

The complete 2024 *Review of Particle Physics* is published online by Physical Review D **110**, 030001 (2024) and on the PDG website (<https://pdg.lbl.gov>). The printed *PDG Book* contains the Summary Tables and all review articles but no longer includes the detailed tables from the Particle Listings. This *Particle Physics Booklet* includes the Summary Tables plus essential tables, figures, and equations from selected review articles.

Copies of this *Booklet* or the *PDG Book* can be ordered from the PDG website or directly at

<https://pdg.lbl.gov/order> .

For special requests only, please email

[pdg@lbl.gov](mailto:pdg@lbl.gov)

in North and South America, Australia, and the Far East, and

[pdg-products@cern.ch](mailto:pdg-products@cern.ch)

in all other areas.

---

Visit our web site: <https://pdg.lbl.gov/>

---

The publication of the *Review of Particle Physics* is supported by the Director, Office of Science, Office of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231; by an implementing arrangement between the governments of Japan (MEXT: Ministry of Education, Culture, Sports, Science and Technology) and the United States (DOE) on cooperative research and development; by the Italian National Institute of Nuclear Physics (INFN); and by the European Laboratory for Particle Physics (CERN). Individual collaborators receive support for their PDG activities from their respective institutes or funding agencies.

# PARTICLE PHYSICS BOOKLET\*

Extracted from the *Review of Particle Physics*

S. Navas *et al* (PDG), Phys. Rev. D **110**, 030001 (2024)

## PARTICLE DATA GROUP

S. Navas, C. Amsler, T. Gutsche, C. Hanhart, J.J. Hernández-Rey, C. Lourenço, A. Masoni, M. Mikhasenko, R.E. Mitchell, C. Patrignani, C. Schwanda, S. Spanier, G. Venanzoni, C.Z. Yuan, K. Agashe, G. Aielli, B.C. Allanach, J. Alvarez-Muñiz, M. Antonelli, E.C. Aschenauer, D.M. Asner, K. Assamagan, H. Baer, Sw. Banerjee, R.M. Barnett, L. Baudis, C.W. Bauer, J.J. Beatty, J. Beringer, A. Bettini, O. Biebel, K.M. Black, E. Blucher, R. Bonventre, R.A. Briere, A. Buckley, V.D. Burkert, M.A. Bychkov, R.N. Cahn, Z. Cao, M. Carena, G. Casarosa, A. Ceccucci, A. Cerri, R.S. Chivukula, G. Cowan, K. Cranmer, V. Crede, O. Cremonesi, G. D'Ambrosio, T. Damour, D. de Florian, A. de Gouvêa, T. DeGrand, S. Demers, Z. Demiragli, B.A. Dobrescu, M. D'Onofrio, M. Doser, H.K. Dreiner, P. Eerola, U. Egede, S. Eidelman, A.X. El-Khadra, J. Ellis, S. C. Eno, J. Erler, V.V. Ezhela, A. Fava, W. Fetscher, B.D. Fields, A. Freitas, H. Gallagher, T. Gershon, Y. Gershtein, T. Gherghetta, M.C. Gonzalez-Garcia, M. Goodman, C. Grab, A.V. Gritsan, C. Grojean, D.E. Groom, M. Grünewald, A. Gurtu, H.E. Haber, M. Hamel, S. Hashimoto, Y. Hayato, A. Hebecker, S. Heinemeyer, K. Hikasa, J. Hisano, A. Höcker, J. Holder, L. Hsu, J. Huston, T. Hyodo, Al. Ianni, M. Kado, M. Karliner, U.F. Katz, M. Kenzie, V.A. Khoze, S.R. Klein, F. Krauss, M. Kreps, P. Križan, B. Krusche, Y. Kwon, O. Lahav, L.P. Lellouch, J. Lesgourgues, A.R. Liddle, Z. Ligeti, C.-J. Lin, C. Lippmann, T.M. Liss, A. Lister, L. Littenberg, K.S. Lugovsky, S.B. Lugovsky, A. Lusiani, Y. Makida, F. Maltoni, A.V. Manohar, W.J. Marciano, J. Matthews, U.-G. Meißner, L.-A. Melzer-Pellmann, P. Mertsch, D.J. Miller, D. Milstead, K. Mönig, P. Molaro, F. Moortgat, M. Moskvic, N. Nagata, K. Nakamura, M. Narain, P. Nason, A. Nelles, M. Neubert, Y. Nir, H.B. O'Connell, C.A.J. O'Hare, K.A. Olive, J.A. Peacock, E. Pianori, A. Pich, A. Piepke, F. Pietropaolo, A. Pomarol, S. Pordes, S. Profumo, A. Quadt, K. Rabbertz, J. Rademacker, G. Raffelt, M. Ramsey-Musolf, P. Richardson, A. Ringwald, D.J. Robinson, S. Roesler, S. Rolli, A. Romaniouk, L.J. Rosenberg, J.L. Rosner, G. Rybka, M.G. Ryskin, R.A. Ryutin, B. Safdi, Y. Sakai, S. Sarkar, F. Sauli, O. Schneider, S. Schönert, K. Scholberg, A.J. Schwartz, J. Schwiening, D. Scott, F. Sefkow, U. Seljak, V. Sharma, S.R. Sharpe, V. Shiltsev, G. Signorelli, M. Silari, F. Simon, T. Sjöstrand, P. Skands, T. Skwarnicki, G.F. Smoot, A. Soffer, M.S. Sozzi, C. Spiering, A. Stahl, Y. Sumino, F. Takahashi, M. Tanabashi, J. Tanaka, M. Taševský, K. Terao, K. Terashi, J. Terning, U. Thoma, R.S. Thorne, L. Tiator, M. Titov, D.R. Tovey, K. Trabelsi, P. Urquijo, G. Valencia, R. Van de Water, N. Varelas, L. Verde, I. Vivarelli, P. Vogel, W. Vogelsang, V. Vorobyev, S.P. Wakely, W. Walkowiak, C.W. Walter, D. Wands, D.H. Weinberg, E.J. Weinberg, N. Wermes, M. White, L.R. Wiencke, S. Willocq, C.L. Woody, R.L. Workman, W.-M. Yao, M. Yokoyama, R. Yoshida, G. Zanderighi, G.P. Zeller, R.-Y. Zhu, S.-L. Zhu, F. Zimmermann, P.A. Zyla

*Technical Associates:*

J. Anderson, M. Kramer, P. Schaffner, W. Zheng

©2024, content licensed under CC BY 4.0

\* This *Particle Physics Booklet* includes the Summary Tables plus essential tables, figures, and equations from selected review articles. The table of contents, on the following pages, lists also additional material available in the full *Review*.

## PARTICLE PHYSICS BOOKLET TABLE OF CONTENTS

1. Physical constants . . . . .	6
2. Astrophysical constants . . . . .	8
<b>Summary Tables of Particle Physics</b>	
Gauge and Higgs bosons . . . . .	10
Leptons . . . . .	16
Quarks . . . . .	25
Mesons . . . . .	27
Baryons . . . . .	166
Searches not in other sections . . . . .	198
Tests of conservation laws . . . . .	203
<b>Reviews, Tables, and Plots</b>	
9. Quantum chromodynamics . . . . .	204
10. Electroweak model and constraints on new physics . . . . .	207
11. Higgs boson physics, status of . . . . .	209
12. CKM quark-mixing matrix . . . . .	211
13. <i>CP</i> violation in the quark sector . . . . .	213
14. Neutrino mass, mixing and oscillations . . . . .	215
15. Quark model . . . . .	218
22. Big-bang cosmology . . . . .	220
27. Dark matter . . . . .	222
29. Cosmic microwave background . . . . .	223
30. Cosmic rays . . . . .	225
31. Accelerator physics of colliders . . . . .	226
32. High-energy collider parameters . . . . .	228
34. Passage of particles through matter . . . . .	229
35. Particle detectors at accelerators . . . . .	236
37. Radioactivity and radiation protection . . . . .	237
38. Commonly used radioactive sources . . . . .	239
39. Probability . . . . .	241
40. Statistics . . . . .	245
45. Monte Carlo particle numbering scheme . . . . .	251
46. Clebsch-Gordan coefficients, spherical harmonics, and <i>d</i> functions . . . . .	253
49. Kinematics . . . . .	255
51. Cross-section formulae for specific processes . . . . .	263
52. Neutrino cross-section measurements . . . . .	268
6. Atomic and nuclear properties of materials . . . . .	269
4. Periodic table of the elements . . . . .	inside back cover

The following are found only in the full *Review*, see

<https://pdg.lbl.gov>

## VOLUME 1: SUMMARY TABLES AND REVIEWS

Highlights

Introduction

History plots

Online particle physics information

### Reviews, Tables, and Plots

#### Constants, Units, Atomic and Nuclear Properties

3. International system of units (SI)
5. Electronic structure of the elements
7. Electromagnetic relations
8. Naming scheme for hadrons

#### Standard Model and Related Topics

16. Heavy-quark & soft-collinear effective theory
17. Lattice quantum chromodynamics
18. Structure functions
19. Fragmentation functions in  $e^+e^-$ ,  $ep$  and  $pp$  collisions
20. High energy soft QCD and diffraction

#### Astrophysics and Cosmology

21. Experimental tests of gravitational theory
23. Inflation
24. Big-bang nucleosynthesis
25. Cosmological parameters
26. Neutrinos in cosmology
28. Dark energy

#### Experimental Methods and Colliders

33. Neutrino beam lines at high-energy proton synchrotrons
36. Particle detectors for non-accelerator physics

#### Mathematical Tools

41. Machine Learning
42. Monte Carlo techniques
43. Monte Carlo event generators
44. Monte Carlo neutrino event generators
47. SU(3) isoscalar factors and representation matrices
48. SU( $n$ ) multiplets and Young diagrams

#### Kinematics, Cross-Section Formulae, and Plots

50. Resonances
53. Plots of cross sections and related quantities

#### Particle Properties

##### Gauge Bosons

54. Mass and width of the  $W$  boson
55.  $Z$  boson

##### Leptons

56. Muon anomalous magnetic moment
57. Muon decay parameters
58.  $\tau$  branching fractions
59.  $\tau$ -lepton decay parameters

##### Quarks

60. Quark masses
61. Top quark

##### Mesons

62. Form factors for semileptonic kaon ( $K_{\ell 3}$ ), radiative pion ( $\pi_{\ell 2\gamma}$ ) & kaon ( $K_{\ell 2\gamma}$ ) decays
63. Spectroscopy of light meson resonances
64. Scalar mesons below 1 GeV

- 65. Rare kaon decays
- 66.  $CPT$  invariance tests in neutral kaon decay
- 67.  $V_{ud}$ ,  $V_{us}$ , Cabibbo angle, and CKM unitarity
- 68.  $CP$ -violation in  $K_L$  decays
- 69. Review of multibody charm analyses
- 70.  $D^0$ - $\bar{D}^0$  mixing
- 71.  $D_s^+$  branching fractions
- 72. Leptonic decays of charged pseudoscalar mesons
- 73. Production and decay of  $b$ -flavored hadrons
- 74. Polarization in  $B$  decays
- 75.  $B^0$ - $\bar{B}^0$  mixing
- 76. Semileptonic  $B$ -hadron decays,  $V_{cb}$  and  $V_{ub}$
- 77. CKM angles from  $B$  hadrons, determination of
- 78. Spectroscopy of mesons containing two heavy quarks
- 79. Heavy non- $q\bar{q}$  mesons

#### Baryons

- 80. Baryon decay parameters
- 81.  $N$  and  $\Delta$  resonances
- 82.  $\Lambda$  and  $\Sigma$  resonances
- 83. Pole structure of the  $\Lambda(1405)$  region
- 84. Pentaquarks

#### Hypothetical Particles and Concepts

- 85. Extra dimensions
- 86.  $W'$ -boson searches
- 87.  $Z'$ -boson searches
- 88. Supersymmetry: theory
- 89. Supersymmetry: experiment
- 90. Axions and other similar particles
- 91. Quark and lepton compositeness, searches for
- 92. Dynamical electroweak symmetry breaking: implications of the  $H^0$
- 93. Grand unified theories
- 94. Leptoquarks
- 95. Magnetic monopoles

## **VOLUME 2: PARTICLE LISTINGS** (available online only)

### **Illustrative key and abbreviations**

#### **Gauge and Higgs bosons**

( $\gamma$ , gluon, graviton,  $W$ ,  $Z$ , Higgs, Axions)

#### **Leptons**

( $e$ ,  $\mu$ ,  $\tau$ , Heavy-charged lepton searches,  
Neutrino properties, Number of neutrino types  
Double- $\beta$  decay, Neutrino mixing,  
Heavy-neutral lepton searches)

#### **Quarks**

( $u$ ,  $d$ ,  $s$ ,  $c$ ,  $b$ ,  $t$ ,  $b'$ ,  $t'$  ( $4^{th}$  gen.), free quarks)

#### **Mesons**

Light unflavored ( $\pi$ ,  $\rho$ ,  $a$ ,  $b$ ) ( $\eta$ ,  $\omega$ ,  $f$ ,  $\phi$ ,  $h$ )

Strange ( $K$ ,  $K^*$ )

Charmed ( $D$ ,  $D^*$ )

Charmed, strange ( $D_s$ ,  $D_s^*$ ,  $D_{sJ}$ )

Bottom ( $B$ ,  $V_{cb}/V_{ub}$ ,  $B^*$ ,  $B_J^*$ )

Bottom, strange ( $B_s$ ,  $B_s^*$ ,  $B_{sJ}^*$ )

Bottom, charmed ( $B_c$ )

$c\bar{c}$  ( $\eta_c$ ,  $J/\psi(1S)$ ,  $\chi_c$ ,  $h_c$ ,  $\psi$ )

$b\bar{b}$  ( $\eta_b$ ,  $\Upsilon$ ,  $\chi_b$ ,  $h_b$ )

Other mesons

**Baryons** $N$  $\Delta$  $\Lambda$  $\Sigma$  $\Xi$  $\Omega$ Charmed ( $\Lambda_c, \Sigma_c, \Xi_c, \Omega_c$ )Doubly charmed ( $\Xi_{cc}$ )Bottom ( $\Lambda_b, \Sigma_b, \Xi_b, \Omega_b$ ,  $b$ -baryon admixture)Exotic baryons ( $P_c$  pentaquarks)**Searches not in Other Sections**

Magnetic monopole searches

Supersymmetric particle searches

Technicolor

Searches for quark and lepton compositeness

Extra dimensions

WIMP and dark matter searches

Other particle searches

**Notes in the Listings**

Triple gauge couplings (TGC's)

Anomalous  $ZZ\gamma$ ,  $Z\gamma\gamma$ , and  $ZZV$  couplingsAnomalous  $W/Z$  quartic couplings

Neutrino properties

Sum of neutrino masses

Number of light neutrino types from collider experiments

Neutrinoless double- $\beta$  decay

Charged kaon mass

Dalitz plot parameters for  $K \rightarrow 3\pi$  decays $CP$ -violation in  $K_S \rightarrow 3\pi$ 

Heavy Flavor Averaging Group

Charmonium system

Branching ratios of  $\psi(2S)$  and  $\chi_{c0,1,2}$ 

Bottomonium system

Width determination of the  $\Upsilon$  states

Radiative hyperon decays

 $\Xi$  resonances

## 1. Physical Constants

**Table 1.1:** Revised 2024 by D. Robinson (LBNL) and P.A. Zyla (LBNL). Mainly from “CODATA Recommended Values of the Fundamental Physical Constants: 2018,” E. Tiesinga, D.B. Newell, P.J. Mohr, and B.N. Taylor, NIST SP961 (May 2019). The last group, beginning with the Fermi coupling constant, comes from PDG. The 1- $\sigma$  uncertainties are given in parentheses. See the full *Review* for references and further explanation.

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	$c$	299 792 458 m s <sup>-1</sup>	exact
Planck constant	$h$	6.626 070 15 × 10 <sup>-34</sup> J s (or J/Hz)	exact
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 571 817... × 10 <sup>-34</sup> J s = 6.582 119 569... × 10 <sup>-22</sup> MeV s	exact
electron charge magnitude	$e$	1.602 176 634 × 10 <sup>-19</sup> C	exact
conversion constant	$\hbar c$	197.326 980 4... MeV fm	exact
conversion constant	$(\hbar c)^2$	0.389 379 372 1... GeV <sup>2</sup> mbarn	exact
electron mass	$m_e$	0.510 998 950 00(15) MeV/c <sup>2</sup> = 9.109 383 7015(28) × 10 <sup>-31</sup> kg	0.30
proton mass	$m_p$	938.272 088 16(29) MeV/c <sup>2</sup> = 1.672 621 923 69(51) × 10 <sup>-27</sup> kg = 1.007 276 466 621(53) u = 1836.152 673 43(11) $m_e$	0.31 0.053, 0.060 0.57, 0.48
neutron mass	$m_n$	939.565 420 52(54) MeV/c <sup>2</sup> = 1.008 664 915 95(49) u	0.30
deuteron mass	$m_d$	1875.612 942 57(57) MeV/c <sup>2</sup>	0.30
unified atomic mass unit (u)	$u = (\text{mass }^{12}\text{C atom})/12$	931.494 102 42(28) MeV/c <sup>2</sup> = 1.660 539 066 60(50) × 10 <sup>-27</sup> kg	0.30
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	8.854 187 8128(13) × 10 <sup>-12</sup> F m <sup>-1</sup>	0.15
permeability of free space	$\mu_0/(4\pi \times 10^{-7})$	1.000 000 000 55(15) N A <sup>-2</sup>	0.15
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297 352 5693(11) × 10 <sup>-3</sup> = 1/137.035 999 084(21) At $Q^2 \approx m_W^2$ the value is $\sim 1/128$ .	0.15
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 3262(13) × 10 <sup>-15</sup> m	0.45
(e <sup>-</sup> Compton wavelength)/2 $\pi$	$\lambda_e = \hbar/m_e c = r_e \alpha^{-1}$	3.861 592 6796(12) × 10 <sup>-13</sup> m	0.30
Bohr radius ( $m_{\text{nucleus}} = \infty$ )	$a_\infty = 4\pi\epsilon_0 \hbar^2 / m_e e^2 = r_e \alpha^{-2}$	0.529 177 210 903(80) × 10 <sup>-10</sup> m	0.15
wavelength of 1 eV/c particle	$\hbar c/(1 \text{ eV})$	1.239 841 984... × 10 <sup>-6</sup> m	exact
Rydberg energy	$\hbar c R_\infty = m_e e^4 / 2(4\pi\epsilon_0)^2 \hbar^2 = m_e c^2 \alpha^2 / 2$	13.605 693 122 994(26) eV	1.9 × 10 <sup>-3</sup>
Thomson cross section	$\sigma_T = 8\pi r_e^2 / 3$	0.665 245 873 21(60) barn	0.91



Bohr magneton	$\mu_B = eh/2m_e$	5.788 381 8060(17) $\times 10^{-11}$ MeV T <sup>-1</sup>	0.30
nuclear magneton	$\mu_N = eh/2m_p$	3.152 451 258 44(96) $\times 10^{-14}$ MeV T <sup>-1</sup>	0.31
electron cyclotron freq./field	$\omega_{\text{cycl}}/B = e/m_e$	1.758 820 010 76(53) $\times 10^{11}$ rad s <sup>-1</sup> T <sup>-1</sup>	0.30
proton cyclotron freq./field	$\omega_{\text{cycl}}/B = e/m_p$	9.578 833 1560(29) $\times 10^7$ rad s <sup>-1</sup> T <sup>-1</sup>	0.31
gravitational constant	$G_N$	6.674 30(15) $\times 10^{-11}$ m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup> = 6.708 83(15) $\times 10^{-39}$ hc (GeV/c <sup>2</sup> ) <sup>-2</sup>	2.2 $\times 10^4$ 2.2 $\times 10^4$
standard gravitational accel.	$g_N$	9.806 65 m s <sup>-2</sup>	exact
Avogadro constant	$N_A$	6.022 140 76 $\times 10^{23}$ mol <sup>-1</sup>	exact
Boltzmann constant	$k$	1.380 649 $\times 10^{-23}$ J K <sup>-1</sup> = 8.617 333 262... $\times 10^{-5}$ eV K <sup>-1</sup>	exact
molar volume, ideal gas at STP	$N_A k$ (273.15 K)/(101 325 Pa)	22.413 969 54... $\times 10^{-3}$ m <sup>3</sup> mol <sup>-1</sup>	exact
Wien displacement law constant	$b = \lambda_{\text{max}} T$	2.897 771 955... $\times 10^{-3}$ m K	exact
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4 / 60h^3 c^2$	5.670 374 419... $\times 10^{-8}$ W m <sup>-2</sup> K <sup>-4</sup>	exact
Fermi coupling constant	$G_F / (hc)^3$	1.166 378 8(6) $\times 10^{-5}$ GeV <sup>-2</sup>	510
weak-mixing angle	$\sin^2 \theta(M_Z)$ ( $\overline{\text{MS}}$ )	0.231 29(4)	$1.7 \times 10^5$
$W^\pm$ boson mass	$m_W$	80.3692(133) GeV/c <sup>2</sup>	$1.7 \times 10^5$
$Z^0$ boson mass	$m_Z$	91.1880(20) GeV/c <sup>2</sup>	$2.2 \times 10^4$
strong coupling constant	$\alpha_s(m_Z)$	0.1180(9)	$7.6 \times 10^6$
$\pi$	$\pi = 3.141 592 653 589 793 238 \dots$	$e = 2.718 281 828 459 045 235 \dots$	$\gamma = 0.577 215 664 901 532 860 \dots$
1 in $\equiv 0.0254$ m	1 G $\equiv 10^{-4}$ T	1 eV = 1.602 176 634 $\times 10^{-19}$ J (exact)	$kT$ at 300 K = [38.681 727 0718 ...] <sup>-1</sup> eV (exact)
1 Å $\equiv 0.1$ nm	1 dyne $\equiv 10^{-5}$ N	(1 kg)c <sup>2</sup> = 5.609 588 603... $\times 10^{35}$ eV(exact)	0 °C $\equiv 273.15$ K
1 barn $\equiv 10^{-28}$ m <sup>2</sup>	1 erg $\equiv 10^{-7}$ J	1 C = 2.997 924 58 $\times 10^9$ esu	1 atmosphere $\equiv 760$ Torr $\equiv 101 325$ Pa

**Table 2.1:** Revised August 2023 by D.E. Groom (LBNL) and D. Scott (U. of British Columbia). The figures in parentheses after some values give the  $1-\sigma$  uncertainties in the last digit(s). Physical constants are from Ref. [1]. While every effort has been made to obtain the most accurate current values of the listed quantities, this table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference. The values and uncertainties for the cosmological parameters depend on the exact data sets, priors, and basis parameters used in the fit. Many of the derived parameters reported in this table have non-Gaussian likelihoods and parameters may be highly correlated, so care must be taken in propagating errors. Unless otherwise specified, cosmological parameters are derived from a 6-parameter  $\Lambda$ CDM cosmology fit to *Planck* cosmic microwave background 2018 temperature (TT) + polarization (TE,EE+lowE) + lensing data [2]. For more information see Ref. [3] and the original papers.

Quantity	Symbol, equation	Value	Reference, footnote
Newtonian constant of gravitation	$G_N$	$6.674\,30(15) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$	[1]
Planck mass	$M_P = \sqrt{\hbar c / G_N}$	$1.220\,806(14) \times 10^{19} \text{ GeV} / c^2 = 2.176\,434(24) \times 10^{-8} \text{ kg}$	[1]
Planck length	$l_P = \sqrt{\hbar G_N / c^3}$	$1.616\,255(18) \times 10^{-35} \text{ m}$	[1]
tropical year (equinox to equinox, 2020)	yr	$31\,556\,925.1 \text{ s} = 365.242\,189 \text{ days}$	[4]
sidereal year (period of Earth around Sun relative to stars)		$31\,558\,149.8 \text{ s} \approx \pi \times 10^7 \text{ s}$	[4]
mean sidereal day (Earth rotation period relative to stars)		$23^{\text{h}}\,56^{\text{m}}\,04^{\text{s}}.0900\,53$	[4]
astronomical unit	au	$149\,597\,870\,700 \text{ m}$	exact [5]
parsec (1 au/1 arcsec)	pc	$3.085\,677\,581\,49 \dots \times 10^{16} \text{ m} = 3.261\,56 \dots \text{ ly}$	exact [6]
light year (deprecated unit)	ly	$0.306\,601 \dots \text{ pc} = 0.946\,073 \dots \times 10^{16} \text{ m}$	exact [6]
solid angle	$\text{deg}^2$	$(\pi/180)^2 \text{ sr} = 3.046\,17 \dots \times 10^{-4} \text{ sr}$	[8]
Schwarzschild radius of the Sun	$2G_N M_\odot / c^2$	$2.953\,250\,1 \text{ km}$	[9]
Solar mass	$M_\odot$	$1.988\,41(4) \times 10^{30} \text{ kg}$	[10]
nominal Solar equatorial radius	$R_\odot$	$6.957 \times 10^8 \text{ m}$	exact [11]
nominal Solar constant	$S_\odot$	$1361 \text{ W m}^{-2}$	exact [11, 12]
nominal Solar photosphere temperature	$T_\odot$	$5772 \text{ K}$	exact [11]
nominal Solar luminosity	$L_\odot$	$3.828 \times 10^{26} \text{ W}$	exact [11, 13]
Schwarzschild radius of the Earth	$2G_N M_E / c^2$	$8.870\,656 \text{ mm}$	[9]
Earth mass	$M_E$	$5.972\,17(13) \times 10^{24} \text{ kg}$	[10]
nominal Earth equatorial radius	$R_E$	$6.378\,1 \times 10^6 \text{ m}$	exact [11]
Chandrasekhar mass	$M_{\text{Ch}}$	$3.087\,972 \mu^2 M_\odot, m_{\text{Ch}}^2 = 1.433\,77(6) (\mu/2)^{-2} M_\odot$	[14, 15]
Eddington luminosity	$L_{\text{Ed}}$	$1.257\,065\,179\,8(12) \times 10^{31} (M/M_\odot) \text{ W}$	[16, 17]
		$= 3.283\,860\,330\,8(31) \times 10^4 (M/M_\odot) L_\odot$	
jansky (flux density)	Jy	$10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$	definition
luminosity conversion	$f_0$	$3.0128 \times 10^{28} \times 10^{-0.4 M_{\text{bol}} \text{ W}}$	exact [18]
	$\mathcal{F}$	$(M_{\text{bol}} = \text{absolute bolometric magnitude} = \text{bolometric magnitude at } 10 \text{ pc})$	
flux conversion	AB	$(m_{\text{bol}} = \text{apparent bolometric magnitude})$	exact [18]
		$-2.5 \log_{10} f_\nu - 56.10 \text{ (for } f_\nu \text{ in } \text{W m}^{-2} \text{ Hz}^{-1})$	
		$= -2.5 \log_{10} J_\nu + 8.90 \text{ (for } J_\nu \text{ in Jy)}$	[19]
Solar distance from Galactic center	$R_0$	$8.275 \pm 0.009(\text{stat.}) \pm 0.033(\text{sys.}) \text{ kpc}$	[20]
local circular angular velocity	$\Theta_0/R_0$	$28.2(1.0) \text{ km s}^{-1} \text{ kpc}^{-1}$	[21]
local escape velocity at $R_0$	$v_0$ or $\Theta_0$	$233.4 \pm 0.3(\text{stat.}) \pm 8.0(\text{sys.}) \text{ km s}^{-1}$	[22]
local escape velocity from the Galaxy	$v_{\text{esc}}$	$477 \text{ km s}^{-1} < v_{\text{esc}} < 502 \text{ km s}^{-1} \text{ (68\%)}$	[23]
local disk density	$\rho_{\text{disk}}$	$0.6(0) \times 10^{-24} \text{ g cm}^{-3} = 3.7(5) \text{ GeV}^4 \text{ cm}^{-3}$	[24]
local dark matter density	$\rho_{\text{DM}}$	$\rho_{\text{disk}} \times \text{factor 0.3 GeV}^4 \text{ cm}^{-3}$ within factor 2-3	[25]
present-day CMB temperature	$T_0$	$2.725\,5(6) \text{ K}$	[26, 27]
redshift of CMB recombination	$z_{\text{rec}}$	$3.291(10)$	[26, 28]
Solar velocity with respect to CMB	$d$	$369\,828(11) \text{ km s}^{-1}$	[26, 28]
Solar velocity with respect to CMB	$d_\odot$	$620(15) \text{ km s}^{-1}$ towards $(l, b) = (264.021(11)^\circ, 48.2538(5)^\circ)$	[28]
Local Group velocity with respect to CMB	$v_{\text{LG}}$	$410.738(27) (7/2, 7.255 \text{ K})^3 \text{ cm}^{-3} = (271.9(20)^\circ, 29.6(14)^\circ)$	[28]
number density of CMB photons	$n_\gamma$	$4.645(4) (7/2, 7.255 \text{ K})^4 \times 10^{-34} \text{ g cm}^{-3} \approx 0.260 \text{ nV cm}^{-3}$	[29]
density of CMB photons	$\rho_\gamma$		[29]

Quantity	Symbol, equation.	Value	Reference, footnote
entropy density/Boltzmann constant	$s/k$	$2.891.2 (T/2.7255\text{K})^3 \text{cm}^{-3}$	[29]
present-day Hubble expansion rate	$H_0$	$100 h \text{km s}^{-1} \text{Mpc}^{-1} = h \times (9.777752 \text{Gyr})^{-1}$	[30]
scaling factor for Hubble expansion rate	$h$	$0.674(5)$ from CMB anisotropies ( <i>Planck</i> ) or $0.739(10)$ from the distance ladder (SH0ES)	[2]
Hubble length	$c/H_0$	$0.9250629 \times 10^{26} h^{-1} \text{m} = 1.372(11)$ or $1.267(18) \times 10^{26} \text{m}$	[31, 32]
scaling for cosmological constant	$c^2/3M_{\text{pl}}^2$	$2.85247 \times 10^{51} h^{-2} \text{m}^2 = 6.29(10)$ or $5.35(15) \times 10^{51} \text{m}^2$	[2, 31]
critical density of the Universe	$\rho_{\text{crit}} = 3H_0^2/8\pi G_N$	$= 1.053\,672(24) \times 10^{-29} h^2 \text{g cm}^{-3}$ $= 2.775\,38627 \times 10^{11} h^2 M_{\odot} \text{Mpc}^{-3}$	[2, 31]
baryon-to-photon ratio (from BBN)	$\eta = n_b/n_\gamma$	$6.04(12) \times 10^{-10}$	[33, 34]
number density of baryons	$n_b$	$2.515(17) \times 10^{-7} \text{cm}^{-3}$ (from CMB)	[2, 35]
CMB radiation density of the Universe	$\Omega_r = \rho_r/\rho_{\text{crit}}$	$2.48(5) \times 10^{-7} \text{cm}^{-3}$ (from BBN, $\eta \times n_s$ )	[3, 33]
primordial helium fraction	$Y_p$	$2.473 \times 10^{-5} (T/2.7255\text{K})^4 h^{-2} = 5.38(15) \times 10^{-5}$	[29]
----- <i>Planck</i> 2018 6-parameter fit to flat $\Lambda$ CDM cosmology -----			[36]
baryon density of the Universe	$\Omega_b = \rho_b/\rho_{\text{crit}}$	$\dagger 0.02237(15) h^{-2} = \dagger 0.0493(6)$	[2, 3, 26]
cold dark matter density of the Universe	$\Omega_c = \rho_c/\rho_{\text{crit}}$	$\dagger 0.1200(12) h^{-2} = \dagger 0.205(7)$	[2, 3, 26]
$100 \times$ approximation to $r_s/D_A$	$100 \times \theta_{8\text{Mpc}}$	$\dagger 1.04092(31)$	[2, 3, 26]
reionization optical depth	$\tau$	$\dagger 0.054(7)$	[2, 3, 26]
ln(power prim. curv. pert.) ( $k_0 = 0.05 \text{Mpc}^{-1}$ ) $\ln(10^{10} \Delta_{\kappa}^2)$		$\dagger 3.044(14)$	[2, 3, 26]
scalar spectral index	$n_s$	$\dagger 0.965(4)$	[2, 3, 26]
pressureless matter density parameter	$\Omega_m = \Omega_c + \Omega_b$	$\dagger 0.315(7)$	[2, 3]
dark energy density parameter	$\Omega_\Lambda$	$\dagger 0.685(7)$	[2, 3]
energy density of dark energy	$\rho_\Lambda$	$\dagger 5.83(16) \times 10^{-30} \text{g cm}^{-3}$	[2]
cosmological constant	$\Lambda$	$\dagger 1.088(30) \times 10^{-56} \text{cm}^{-2}$	[2]
fluctuation amplitude at $8 h^{-1} \text{Mpc}$ scale	$\sigma_8$	$\dagger 0.811(6)$	[2, 3]
amplitude of matter fluctuations	$\sigma_8(\Omega_m/0.3)^{0.5}$	$\dagger 0.832(13)$	[2, 3]
redshift of matter-radiation equality	$z_{\text{eq}}$	$\dagger 3402(26)$	[2, 37]
age at matter-radiation equality	$t_{\text{eq}}$	$\dagger 51.0(8) \text{kyr}$	[2, 38]
redshift at which optical depth equals unity	$z_*$	$\dagger 1089.92(25)$	[2]
comoving size of sound horizon at $z_*$	$r_*$	$\dagger 144.49(26) \text{Mpc}$	[2, 39]
age when optical depth equals unity	$t_*$	$\dagger 371.8(10) \text{kyr}$	[2, 38]
redshift at half reionization	$z_1$	$\dagger 7.7(7)$	[2, 40]
age at half reionization	$t_1$	$\dagger 690(90) \text{Myr}$	[2]
redshift when acceleration was zero	$z_q$	$\dagger 0.656(18)$	[2, 38]
age when acceleration was zero	$t_q$	$\dagger 7.70(10) \text{Gyr}$	[2]
age of the Universe today	$t_0$	$\dagger 13.797(23) \text{Gyr}$	[2]
effective number of neutrinos	$N_{\text{eff}}$	$\dagger 2.99(17)$ (CMB + BAO)	[2]
sum of neutrino masses	$\Sigma m_\nu$	$\dagger 0.12 \text{eV}$ (95%, CMB + BAO); $\geq 0.06 \text{eV}$ (mixing)	[2, 41, 42]
neutrino density of the Universe	$\Omega_\nu = h^{-2} \Sigma m_\nu/93.14 \text{eV}$	$\dagger < 0.003$ (96%, CMB + BAO); $\geq 0.0012$ (mixing)	[2, 42-44]
curvature	$\Omega_K$	$\dagger 0.0007(19)$ (CMB + BAO)	[2]
running spectral index, $k_0 = 0.05 \text{Mpc}^{-1}$	$d n_s/d \ln k$	$\dagger -0.004(7)$	[2]
tensor-to-scalar perturbation ratio	$r_{0.005} = T/S$	$< 0.036$ (95%, $k_0 = 0.05 \text{Mpc}^{-1}$ )	[2, 45-48]
dark energy equation of state parameter	$w_{0.05}$	$\dagger -1.028(31)$ (CMB + BAO + SNe)	[2, 49]

## SUMMARY TABLES OF PARTICLE PROPERTIES

Extracted from the Particle Listings of the  
*Review of Particle Physics*

S. Navas *et al.* (Particle Data Group),  
Phys. Rev. D **110**, 030001 (2024)

Available at <https://pdg.lbl.gov>

©2024 (CC BY 4.0)

(Approximate closing date for data: January 15, 2024)

### GAUGE AND HIGGS BOSONS

**$\gamma$  (photon)**

$$I(J^{PC}) = 0,1(1^{--})$$

Mass  $m < 1 \times 10^{-18}$  eV

Charge  $q < 1 \times 10^{-46} e$  (mixed charge)

Charge  $q < 1 \times 10^{-35} e$  (single charge)

Mean life  $\tau = \text{Stable}$

**$g$  (gluon)**

$$I(J^P) = 0(1^-)$$

Mass  $m = 0$  [a]

SU(3) color octet

**graviton**

$$J = 2$$

Mass  $m < 1.76 \times 10^{-23}$  eV

**$W$**

$$J = 1$$

Charge =  $\pm 1 e$

Mass  $m = 80.3692 \pm 0.0133$  GeV [b]

$W/Z$  mass ratio =  $0.88136 \pm 0.00015$

$m_Z - m_W = 10.818 \pm 0.013$  GeV

$m_{W^+} - m_{W^-} = -0.029 \pm 0.028$  GeV

Full width  $\Gamma = 2.085 \pm 0.042$  GeV

$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$

$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$

$\langle N_p \rangle = 0.92 \pm 0.14$

$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

$W^-$  modes are charge conjugates of the modes below.

<b><math>W^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$P$ (MeV/c)
$\ell^+ \nu$	[c] $(10.86 \pm 0.09) \%$		—
$e^+ \nu$	$(10.71 \pm 0.16) \%$		40185
$\mu^+ \nu$	$(10.63 \pm 0.15) \%$		40185
$\tau^+ \nu$	$(11.38 \pm 0.21) \%$		40165

hadrons	(67.41 ± 0.27) %			–
$\pi^+ \gamma$	< 7	$\times 10^{-6}$	95%	40184
$D_S^+ \gamma$	< 6	$\times 10^{-4}$	95%	40160
$cX$	(33.3 ± 2.6) %			–
$c\bar{3}$	(31 $^{+13}_{-11}$ ) %			–
invisible	[d] (1.4 ± 2.9) %			–
$\pi^+ \pi^+ \pi^-$	< 1.01	$\times 10^{-6}$	95%	40184

**Z**

$J = 1$

Charge = 0

Mass  $m = 91.1880 \pm 0.0020$  GeV [e]Full width  $\Gamma = 2.4955 \pm 0.0023$  GeV $\Gamma(\ell^+ \ell^-) = 83.984 \pm 0.086$  MeV [c] $\Gamma(\text{invisible}) = 499.2 \pm 1.5$  MeV [f] $\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$  MeV $\Gamma(\mu^+ \mu^-) / \Gamma(e^+ e^-) = 1.0001 \pm 0.0024$  $\Gamma(\tau^+ \tau^-) / \Gamma(e^+ e^-) = 1.0020 \pm 0.0032$  [g]**Average charged multiplicity**

$\langle N_{\text{charged}} \rangle = 20.76 \pm 0.16 \quad (S = 2.1)$

**Couplings to quarks and leptons**

$g_V^\ell = -0.03783 \pm 0.00041$

$g_V^u = 0.266 \pm 0.034$

$g_V^d = -0.38^{+0.04}_{-0.05}$

$g_A^\ell = -0.50123 \pm 0.00026$

$g_A^u = 0.519^{+0.028}_{-0.033}$

$g_A^d = -0.527^{+0.040}_{-0.028}$

$g^{\nu\ell} = 0.5008 \pm 0.0008$

$g^{\nu e} = 0.53 \pm 0.09$

$g^{\nu\mu} = 0.502 \pm 0.017$

**Asymmetry parameters [h]**

$A_e = 0.1515 \pm 0.0019$

$A_\mu = 0.142 \pm 0.015$

$A_\tau = 0.143 \pm 0.004$

$A_S = 0.90 \pm 0.09$

$A_C = 0.670 \pm 0.027$

$A_b = 0.923 \pm 0.020$

**Charge asymmetry (%) at Z pole**

$A_{FB}^{(0\ell)} = 1.71 \pm 0.10$

$A_{FB}^{(0u)} = 4 \pm 7$

$A_{FB}^{(0S)} = 9.8 \pm 1.1$

$A_{FB}^{(0C)} = 7.07 \pm 0.35$

$A_{FB}^{(0b)} = 9.92 \pm 0.16$

Z DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$e^+ e^-$	( 3.3632 ± 0.0042) %		45594
$\mu^+ \mu^-$	( 3.3662 ± 0.0066) %		45594

## 12 Gauge & Higgs Boson Summary Table

$\tau^+ \tau^-$	( 3.3696 ± 0.0083 ) %		45559
$\ell^+ \ell^-$	[c] ( 3.3658 ± 0.0023 ) %		—
$\ell^+ \ell^- \ell^+ \ell^-$	[f] ( 4.55 ± 0.17 ) × 10 <sup>-6</sup>		45594
invisible	(20.000 ± 0.055 ) %		—
hadrons	(69.911 ± 0.056 ) %		—
$(u\bar{u} + c\bar{c})/2$	(11.6 ± 0.6 ) %		—
$(d\bar{d} + s\bar{s} + b\bar{b})/3$	(15.6 ± 0.4 ) %		—
$c\bar{c}$	(12.03 ± 0.21 ) %		—
$b\bar{b}$	(15.12 ± 0.05 ) %		—
$b\bar{b}b\bar{b}$	( 3.6 ± 1.3 ) × 10 <sup>-4</sup>		—
$g g g$	< 1.1	%	CL=95% —
$\pi^0 \gamma$	< 2.01	× 10 <sup>-5</sup>	CL=95% 45594
$\eta \gamma$	< 5.1	× 10 <sup>-5</sup>	CL=95% 45592
$\rho^0 \gamma$	< 4.0	× 10 <sup>-6</sup>	CL=95% 45591
$\omega \gamma$	< 3.9	× 10 <sup>-6</sup>	CL=95% 45591
$\eta'(958) \gamma$	< 4.2	× 10 <sup>-5</sup>	CL=95% 45589
$\phi \gamma$	< 7	× 10 <sup>-7</sup>	CL=95% 45588
$\gamma \gamma$	< 1.46	× 10 <sup>-5</sup>	CL=95% 45594
$\pi^0 \pi^0$	< 1.52	× 10 <sup>-5</sup>	CL=95% 45594
$\gamma \gamma \gamma$	< 2.2	× 10 <sup>-6</sup>	CL=95% 45594
$\pi^\pm W^\mp$	[j] < 7	× 10 <sup>-5</sup>	CL=95% 10176
$\rho^\pm W^\mp$	[j] < 8.3	× 10 <sup>-5</sup>	CL=95% 10151
$J/\psi(1S) X$	( 3.51 <sup>+0.23</sup> <sub>-0.25</sub> ) × 10 <sup>-3</sup>	S=1.1	—
$J/\psi(1S) \gamma$	< 1.2	× 10 <sup>-6</sup>	CL=95% 45541
$\psi(2S) X$	( 1.60 ± 0.29 ) × 10 <sup>-3</sup>		—
$\psi(2S) \gamma$	< 2.4	× 10 <sup>-6</sup>	CL=95% 45519
$J/\psi(1S) J/\psi(1S)$	< 2.2	× 10 <sup>-6</sup>	CL=95% 45489
$\chi_{c1}(1P) X$	( 2.9 ± 0.7 ) × 10 <sup>-3</sup>		—
$\chi_{c2}(1P) X$	< 3.2	× 10 <sup>-3</sup>	CL=90% —
$\Upsilon(1S) X + \Upsilon(2S) X$ $+ \Upsilon(3S) X$	( 1.0 ± 0.5 ) × 10 <sup>-4</sup>		—
$\Upsilon(1S) X$	< 4.4	× 10 <sup>-5</sup>	CL=95% —
$\Upsilon(1S) \gamma$	< 1.1	× 10 <sup>-6</sup>	CL=95% 45103
$\Upsilon(2S) X$	< 1.39	× 10 <sup>-4</sup>	CL=95% —
$\Upsilon(2S) \gamma$	< 1.3	× 10 <sup>-6</sup>	CL=95% 45043
$\Upsilon(3S) X$	< 9.4	× 10 <sup>-5</sup>	CL=95% —
$\Upsilon(3S) \gamma$	< 2.4	× 10 <sup>-6</sup>	CL=95% 45006
$\Upsilon(1, 2, 3S) \Upsilon(1, 2, 3S)$	< 1.5	× 10 <sup>-6</sup>	CL=95% —
$D^0 \gamma$	< 2.2	× 10 <sup>-3</sup>	CL=95% 45575
$(D^0 / \bar{D}^0) X$	(20.7 ± 2.0 ) %		—
$D^\pm X$	(12.2 ± 1.7 ) %		—
$D^*(2010)^\pm X$	[j] (11.4 ± 1.3 ) %		—
$D_{s1}(2536)^\pm X$	( 3.6 ± 0.8 ) × 10 <sup>-3</sup>		—
$D_{sJ}(2573)^\pm X$	( 5.8 ± 2.2 ) × 10 <sup>-3</sup>		—
$B^+ X$	[k] ( 6.08 ± 0.13 ) %		—
$B_s^0 X$	[k] ( 1.59 ± 0.13 ) %		—
$\Lambda_c^+ X$	( 1.54 ± 0.33 ) %		—
$b$ -baryon $X$	[k] ( 1.38 ± 0.22 ) %		—
anomalous $\gamma +$ hadrons	[f] < 3.2	× 10 <sup>-3</sup>	CL=95% —
$e^+ e^- \gamma$	[f] < 5.2	× 10 <sup>-4</sup>	CL=95% 45594
$\mu^+ \mu^- \gamma$	[f] < 5.6	× 10 <sup>-4</sup>	CL=95% 45594
$\tau^+ \tau^- \gamma$	[f] < 7.3	× 10 <sup>-4</sup>	CL=95% 45559
$\ell^+ \ell^- \gamma \gamma$	[n] < 6.8	× 10 <sup>-6</sup>	CL=95% —
$q \bar{q} \gamma \gamma$	[n] < 5.5	× 10 <sup>-6</sup>	CL=95% —

$\nu\bar{\nu}\gamma\gamma$		$[n] < 3.1$	$\times 10^{-6}$	CL=95%	45594
$e^{\pm}\mu^{\mp}$	LF	$[j] < 2.62$	$\times 10^{-7}$	CL=95%	45594
$e^{\pm}\tau^{\mp}$	LF	$[j] < 5.0$	$\times 10^{-6}$	CL=95%	45577
$\mu^{\pm}\tau^{\mp}$	LF	$[j] < 6.5$	$\times 10^{-6}$	CL=95%	45577
$pe$	L,B	$< 1.8$	$\times 10^{-6}$	CL=95%	45589
$p\mu$	L,B	$< 1.8$	$\times 10^{-6}$	CL=95%	45589

See Particle Listings for 4 decay modes that have been seen / not seen.

**H**

$J = 0$

was  $H^0$

Mass  $m = 125.20 \pm 0.11$  GeV ( $S = 1.4$ )  
 Full width  $\Gamma = 3.7^{+1.9}_{-1.4}$  MeV (assumes equal  
 on-shell and off-shell effective couplings)

### H Signal Strengths in Different Channels

Combined Final States =  $1.03 \pm 0.04$

$W W^* = 1.00 \pm 0.08$

$Z Z^* = 1.02 \pm 0.08$

$\gamma\gamma = 1.10 \pm 0.06$

$c\bar{c}$  Final State  $< 14$ , CL = 95%

$b\bar{b} = 0.99 \pm 0.12$

$\mu^+\mu^- = 1.21 \pm 0.35$

$\tau^+\tau^- = 0.91 \pm 0.09$

$Z\gamma = 2.2 \pm 0.7$

$\gamma^*\gamma$  Final State =  $1.5 \pm 0.5$

Fermion coupling ( $\kappa_F$ ) =  $0.94 \pm 0.05$

Gauge boson coupling ( $\kappa_V$ ) =  $1.023 \pm 0.026$

$t\bar{t}H$  Production =  $1.10 \pm 0.18$

$HH$  Production Cross Section in  $pp$  Collisions  $< 2.4$ , CL = 95%

$tH$  production =  $6 \pm 4$

$H$  Production Cross Section in  $pp$  Collisions at  $\sqrt{s} = 13$  TeV =  
 $56.8 \pm 3.4$  pb

H DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\frac{p}{(\text{MeV}/c)}$
$W W^*$	(25.7 $\pm$ 2.5 ) %		—
$Z Z^*$	( 2.80 $\pm$ 0.30) %		—
$\gamma\gamma$	( 2.50 $\pm$ 0.20) $\times 10^{-3}$		62600
$b\bar{b}$	(53 $\pm$ 8 ) %		—
$e^+e^-$	$< 3.0$ $\times 10^{-4}$	95%	62600
$\mu^+\mu^-$	( 2.6 $\pm$ 1.3 ) $\times 10^{-4}$		62600
$\tau^+\tau^-$	( 6.0 $^{+0.8}_{-0.7}$ ) %		62575
$Z\gamma$	( 3.4 $\pm$ 1.1 ) $\times 10^{-3}$		29392
$Z\rho(770)$	$< 1.21$ %	95%	29384
$Z\phi(1020)$	$< 3.6$ $\times 10^{-3}$	95%	29378
$ZJ/\psi$	$< 1.9$ $\times 10^{-3}$	95%	29267
$Z\psi(2S)$	$< 6.6$ $\times 10^{-3}$	95%	29214
$J/\psi\gamma$	$< 2.0$ $\times 10^{-4}$	95%	62561
$J/\psi J/\psi$	$< 3.8$ $\times 10^{-4}$	95%	62523
$\psi(2S)\gamma$	$< 1.05$ $\times 10^{-3}$	95%	62546
$\psi(2S)J/\psi$	$< 2.1$ $\times 10^{-3}$	95%	62507
$\psi(2S)\psi(2S)$	$< 3.0$ $\times 10^{-3}$	95%	62491

$\Upsilon(1S)\gamma$		< 2.5	$\times 10^{-4}$	95%	62242
$\Upsilon(1S)\Upsilon(1S)$		< 1.7	$\times 10^{-3}$	95%	61881
$\Upsilon(2S)\gamma$		< 4.2	$\times 10^{-4}$	95%	62199
$\Upsilon(3S)\gamma$		< 3.4	$\times 10^{-4}$	95%	62172
$\Upsilon(nS)\Upsilon(mS)$		< 3.5	$\times 10^{-4}$	95%	—
$\rho(770)\gamma$		< 1.04	$\times 10^{-3}$	95%	62597
$\omega(782)\gamma$		< 5.5	$\times 10^{-4}$	95%	62597
$K^*(892)\gamma$		< 2.2	$\times 10^{-4}$	95%	62597
$\phi(1020)\gamma$		< 5	$\times 10^{-4}$	95%	62596
$e\mu$	LF	< 4.4	$\times 10^{-5}$	95%	62600
$e\tau$	LF	< 2.0	$\times 10^{-3}$	95%	62587
$\mu\tau$	LF	< 1.5	$\times 10^{-3}$	95%	62587
invisible		< 10.7	%	95%	—
$\gamma$ invisible		< 2.9	%	95%	—

### Neutral Higgs Bosons, Searches for

#### Mass limits for heavy neutral Higgs bosons ( $H_2^0, A^0$ ) in the MSSM

$m > 1121$ GeV, CL = 95%	( $\tan\beta = 10$ )
$m > 1475$ GeV, CL = 95%	( $\tan\beta = 20$ )
$m > 1677$ GeV, CL = 95%	( $\tan\beta = 30$ )
$m > 1826$ GeV, CL = 95%	( $\tan\beta = 40$ )
$m > 1950$ GeV, CL = 95%	( $\tan\beta = 50$ )
$m > 2062$ GeV, CL = 95%	( $\tan\beta = 60$ )

### Charged Higgs Bosons ( $H^\pm$ and $H^{\pm\pm}$ ), Searches for

#### Mass limits for $m_{H^\pm} < m(\text{top})$ in the MSSM

$m > 155$ GeV, CL = 95%
-------------------------

#### Mass limits for $m_{H^\pm} > m(\text{top})$ in the MSSM

$m > 181$ GeV, CL = 95%	( $\tan\beta = 10$ )
$m > 249$ GeV, CL = 95%	( $\tan\beta = 20$ )
$m > 390$ GeV, CL = 95%	( $\tan\beta = 30$ )
$m > 894$ GeV, CL = 95%	( $\tan\beta = 40$ )
$m > 1017$ GeV, CL = 95%	( $\tan\beta = 50$ )
$m > 1103$ GeV, CL = 95%	( $\tan\beta = 60$ )

### New Heavy Bosons ( $W', Z', \text{leptoquarks, etc.}$ ), Searches for

#### Additional $W$ Bosons

$W'$  with standard couplings

Mass  $m > 6000$  GeV, CL = 95% ( $p\bar{p}$  direct search)

$W_R$  (Right-handed  $W$  Boson)

Mass  $m > 715$  GeV, CL = 90% (electroweak fit)



**Additional Z Bosons** $Z'_{SM}$  with standard couplingsMass  $m > 5150$  GeV, CL = 95% ( $p\bar{p}$  direct search) $Z_{LR}$  of  $SU(2)_L \times SU(2)_R \times U(1)$  (with  $g_L = g_R$ )Mass  $m > 630$  GeV, CL = 95% ( $p\bar{p}$  direct search)Mass  $m > 1162$  GeV, CL = 95% (electroweak fit) $Z_\chi$  of  $SO(10) \rightarrow SU(5) \times U(1)_\chi$  (with  $g_\chi = e/\cos\theta_W$ )Mass  $m > 4800$  GeV, CL = 95% ( $p\bar{p}$  direct search) $Z_\psi$  of  $E_6 \rightarrow SO(10) \times U(1)_\psi$  (with  $g_\psi = e/\cos\theta_W$ )Mass  $m > 4560$  GeV, CL = 95% ( $p\bar{p}$  direct search) $Z_\eta$  of  $E_6 \rightarrow SU(3) \times SU(2) \times U(1) \times U(1)_\eta$  (with  $g_\eta = e/\cos\theta_W$ )Mass  $m > 3.900 \times 10^3$  GeV, CL = 95% ( $p\bar{p}$  direct search)**Scalar Leptoquarks** $m > 1800$  GeV, CL = 95% (1st gen., pair prod.,  $B(eq)=1$ ) $m > 1755$  GeV, CL = 95% (1st gen., single prod.,  $B(eq)=1$ ) $m > 1700$  GeV, CL = 95% (2nd gen., pair prod.,  $B(\mu q)=1$ ) $m > 660$  GeV, CL = 95% (2nd gen., single prod.,  $B(\mu q)=1$ ) $m > 1460$  GeV, CL = 95% (3rd gen., pair prod.,  $B(\tau b)=1$ ) $m > 1280$  GeV, CL = 95% (3rd gen., single prod.,  $B(\tau b)=1$ )

(See the Particle Listings in the Full *Review of Particle Physics* for assumptions on leptoquark quantum numbers and branching fractions.)

**Diquarks**Mass  $m > 7200$  GeV, CL = 95% ( $E_6$  diquark)**Axigluon**Mass  $m > 6600$  GeV, CL = 95%**Axions ( $A^0$ ) and Other  
Very Light Bosons, Searches for**

See the review on "Axions and other similar particles."

The best limit for the half-life of neutrinoless double beta decay with Majoron emission is  $> 7.2 \times 10^{24}$  years (CL = 90%).

## NOTES

In this Summary Table:

When a quantity has “(S = ...)” to its right, the error on the quantity has been enlarged by the “scale factor” S, defined as  $S = \sqrt{\chi^2/(N-1)}$ , where  $N$  is the number of measurements used in calculating the quantity.

A decay momentum  $p$  is given for each decay mode. For a 2-body decay,  $p$  is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay,  $p$  is the largest momentum any of the products can have in this frame.

- [a] Theoretical value. A mass as large as a few MeV may not be precluded.
- [b] This value does not include the AALTONEN 22 measurement by CDF. See the  $W$  mass section in the listings for details.
- [c]  $\ell$  indicates each type of lepton ( $e$ ,  $\mu$ , and  $\tau$ ), not sum over them.
- [d] This represents the width for the decay of the  $W$  boson into a charged particle with momentum below detectability,  $p < 200$  MeV.
- [e] The  $Z$ -boson mass listed here corresponds to a Breit-Wigner resonance parameter. It lies approximately 34 MeV above the real part of the position of the pole (in the energy-squared plane) in the  $Z$ -boson propagator.
- [f] This partial width takes into account  $Z$  decays into  $\nu\bar{\nu}$  and any other possible undetected modes.
- [g] This ratio has not been corrected for the  $\tau$  mass.
- [h] Here  $A \equiv 2g_V g_A / (g_V^2 + g_A^2)$ .
- [i] Here  $\ell$  indicates  $e$  or  $\mu$ .
- [j] The value is for the sum of the charge states or particle/antiparticle states indicated.
- [k] This value is updated using the product of (i) the  $Z \rightarrow b\bar{b}$  fraction from this listing and (ii) the  $b$ -hadron fraction in an unbiased sample of weakly decaying  $b$ -hadrons produced in  $Z$ -decays provided by the Heavy Flavor Averaging Group (HFLAV, [http://www.slac.stanford.edu/xorg/hflav/osc/PDG\\_2009/#FRACZ](http://www.slac.stanford.edu/xorg/hflav/osc/PDG_2009/#FRACZ)).
- [l] See the  $Z$  Particle Listings in the Full *Review of Particle Physics* for the  $\gamma$  energy range used in this measurement.
- [n] For  $m_{\gamma\gamma} = (60 \pm 5)$  GeV.

# LEPTONS

**e**

$$J = \frac{1}{2}$$

Mass  $m = (548.579909065 \pm 0.000000016) \times 10^{-6}$  uMass  $m = 0.51099895000 \pm 0.00000000015$  MeV $|m_{e^+} - m_{e^-}|/m < 8 \times 10^{-9}$ , CL = 90% $|q_{e^+} + q_{e^-}|/e < 4 \times 10^{-8}$ 

Magnetic moment anomaly

$$(g-2)/2 = (1159.65218062 \pm 0.00000012) \times 10^{-6}$$

 $(g_{e^+} - g_{e^-}) / g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$ Electric dipole moment  $d < 0.041 \times 10^{-28}$  e cm, CL = 90%Mean life  $\tau > 6.6 \times 10^{28}$  yr, CL = 90% [a] **$\mu$** 

$$J = \frac{1}{2}$$

Mass  $m = 0.1134289259 \pm 0.0000000025$  uMass  $m = 105.6583755 \pm 0.0000023$  MeVMean life  $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$  s $\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$ 

$$c\tau = 658.6384 \text{ m}$$

Magnetic moment anomaly  $(g-2)/2 = (11659205.9 \pm 2.2) \times 10^{-10}$  $(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}} = (-0.11 \pm 0.12) \times 10^{-8}$ Electric dipole moment  $|d| < 1.8 \times 10^{-19}$  e cm, CL = 95%**Decay parameters** [b]

$$\rho = 0.74979 \pm 0.00026$$

$$\eta = 0.057 \pm 0.034$$

$$\delta = 0.75047 \pm 0.00034$$

$$\xi P_{\mu} = 1.0009^{+0.0016}_{-0.0007} \text{ [c]}$$

$$\xi P_{\mu} \delta / \rho = 1.0018^{+0.0016}_{-0.0007} \text{ [c]}$$

$$\xi' = 1.00 \pm 0.04$$

$$\xi'' = 0.98 \pm 0.04$$

$$\alpha/A = (0 \pm 4) \times 10^{-3}$$

$$\alpha'/A = (-10 \pm 20) \times 10^{-3}$$

$$\beta/A = (4 \pm 6) \times 10^{-3}$$

$$\beta'/A = (2 \pm 7) \times 10^{-3}$$

$$\bar{\eta} = 0.02 \pm 0.08$$

 $\mu^+$  modes are charge conjugates of the modes below.

$\mu^-$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Confidence level	$P$ (MeV/c)
$e^- \bar{\nu}_e \nu_{\mu}$	$\approx 100\%$		53
$e^- \bar{\nu}_e \nu_{\mu} \gamma$	[d] $(6.0 \pm 0.5) \times 10^{-8}$		53
$e^- \bar{\nu}_e \nu_{\mu} e^+ e^-$	[e] $(3.4 \pm 0.4) \times 10^{-5}$		53
<b>Lepton Family number (LF) violating modes</b>			
$e^- \nu_e \bar{\nu}_{\mu}$	LF [f] $< 1.2$	%	90% 53
$e^- \gamma$	LF $< 4.2$	$\times 10^{-13}$	90% 53
$e^- e^+ e^-$	LF $< 1.0$	$\times 10^{-12}$	90% 53
$e^- 2\gamma$	LF $< 7.2$	$\times 10^{-11}$	90% 53

**$\tau$**

$$J = \frac{1}{2}$$

Mass  $m = 1776.93 \pm 0.09$  MeV

$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8 \times 10^{-4}$ , CL = 90%

Mean life  $\tau = (290.3 \pm 0.5) \times 10^{-15}$  s

$$c\tau = 87.03 \text{ } \mu\text{m}$$

Magnetic moment anomaly =  $-0.057$  to  $0.024$ , CL = 95%

$\text{Re}(d_\tau) = -0.185$  to  $0.061 \times 10^{-16}$  e cm, CL = 95%

$\text{Im}(d_\tau) = -0.103$  to  $0.0230 \times 10^{-16}$  e cm, CL = 95%

**Weak dipole moment**

$\text{Re}(d_\tau^W) < 0.50 \times 10^{-17}$  e cm, CL = 95%

$\text{Im}(d_\tau^W) < 1.1 \times 10^{-17}$  e cm, CL = 95%

**Weak anomalous magnetic dipole moment**

$\text{Re}(\alpha_\tau^W) < 1.1 \times 10^{-3}$ , CL = 95%

$\text{Im}(\alpha_\tau^W) < 2.7 \times 10^{-3}$ , CL = 95%

$\tau^\pm \rightarrow \pi^\pm K_S^0 \nu_\tau$  (RATE DIFFERENCE) / (RATE SUM) =  $(-0.36 \pm 0.25)\%$

**Decay parameters**

See the  $\tau$  Particle Listings in the Full *Review of Particle Physics* for a note concerning  $\tau$ -decay parameters.

$$\rho(e \text{ or } \mu) = 0.745 \pm 0.008$$

$$\rho(e) = 0.747 \pm 0.010$$

$$\rho(\mu) = 0.763 \pm 0.020$$

$$\xi(e \text{ or } \mu) = 0.985 \pm 0.030$$

$$\xi(e) = 0.994 \pm 0.040$$

$$\xi(\mu) = 1.030 \pm 0.059$$

$$\eta(e \text{ or } \mu) = 0.013 \pm 0.020$$

$$\eta(\mu) = 0.094 \pm 0.073$$

$$(\delta\xi)(e \text{ or } \mu) = 0.746 \pm 0.021$$

$$(\delta\xi)(e) = 0.734 \pm 0.028$$

$$(\delta\xi)(\mu) = 0.778 \pm 0.037$$

$$\xi(\pi) = 0.993 \pm 0.022$$

$$\xi(\rho) = 0.994 \pm 0.008$$

$$\xi(a_1) = 1.001 \pm 0.027$$

$$\xi(\text{all hadronic modes}) = 0.995 \pm 0.007$$

$$\xi'(\mu) = 0.2 \pm 1.0$$

$$\bar{\eta}(\mu) = -1.3 \pm 1.7$$

$$(\xi\kappa)(e \text{ or } \mu) = 0.5 \pm 0.4$$

$$(\xi\kappa)(e) = -0.4 \pm 1.2$$

$$(\xi\kappa)(\mu) = 0.8 \pm 0.6$$

$\tau^+$  modes are charge conjugates of the modes below. " $h^\pm$ " stands for  $\pi^\pm$  or  $K^\pm$ . " $l$ " stands for  $e$  or  $\mu$ . "Neutrals" stands for  $\gamma$ 's and/or  $\pi^0$ 's.

$\tau^-$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Modes with one charged particle</b>			
particle <sup>-</sup> $\geq 0$ neutrals $\geq 0 K^0 \nu_\tau$ ("1-prong")	(85.24 $\pm$ 0.06 ) %		—
particle <sup>-</sup> $\geq 0$ neutrals $\geq 0 K_L^0 \nu_\tau$	(84.58 $\pm$ 0.06 ) %		—
$\mu^- \bar{\nu}_\mu \nu_\tau$	[g] (17.39 $\pm$ 0.04 ) %		885

$\mu^- \bar{\nu}_\mu \nu_\tau \gamma$	[e]	$(3.67 \pm 0.08) \times 10^{-3}$	885
$e^- \bar{\nu}_e \nu_\tau$	[g]	$(17.82 \pm 0.04) \%$	888
$e^- \bar{\nu}_e \nu_\tau \gamma$	[e]	$(1.83 \pm 0.05) \%$	888
$h^- \geq 0 K_L^0 \nu_\tau$		$(12.03 \pm 0.05) \%$	883
$h^- \nu_\tau$		$(11.51 \pm 0.05) \%$	883
$\pi^- \nu_\tau$	[g]	$(10.82 \pm 0.05) \%$	883
$K^- \nu_\tau$	[g]	$(6.96 \pm 0.10) \times 10^{-3}$	820
$h^- \geq 1 \text{ neutrals } \nu_\tau$		$(37.00 \pm 0.09) \%$	-
$h^- \geq 1 \pi^0 \nu_\tau \text{ (ex. } K^0)$		$(36.50 \pm 0.09) \%$	-
$h^- \pi^0 \nu_\tau$		$(25.93 \pm 0.09) \%$	878
$\pi^- \pi^0 \nu_\tau$	[g]	$(25.49 \pm 0.09) \%$	878
$\pi^- \pi^0 \text{ non-}\rho(770) \nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$	878
$K^- \pi^0 \nu_\tau$	[g]	$(4.33 \pm 0.15) \times 10^{-3}$	814
$h^- \geq 2 \pi^0 \nu_\tau$		$(10.81 \pm 0.09) \%$	-
$h^- 2 \pi^0 \nu_\tau$		$(9.48 \pm 0.10) \%$	862
$h^- 2 \pi^0 \nu_\tau \text{ (ex. } K^0)$		$(9.32 \pm 0.10) \%$	862
$\pi^- 2 \pi^0 \nu_\tau \text{ (ex. } K^0)$	[g]	$(9.26 \pm 0.10) \%$	862
$\pi^- 2 \pi^0 \nu_\tau \text{ (ex. } K^0),$ scalar		$< 9 \times 10^{-3}$	CL=95% 862
$\pi^- 2 \pi^0 \nu_\tau \text{ (ex. } K^0),$ vector		$< 7 \times 10^{-3}$	CL=95% 862
$K^- 2 \pi^0 \nu_\tau \text{ (ex. } K^0)$	[g]	$(6.5 \pm 2.2) \times 10^{-4}$	796
$h^- \geq 3 \pi^0 \nu_\tau$		$(1.34 \pm 0.07) \%$	-
$h^- \geq 3 \pi^0 \nu_\tau \text{ (ex. } K^0)$		$(1.25 \pm 0.07) \%$	-
$h^- 3 \pi^0 \nu_\tau$		$(1.18 \pm 0.07) \%$	836
$\pi^- 3 \pi^0 \nu_\tau \text{ (ex. } K^0)$	[g]	$(1.04 \pm 0.07) \%$	836
$K^- 3 \pi^0 \nu_\tau \text{ (ex. } K^0, \eta)$	[g]	$(4.8 \pm 2.1) \times 10^{-4}$	766
$h^- 4 \pi^0 \nu_\tau \text{ (ex. } K^0)$		$(1.6 \pm 0.4) \times 10^{-3}$	800
$h^- 4 \pi^0 \nu_\tau \text{ (ex. } K^0, \eta)$	[g]	$(1.1 \pm 0.4) \times 10^{-3}$	800
$a_1(1260) \nu_\tau \rightarrow \pi^- \gamma \nu_\tau$		$(4.0 \pm 1.5) \times 10^{-4}$	-
$K^- \geq 0 \pi^0 \geq 0 K^0 \geq 0 \gamma \nu_\tau$		$(1.552 \pm 0.029) \%$	820
$K^- \geq 1 (\pi^0 \text{ or } K^0 \text{ or } \gamma) \nu_\tau$		$(8.59 \pm 0.28) \times 10^{-3}$	-

**Modes with  $K^0$ 's**

$K_S^0 \text{ (particles)}^- \nu_\tau$		$(9.43 \pm 0.28) \times 10^{-3}$	-
$h^- \bar{K}^0 \nu_\tau$		$(9.87 \pm 0.14) \times 10^{-3}$	812
$\pi^- \bar{K}^0 \nu_\tau$	[g]	$(8.38 \pm 0.14) \times 10^{-3}$	812
$\pi^- \bar{K}^0 \text{ (non-} K^*(892)^- \nu_\tau)$		$(5.4 \pm 2.1) \times 10^{-4}$	812
$K^- K^0 \nu_\tau$	[g]	$(1.486 \pm 0.034) \times 10^{-3}$	737
$K^- K^0 \geq 0 \pi^0 \nu_\tau$		$(2.99 \pm 0.07) \times 10^{-3}$	737
$h^- \bar{K}^0 \pi^0 \nu_\tau$		$(5.32 \pm 0.13) \times 10^{-3}$	794
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	[g]	$(3.82 \pm 0.13) \times 10^{-3}$	794
$\bar{K}^0 \rho^- \nu_\tau$		$(2.2 \pm 0.5) \times 10^{-3}$	612
$K^- K^0 \pi^0 \nu_\tau$	[g]	$(1.50 \pm 0.07) \times 10^{-3}$	685
$\pi^- \bar{K}^0 \geq 1 \pi^0 \nu_\tau$		$(4.08 \pm 0.25) \times 10^{-3}$	-
$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau \text{ (ex. } K^0)$	[g]	$(2.6 \pm 2.3) \times 10^{-4}$	763
$K^- K^0 \pi^0 \pi^0 \nu_\tau$		$< 1.6 \times 10^{-4}$	CL=95% 619
$\pi^- K^0 \bar{K}^0 \nu_\tau$		$(1.55 \pm 0.24) \times 10^{-3}$	682
$\pi^- K_S^0 K_S^0 \nu_\tau$	[g]	$(2.35 \pm 0.06) \times 10^{-4}$	682
$\pi^- K_S^0 K_L^0 \nu_\tau$	[g]	$(1.08 \pm 0.24) \times 10^{-3}$	682
$\pi^- K_L^0 K_L^0 \nu_\tau$		$(2.35 \pm 0.06) \times 10^{-4}$	682
$\pi^- K^0 \frac{1}{2} K^0 \pi^0 \nu_\tau$		$(3.6 \pm 1.2) \times 10^{-4}$	614
$\pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$	[g]	$(1.82 \pm 0.21) \times 10^{-5}$	614
$K^{*-} K^0 \pi^0 \nu_\tau \rightarrow$ $\pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$		$(1.08 \pm 0.21) \times 10^{-5}$	-

$f_1(1285)\pi^-\nu_\tau \rightarrow$ $\pi^-K_S^0K_S^0\pi^0\nu_\tau$	( 6.8 ± 1.5 ) × 10 <sup>-6</sup>	-
$f_1(1420)\pi^-\nu_\tau \rightarrow$ $\pi^-K_S^0K_S^0\pi^0\nu_\tau$	( 2.4 ± 0.8 ) × 10 <sup>-6</sup>	-
$\pi^-K_S^0K_L^0\pi^0\nu_\tau$	[g] ( 3.2 ± 1.2 ) × 10 <sup>-4</sup>	614
$\pi^-K_L^0K_L^0\pi^0\nu_\tau$	( 1.82 ± 0.21 ) × 10 <sup>-5</sup>	614
$K^-K_S^0K_S^0\nu_\tau$	< 6.3 × 10 <sup>-7</sup>	CL=90% 466
$K^-K_S^0K_S^0\pi^0\nu_\tau$	< 4.0 × 10 <sup>-7</sup>	CL=90% 337
$K^0h^+h^-h^- \geq 0$ neutrals $\nu_\tau$	< 1.7 × 10 <sup>-3</sup>	CL=95% 760
$K^0h^+h^-h^-\nu_\tau$	[g] ( 2.5 ± 2.0 ) × 10 <sup>-4</sup>	760
<b>Modes with three charged particles</b>		
$h^-h^-h^+ \geq 0$ neutrals $\geq 0K_L^0\nu_\tau$	(15.20 ± 0.06 ) %	861
$h^-h^-h^+ \geq 0$ neutrals $\nu_\tau$ (ex. $K_S^0 \rightarrow \pi^+\pi^-$ ) ("3-prong")	(14.55 ± 0.06 ) %	861
$h^-h^-h^+\nu_\tau$	( 9.80 ± 0.05 ) %	861
$h^-h^-h^+\nu_\tau$ (ex. $K^0$ )	( 9.46 ± 0.05 ) %	861
$h^-h^-h^+\nu_\tau$ (ex. $K^0, \omega$ )	( 9.43 ± 0.05 ) %	861
$\pi^-\pi^+\pi^-\nu_\tau$	( 9.31 ± 0.05 ) %	861
$\pi^-\pi^+\pi^-\nu_\tau$ (ex. $K^0$ )	( 9.02 ± 0.05 ) %	861
$\pi^-\pi^+\pi^-\nu_\tau$ (ex. $K^0$ ), non-axial vector	< 2.4 %	CL=95% 861
$\pi^-\pi^+\pi^-\nu_\tau$ (ex. $K^0, \omega$ )	[g] ( 8.99 ± 0.05 ) %	861
$h^-h^-h^+ \geq 1$ neutrals $\nu_\tau$	( 5.29 ± 0.05 ) %	-
$h^-h^-h^+ \geq 1\pi^0\nu_\tau$ (ex. $K^0$ )	( 5.09 ± 0.05 ) %	-
$h^-h^-h^+\pi^0\nu_\tau$	( 4.76 ± 0.05 ) %	834
$h^-h^-h^+\pi^0\nu_\tau$ (ex. $K^0$ )	( 4.57 ± 0.05 ) %	834
$h^-h^-h^+\pi^0\nu_\tau$ (ex. $K^0, \omega$ )	( 2.79 ± 0.07 ) %	834
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$	( 4.62 ± 0.05 ) %	834
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. $K^0$ )	( 4.49 ± 0.05 ) %	834
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. $K^0, \omega$ )	[g] ( 2.74 ± 0.07 ) %	834
$h^-h^-h^+ \geq 2\pi^0\nu_\tau$ (ex. $K^0$ )	( 5.17 ± 0.31 ) × 10 <sup>-3</sup>	-
$h^-h^-h^+2\pi^0\nu_\tau$	( 5.05 ± 0.31 ) × 10 <sup>-3</sup>	797
$h^-h^-h^+2\pi^0\nu_\tau$ (ex. $K^0$ )	( 4.95 ± 0.31 ) × 10 <sup>-3</sup>	797
$h^-h^-h^+2\pi^0\nu_\tau$ (ex. $K^0, \omega, \eta$ )	[g] (10 ± 4 ) × 10 <sup>-4</sup>	797
$h^-h^-h^+3\pi^0\nu_\tau$	( 2.13 ± 0.30 ) × 10 <sup>-4</sup>	749
$2\pi^-\pi^+3\pi^0\nu_\tau$ (ex. $K^0$ )	( 1.94 ± 0.30 ) × 10 <sup>-4</sup>	749
$2\pi^-\pi^+3\pi^0\nu_\tau$ (ex. $K^0, \eta$ )	( 1.7 ± 0.4 ) × 10 <sup>-4</sup>	-
$f_1(1285)$ $2\pi^-\pi^+3\pi^0\nu_\tau$ (ex. $K^0, \eta$ , $\omega, f_1(1285)$ )	[g] ( 1.4 ± 2.7 ) × 10 <sup>-5</sup>	-
$K^-h^+h^- \geq 0$ neutrals $\nu_\tau$	( 6.29 ± 0.14 ) × 10 <sup>-3</sup>	794
$K^-h^+\pi^-\nu_\tau$ (ex. $K^0$ )	( 4.37 ± 0.07 ) × 10 <sup>-3</sup>	794
$K^-h^+\pi^-\pi^0\nu_\tau$ (ex. $K^0$ )	( 8.6 ± 1.2 ) × 10 <sup>-4</sup>	763
$K^-\pi^+\pi^- \geq 0$ neutrals $\nu_\tau$	( 4.77 ± 0.14 ) × 10 <sup>-3</sup>	794
$K^-\pi^+\pi^- \geq 0\pi^0\nu_\tau$ (ex. $K^0$ )	( 3.73 ± 0.13 ) × 10 <sup>-3</sup>	794
$K^-\pi^+\pi^-\nu_\tau$	( 3.45 ± 0.07 ) × 10 <sup>-3</sup>	794
$K^-\pi^+\pi^-\nu_\tau$ (ex. $K^0$ )	( 2.93 ± 0.07 ) × 10 <sup>-3</sup>	794
$K^-\pi^+\pi^-\nu_\tau$ (ex. $K^0, \omega$ )	[g] ( 2.93 ± 0.07 ) × 10 <sup>-3</sup>	794
$K^-\rho^0\nu_\tau \rightarrow K^-\pi^+\pi^-\nu_\tau$	( 1.4 ± 0.5 ) × 10 <sup>-3</sup>	-
$K^-\pi^+\pi^-\pi^0\nu_\tau$	( 1.31 ± 0.12 ) × 10 <sup>-3</sup>	763
$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. $K^0$ )	( 7.9 ± 1.2 ) × 10 <sup>-4</sup>	763
$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. $K^0, \eta$ )	( 7.6 ± 1.2 ) × 10 <sup>-4</sup>	763
$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. $K^0, \omega$ )	( 3.7 ± 0.9 ) × 10 <sup>-4</sup>	763

$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex. $K^0, \omega, \eta$ ) [g]	$(3.9 \pm 1.4) \times 10^{-4}$		763
$K^- \pi^+ K^- \geq 0$ neut. $\nu_\tau$	$< 9$	$\times 10^{-4}$	CL=95% 685
$K^- K^+ \pi^- \geq 0$ neut. $\nu_\tau$	$(1.496 \pm 0.033) \times 10^{-3}$		685
$K^- K^+ \pi^- \nu_\tau$ [g]	$(1.435 \pm 0.027) \times 10^{-3}$		685
$K^- K^+ \pi^- \pi^0 \nu_\tau$ [g]	$(6.1 \pm 1.8) \times 10^{-5}$		618
$K^- K^+ K^- \nu_\tau$	$(2.2 \pm 0.8) \times 10^{-5}$	S=5.4	472
$K^- K^+ K^- \nu_\tau$ (ex. $\phi$ )	$< 2.5$	$\times 10^{-6}$	CL=90% -
$K^- K^+ K^- \pi^0 \nu_\tau$	$< 4.8$	$\times 10^{-6}$	CL=90% 346
$\pi^- K^+ \pi^- \geq 0$ neut. $\nu_\tau$	$< 2.5$	$\times 10^{-3}$	CL=95% 794
$e^- e^- e^+ \bar{\nu}_e \nu_\tau$	$(2.8 \pm 1.5) \times 10^{-5}$		888
$\mu^- e^- e^+ \bar{\nu}_\mu \nu_\tau$	$< 3.2$	$\times 10^{-5}$	CL=90% 885
$\pi^- \mu^- \mu^+ \nu_\tau$	$< 1.14$	$\times 10^{-5}$	CL=90% 870

### Modes with five charged particles

$3h^- 2h^+ \geq 0$ neutrals $\nu_\tau$	$(9.9 \pm 0.4) \times 10^{-4}$		794
(ex. $K_S^0 \rightarrow \pi^- \pi^+$ )			
("5-prong")			
$3h^- 2h^+ \nu_\tau$ (ex. $K^0$ )	$(8.29 \pm 0.31) \times 10^{-4}$		794
$3\pi^- 2\pi^+ \nu_\tau$ (ex. $K^0, \omega$ )	$(8.27 \pm 0.31) \times 10^{-4}$		794
$3\pi^- 2\pi^+ \nu_\tau$ (ex. $K^0, \omega,$	[g] $(7.75 \pm 0.30) \times 10^{-4}$		-
$f_1(1285)$ )			
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. $K^0$ )	[g] $(6 \pm 12) \times 10^{-7}$		716
$K^+ 3\pi^- \pi^+ \nu_\tau$	$< 5.0$	$\times 10^{-6}$	CL=90% 716
$K^+ K^- 2\pi^- \pi^+ \nu_\tau$	$< 4.5$	$\times 10^{-7}$	CL=90% 528
$3h^- 2h^+ \pi^0 \nu_\tau$ (ex. $K^0$ )	$(1.65 \pm 0.11) \times 10^{-4}$		746
$3\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. $K^0$ )	$(1.64 \pm 0.11) \times 10^{-4}$		746
$3\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. $K^0, \eta,$	$(1.11 \pm 0.10) \times 10^{-4}$		-
$f_1(1285)$ )			
$3\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. $K^0, \eta, \omega,$	[g] $(3.8 \pm 0.9) \times 10^{-5}$		-
$f_1(1285)$ )			
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. $K^0$ )	[g] $(1.1 \pm 0.6) \times 10^{-6}$		657
$K^+ 3\pi^- \pi^+ \pi^0 \nu_\tau$	$< 8$	$\times 10^{-7}$	CL=90% 657
$3h^- 2h^+ 2\pi^0 \nu_\tau$	$< 3.4$	$\times 10^{-6}$	CL=90% 687

### Miscellaneous other allowed modes

$(5\pi)^- \nu_\tau$	$(7.8 \pm 0.5) \times 10^{-3}$		800
$4h^- 3h^+ \geq 0$ neutrals $\nu_\tau$	$< 3.0$	$\times 10^{-7}$	CL=90% 682
("7-prong")			
$4h^- 3h^+ \nu_\tau$	$< 4.3$	$\times 10^{-7}$	CL=90% 682
$4h^- 3h^+ \pi^0 \nu_\tau$	$< 2.5$	$\times 10^{-7}$	CL=90% 612
$X^-(S=-1) \nu_\tau$	$(2.92 \pm 0.04) \%$		-
$K^*(892)^- \geq 0$ neutrals $\geq$	$(1.42 \pm 0.18) \%$	S=1.4	665
$0K_L^0 \nu_\tau$			
$K^*(892)^- \nu_\tau$	$(1.20 \pm 0.07) \%$	S=1.8	665
$K^*(892)^- \nu_\tau \rightarrow \pi^- \bar{K}^0 \nu_\tau$	$(7.82 \pm 0.26) \times 10^{-3}$		-
$K^*(892)^0 K^- \geq 0$ neutrals $\nu_\tau$	$(3.2 \pm 1.4) \times 10^{-3}$		542
$K^*(892)^0 K^- \nu_\tau$	$(2.1 \pm 0.4) \times 10^{-3}$		542
$\bar{K}^*(892)^0 \pi^- \geq 0$ neutrals $\nu_\tau$	$(3.8 \pm 1.7) \times 10^{-3}$		656
$\bar{K}^*(892)^0 \pi^- \nu_\tau$	$(2.2 \pm 0.5) \times 10^{-3}$		656
$(\bar{K}^*(892) \pi)^- \nu_\tau \rightarrow \pi^- \bar{K}^0 \pi^0 \nu_\tau$	$(1.0 \pm 0.4) \times 10^{-3}$		-
$K_1(1270)^- \nu_\tau$	$(4.7 \pm 1.1) \times 10^{-3}$		447
$K_1(1400)^- \nu_\tau$	$(1.7 \pm 2.6) \times 10^{-3}$	S=1.7	335
$K^*(1410)^- \nu_\tau$	$(1.5 \pm 1.4) \times 10^{-3}$		326
$K_0^*(1430)^- \nu_\tau$	$< 5$	$\times 10^{-4}$	CL=95% 317
$K_2^*(1430)^- \nu_\tau$	$< 3$	$\times 10^{-3}$	CL=95% 315

$\eta\pi^-\nu_\tau$		$< 9.9$	$\times 10^{-5}$	CL=95%	797
$\eta\pi^-\pi^0\nu_\tau$	[g]	$(1.39 \pm 0.07)$	$\times 10^{-3}$		778
$\eta\pi^-\pi^0\pi^0\nu_\tau$	[g]	$(1.9 \pm 0.4)$	$\times 10^{-4}$		746
$\eta K^-\nu_\tau$	[g]	$(1.55 \pm 0.08)$	$\times 10^{-4}$		720
$\eta K^*(892)^-\nu_\tau$		$(1.38 \pm 0.15)$	$\times 10^{-4}$		511
$\eta K^-\pi^0\nu_\tau$	[g]	$(4.8 \pm 1.2)$	$\times 10^{-5}$		665
$\eta K^-\pi^0(\text{non-}K^*(892))\nu_\tau$		$< 3.5$	$\times 10^{-5}$	CL=90%	-
$\eta\bar{K}^0\pi^-\nu_\tau$	[g]	$(9.4 \pm 1.5)$	$\times 10^{-5}$		661
$\eta\bar{K}^0\pi^-\pi^0\nu_\tau$		$< 5.0$	$\times 10^{-5}$	CL=90%	590
$\eta K^-K^0\nu_\tau$		$< 9.0$	$\times 10^{-6}$	CL=90%	430
$\eta\pi^+\pi^-\pi^-\geq 0$ neutrals $\nu_\tau$		$< 3$	$\times 10^{-3}$	CL=90%	744
$\eta\pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0)$	[g]	$(2.20 \pm 0.13)$	$\times 10^{-4}$		744
$\eta\pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0, f_1(1285))$		$(9.9 \pm 1.6)$	$\times 10^{-5}$		-
$\eta a_1(1260)^-\nu_\tau \rightarrow \eta\pi^-\rho^0\nu_\tau$		$< 3.9$	$\times 10^{-4}$	CL=90%	-
$\eta\eta\pi^-\nu_\tau$		$< 7.4$	$\times 10^{-6}$	CL=90%	637
$\eta\eta\pi^-\pi^0\nu_\tau$		$< 2.0$	$\times 10^{-4}$	CL=95%	559
$\eta\eta K^-\nu_\tau$		$< 3.0$	$\times 10^{-6}$	CL=90%	382
$\eta'(958)\pi^-\nu_\tau$		$< 4.0$	$\times 10^{-6}$	CL=90%	620
$\eta'(958)\pi^-\pi^0\nu_\tau$		$< 1.2$	$\times 10^{-5}$	CL=90%	591
$\eta'(958)K^-\nu_\tau$		$< 2.4$	$\times 10^{-6}$	CL=90%	495
$\phi\pi^-\nu_\tau$		$(3.4 \pm 0.6)$	$\times 10^{-5}$		585
$\phi K^-\nu_\tau$	[g]	$(4.4 \pm 1.6)$	$\times 10^{-5}$		445
$f_1(1285)\pi^-\nu_\tau$		$(3.9 \pm 0.5)$	$\times 10^{-4}$	S=1.9	408
$f_1(1285)\pi^-\nu_\tau \rightarrow$ $\eta\pi^-\pi^+\pi^-\nu_\tau$		$(1.18 \pm 0.07)$	$\times 10^{-4}$	S=1.3	-
$f_1(1285)\pi^-\nu_\tau \rightarrow 3\pi^-2\pi^+\nu_\tau$	[g]	$(5.2 \pm 0.4)$	$\times 10^{-5}$		-
$\pi(1300)^-\nu_\tau \rightarrow (\rho\pi)^-\nu_\tau \rightarrow$ $(3\pi)^-\nu_\tau$		$< 1.0$	$\times 10^{-4}$	CL=90%	-
$\pi(1300)^-\nu_\tau \rightarrow$ $((\pi\pi)_{S\text{-wave}}\pi)^-\nu_\tau \rightarrow$ $(3\pi)^-\nu_\tau$		$< 1.9$	$\times 10^{-4}$	CL=90%	-
$h^-\omega \geq 0$ neutrals $\nu_\tau$		$(2.40 \pm 0.08)$	%		708
$h^-\omega\nu_\tau$		$(1.99 \pm 0.06)$	%		708
$\pi^-\omega\nu_\tau$	[g]	$(1.95 \pm 0.06)$	%		708
$K^-\omega\nu_\tau$	[g]	$(4.1 \pm 0.9)$	$\times 10^{-4}$		610
$h^-\omega\pi^0\nu_\tau$	[g]	$(4.1 \pm 0.4)$	$\times 10^{-3}$		684
$h^-\omega 2\pi^0\nu_\tau$		$(1.4 \pm 0.5)$	$\times 10^{-4}$		644
$\pi^-\omega 2\pi^0\nu_\tau$	[g]	$(7.2 \pm 1.6)$	$\times 10^{-5}$		644
$h^-2\omega\nu_\tau$		$< 5.4$	$\times 10^{-7}$	CL=90%	250
$2h^-h^+\omega\nu_\tau$		$(1.20 \pm 0.22)$	$\times 10^{-4}$		641
$2\pi^-\pi^+\omega\nu_\tau(\text{ex.}K^0)$	[g]	$(8.4 \pm 0.6)$	$\times 10^{-5}$		641

**Lepton Family number (LF), Lepton number (L),  
or Baryon number (B) violating modes**

*L* means lepton number violation (e.g.  $\tau^- \rightarrow e^+\pi^-\pi^-$ ). Following common usage, *LF* means lepton family violation *and not* lepton number violation (e.g.  $\tau^- \rightarrow e^-\pi^+\pi^-$ ). *B* means baryon number violation.

$e^-\gamma$	LF	$< 3.3$	$\times 10^{-8}$	CL=90%	888
$e^-\gamma\gamma$	LF	$< 2.5$	$\times 10^{-4}$	CL=90%	888
$\mu^-\gamma$	LF	$< 4.2$	$\times 10^{-8}$	CL=90%	885
$\mu^-\gamma\gamma$	LF	$< 5.8$	$\times 10^{-4}$	CL=90%	885
$e^-\pi^0$	LF	$< 8.0$	$\times 10^{-8}$	CL=90%	883
$\mu^-\pi^0$	LF	$< 1.1$	$\times 10^{-7}$	CL=90%	880
$e^-K_S^0$	LF	$< 2.6$	$\times 10^{-8}$	CL=90%	819
$\mu^-K_S^0$	LF	$< 2.3$	$\times 10^{-8}$	CL=90%	815



$e^- \eta$	LF	< 9.2	$\times 10^{-8}$	CL=90%	804
$\mu^- \eta$	LF	< 6.5	$\times 10^{-8}$	CL=90%	800
$e^- \rho^0$	LF	< 2.2	$\times 10^{-8}$	CL=90%	719
$\mu^- \rho^0$	LF	< 1.7	$\times 10^{-8}$	CL=90%	715
$e^- \omega$	LF	< 2.4	$\times 10^{-8}$	CL=90%	716
$\mu^- \omega$	LF	< 3.9	$\times 10^{-8}$	CL=90%	711
$e^- K^*(892)^0$	LF	< 1.9	$\times 10^{-8}$	CL=90%	665
$\mu^- K^*(892)^0$	LF	< 2.9	$\times 10^{-8}$	CL=90%	659
$e^- \bar{K}^*(892)^0$	LF	< 1.7	$\times 10^{-8}$	CL=90%	665
$\mu^- \bar{K}^*(892)^0$	LF	< 4.3	$\times 10^{-8}$	CL=90%	659
$e^- \eta'(958)$	LF	< 1.6	$\times 10^{-7}$	CL=90%	630
$\mu^- \eta'(958)$	LF	< 1.3	$\times 10^{-7}$	CL=90%	625
$e^- f_0(980) \rightarrow e^- \pi^+ \pi^-$	LF	< 3.2	$\times 10^{-8}$	CL=90%	—
$\mu^- f_0(980) \rightarrow \mu^- \pi^+ \pi^-$	LF	< 3.4	$\times 10^{-8}$	CL=90%	—
$e^- \phi$	LF	< 2.0	$\times 10^{-8}$	CL=90%	596
$\mu^- \phi$	LF	< 2.3	$\times 10^{-8}$	CL=90%	590
$e^- e^+ e^-$	LF	< 2.7	$\times 10^{-8}$	CL=90%	888
$e^- \mu^+ \mu^-$	LF	< 2.7	$\times 10^{-8}$	CL=90%	882
$e^+ \mu^- \mu^-$	LF	< 1.7	$\times 10^{-8}$	CL=90%	882
$\mu^- e^+ e^-$	LF	< 1.8	$\times 10^{-8}$	CL=90%	885
$\mu^+ e^- e^-$	LF	< 1.5	$\times 10^{-8}$	CL=90%	885
$\mu^- \mu^+ \mu^-$	LF	< 2.1	$\times 10^{-8}$	CL=90%	873
$e^- \pi^+ \pi^-$	LF	< 2.3	$\times 10^{-8}$	CL=90%	877
$e^+ \pi^- \pi^-$	L	< 2.0	$\times 10^{-8}$	CL=90%	877
$\mu^- \pi^+ \pi^-$	LF	< 2.1	$\times 10^{-8}$	CL=90%	866
$\mu^+ \pi^- \pi^-$	L	< 3.9	$\times 10^{-8}$	CL=90%	866
$e^- \pi^+ K^-$	LF	< 3.7	$\times 10^{-8}$	CL=90%	813
$e^- \pi^- K^+$	LF	< 3.1	$\times 10^{-8}$	CL=90%	813
$e^+ \pi^- K^-$	L	< 3.2	$\times 10^{-8}$	CL=90%	813
$e^- K_S^0 K_S^0$	LF	< 7.1	$\times 10^{-8}$	CL=90%	736
$e^- K^+ K^-$	LF	< 3.4	$\times 10^{-8}$	CL=90%	739
$e^+ K^- K^-$	L	< 3.3	$\times 10^{-8}$	CL=90%	739
$\mu^- \pi^+ K^-$	LF	< 8.6	$\times 10^{-8}$	CL=90%	800
$\mu^- \pi^- K^+$	LF	< 4.5	$\times 10^{-8}$	CL=90%	800
$\mu^+ \pi^- K^-$	L	< 4.8	$\times 10^{-8}$	CL=90%	800
$\mu^- K_S^0 K_S^0$	LF	< 8.0	$\times 10^{-8}$	CL=90%	696
$\mu^- K^+ K^-$	LF	< 4.4	$\times 10^{-8}$	CL=90%	699
$\mu^+ K^- K^-$	L	< 4.7	$\times 10^{-8}$	CL=90%	699
$e^- \pi^0 \pi^0$	LF	< 6.5	$\times 10^{-6}$	CL=90%	878
$\mu^- \pi^0 \pi^0$	LF	< 1.4	$\times 10^{-5}$	CL=90%	867
$e^- \eta \eta$	LF	< 3.5	$\times 10^{-5}$	CL=90%	699
$\mu^- \eta \eta$	LF	< 6.0	$\times 10^{-5}$	CL=90%	653
$e^- \pi^0 \eta$	LF	< 2.4	$\times 10^{-5}$	CL=90%	798
$\mu^- \pi^0 \eta$	LF	< 2.2	$\times 10^{-5}$	CL=90%	784
$p e^- e^-$	L,B	< 3.0	$\times 10^{-8}$	CL=90%	641
$\bar{p} e^+ e^-$	L,B	< 3.0	$\times 10^{-8}$	CL=90%	641
$\bar{p} e^+ \mu^-$	L,B	< 2.0	$\times 10^{-8}$	CL=90%	635
$\bar{p} e^- \mu^+$	L,B	< 1.8	$\times 10^{-8}$	CL=90%	635
$p \mu^- \mu^-$	L,B	< 4.0	$\times 10^{-8}$	CL=90%	618
$\bar{p} \mu^+ \mu^-$	L,B	< 1.8	$\times 10^{-8}$	CL=90%	618
$\bar{p} \gamma$	L,B	< 3.5	$\times 10^{-6}$	CL=90%	641
$\bar{p} \pi^0$	L,B	< 1.5	$\times 10^{-5}$	CL=90%	632
$\bar{p} 2\pi^0$	L,B	< 3.3	$\times 10^{-5}$	CL=90%	604
$\bar{p} \eta$	L,B	< 8.9	$\times 10^{-6}$	CL=90%	475
$\bar{p} \pi^0 \eta$	L,B	< 2.7	$\times 10^{-5}$	CL=90%	360

$\Lambda\pi^-$	$L, B$	$< 7.2$	$\times 10^{-8}$	CL=90%	525
$\bar{\Lambda}\pi^-$	$L, B$	$< 1.4$	$\times 10^{-7}$	CL=90%	525
$e^-$ light boson	$LF$	$< 9$	$\times 10^{-4}$	CL=95%	—
$\mu^-$ light boson	$LF$	$< 6$	$\times 10^{-4}$	CL=95%	—

See Particle Listings for 1 decay modes that have been seen / not seen.

### Heavy Charged Lepton Searches

#### $L^\pm$ – charged lepton

Mass  $m > 100.8$  GeV, CL = 95% <sup>[h]</sup> Decay to  $\nu W$ .

#### $L^\pm$ – stable charged heavy lepton

Mass  $m > 102.6$  GeV, CL = 95%

### Neutrino Properties

See the note on “Neutrino properties listings” in the Particle Listings.

Mass  $m < 0.8$  eV, CL = 90% (tritium decay)

Mean life/mass,  $\tau/m > 300$  s/eV, CL = 90% (reactor)

Mean life/mass,  $\tau/m > 7 \times 10^9$  s/eV (solar)

Mean life/mass,  $\tau/m > 15.4$  s/eV, CL = 90% (accelerator)

Magnetic moment  $\mu < 0.064 \times 10^{-10} \mu_B$ , CL = 90% (solar + radiochemical)

### Number of Neutrino Types

Number  $N = 2.996 \pm 0.007$  (Standard Model fits to LEP-SLC data)

Number  $N = 2.92 \pm 0.05$  ( $S = 1.2$ ) (Direct measurement of invisible  $Z$  width)

### Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review “Neutrino Masses, Mixing, and Oscillations.”

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$

$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$$

$$\sin^2(\theta_{23}) = 0.553^{+0.016}_{-0.024} \quad (S = 1.1) \quad (\text{Inverted order})$$

$$\sin^2(\theta_{23}) = 0.558^{+0.015}_{-0.021} \quad (\text{Normal order})$$

$$\Delta m_{32}^2 = (-2.529 \pm 0.029) \times 10^{-3} \text{ eV}^2 \quad (\text{Inverted order})$$

$$\Delta m_{32}^2 = (2.455 \pm 0.028) \times 10^{-3} \text{ eV}^2 \quad (\text{Normal order})$$

$$\sin^2(\theta_{13}) = (2.19 \pm 0.07) \times 10^{-2} \quad (S = 1.2)$$

$$\delta, CP \text{ violating phase} = 1.19 \pm 0.22 \pi \text{ rad} \quad (S = 1.2)$$

$$\langle \Delta m_{21}^2 - \Delta \bar{m}_{21}^2 \rangle < 1.1 \times 10^{-4} \text{ eV}^2, \text{ CL} = 99.7\%$$

$$\langle \Delta m_{32}^2 - \Delta \bar{m}_{32}^2 \rangle = (-0.12 \pm 0.25) \times 10^{-3} \text{ eV}^2$$

## NOTES

In this Summary Table:

When a quantity has “(S = ...)” to its right, the error on the quantity has been enlarged by the “scale factor” S, defined as  $S = \sqrt{\chi^2/(N-1)}$ , where  $N$  is the number of measurements used in calculating the quantity.

A decay momentum  $p$  is given for each decay mode. For a 2-body decay,  $p$  is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay,  $p$  is the largest momentum any of the products can have in this frame.

- [a] This is the best limit for the mode  $e^- \rightarrow \nu\gamma$ .
- [b] See the review on “Muon Decay Parameters” for definitions and details.
- [c]  $P_\mu$  is the longitudinal polarization of the muon from pion decay. For  $V-A$  coupling,  $P_\mu = 1$  and  $\rho = \delta = 3/4$ .
- [d] This only includes events with energy of  $e > 45$  MeV and energy of  $\gamma > 40$  MeV. Since the  $e^- \bar{\nu}_e \nu_\mu$  and  $e^- \bar{\nu}_e \nu_\mu \gamma$  modes cannot be clearly separated, we regard the latter mode as a subset of the former.
- [e] See the relevant Particle Listings in the Full *Review of Particle Physics* for the energy limits used in this measurement.
- [f] A test of additive vs. multiplicative lepton family number conservation.
- [g] Basis mode for the  $\tau$ .
- [h]  $L^\pm$  mass limit depends on decay assumptions; see the Full Listings.

# QUARKS

The  $u$ -,  $d$ -, and  $s$ -quark masses are the  $\overline{MS}$  masses at the scale  $\mu = 2$  GeV. The  $c$ - and  $b$ -quark masses are the  $\overline{MS}$  masses renormalized at the  $\overline{MS}$  mass, i.e.  $\overline{m} = \overline{m}(\mu = \overline{m})$ . The  $t$ -quark mass is extracted from event kinematics (see the review "The Top Quark").

**u**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$$m_u = 2.16 \pm 0.07 \text{ MeV, CL} = 90\% \quad \text{Charge} = \frac{2}{3} e \quad I_z = +\frac{1}{2}$$

$$m_u/m_d = 0.462 \pm 0.020, \text{ CL} = 90\%$$

**d**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$$m_d = 4.70 \pm 0.07 \text{ MeV, CL} = 90\% \quad \text{Charge} = -\frac{1}{3} e \quad I_z = -\frac{1}{2}$$

$$m_s/m_d = 17-22$$

$$\overline{m} = (m_u + m_d)/2 = 3.49 \pm 0.07 \text{ MeV, CL} = 90\%$$

**s**

$$I(J^P) = 0(\frac{1}{2}^+)$$

$$m_s = 93.5 \pm 0.8 \text{ MeV, CL} = 90\% \quad \text{Charge} = -\frac{1}{3} e \quad \text{Strangeness} = -1$$

$$m_s / ((m_u + m_d)/2) = 27.33^{+0.18}_{-0.14}, \text{ CL} = 90\%$$

**c**

$$I(J^P) = 0(\frac{1}{2}^+)$$

$$m_c = 1.2730 \pm 0.0046 \text{ GeV, CL} = 90\% \quad \text{Charge} = \frac{2}{3} e \quad \text{Charm} = +1$$

$$m_b - m_c = 3.45 \pm 0.05 \text{ GeV}$$

**b**

$$I(J^P) = 0(\frac{1}{2}^+)$$

$$m_b = 4.183 \pm 0.007 \text{ GeV, CL} = 90\% \quad \text{Charge} = -\frac{1}{3} e \quad \text{Bottom} = -1$$

**t**

$$I(J^P) = 0(\frac{1}{2}^+)$$

$$\text{Charge} = \frac{2}{3} e \quad \text{Top} = +1$$

Mass (direct measurements)  $m = 172.57 \pm 0.29 \text{ GeV}^{[a,b]}$  (S = 1.5)

Mass (from cross-section measurements)  $m = 162.5^{+2.1}_{-1.5} \text{ GeV}^{[a]}$

Mass (Pole from cross-section measurements)  $m = 172.4 \pm 0.7 \text{ GeV}$

$m_t - m_{\overline{t}} = -0.15 \pm 0.20 \text{ GeV}$  (S = 1.1)

Full width  $\Gamma = 1.42^{+0.19}_{-0.15} \text{ GeV}$  (S = 1.4)

$\Gamma(Wb)/\Gamma(Wq(q = b, s, d)) = 0.957 \pm 0.034$  (S = 1.5)

### t-quark EW Couplings

$$F_0 = 0.693 \pm 0.013$$

$$F_- = 0.315 \pm 0.010$$

$$F_+ = -0.005 \pm 0.007$$

$$F_{V+A} < 0.29, \text{ CL} = 95\%$$

<b>t DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\frac{p}{(MeV/c)}$	
$W q (q = b, s, d)$			—	
$W b$			—	
$e \nu_e b$	$(11.10 \pm 0.30) \%$		—	
$\mu \nu_\mu b$	$(11.40 \pm 0.20) \%$		—	
$\tau \nu_\tau b$	$(10.7 \pm 0.5) \%$		—	
$q \bar{q} b$	$(66.5 \pm 1.4) \%$		—	
$\gamma q (q=u,c)$	$[c] < 4.5$	$\times 10^{-5}$	95%	
<b><math>\Delta T = 1</math> weak neutral current (<math>T1</math>) modes</b>				
$Z q (q=u,c)$	$T1$	$[d] < 1.2$	$\times 10^{-4}$	95%
$H u$	$T1$	$< 1.9$	$\times 10^{-4}$	95%
$H c$	$T1$	$< 4.3$	$\times 10^{-4}$	95%
$\ell^+ \bar{q} q' (q=d,s,b; q'=u,c)$	$T1$	$< 1.6$	$\times 10^{-3}$	95%
<b>Lepton Family number (<math>LF</math>) violating modes</b>				
$e^\pm \mu^\mp c$	$LF$	$< 8.9$	$\times 10^{-7}$	—
$e^\pm \mu^\mp u$	$LF$	$< 7$	$\times 10^{-8}$	—

### **$b'$ ( $4^{th}$ Generation) Quark, Searches for**

Mass $m > 190$ GeV, CL = 95%	$(p\bar{p}, \text{quasi-stable } b')$
Mass $m > 1390$ GeV, CL = 95%	$(B(b' \rightarrow Z b) = 1)$
Mass $m > 1350$ GeV, CL = 95%	$(B(b' \rightarrow W t) = 1)$
Mass $m > 1570$ GeV, CL = 95%	$(B(b' \rightarrow H b) = 1)$
Mass $m > 46.0$ GeV, CL = 95%	$(e^+ e^-, \text{all decays})$

### **$t'$ ( $4^{th}$ Generation) Quark, Searches for**

$m(t'(2/3)) > 1280$ GeV, CL = 95%	$(B(t' \rightarrow Z t) = 1)$
$m(t'(2/3)) > 1295$ GeV, CL = 95%	$(B(t' \rightarrow W b) = 1)$
$m(t'(2/3)) > 1310$ GeV, CL = 95%	(singlet $t'$ )
$m(t'(2/3)) > 1350$ GeV, CL = 95%	$(t' \text{ in a weak isospin doublet } (t', b'))$
$m(t'(5/3)) > 1.460 \times 10^3$ GeV, CL = 95%	$(t'(5/3) \rightarrow t W^+)$

### **Free Quark Searches**

All searches since 1977 have had negative results.

#### NOTES

- [a] A discussion of the definition of the top quark mass in these measurements can be found in the review “The Top Quark.”
- [b] Based on published top mass measurements using data from Tevatron Run-I and Run-II and LHC at  $\sqrt{s} = 7$  TeV. Including the most recent unpublished results from Tevatron Run-II, the Tevatron Electroweak Working Group reports a top mass of  $173.2 \pm 0.9$  GeV. See the note “The Top Quark” in the Quark Particle Listings of this Review.
- [c] This limit is for  $\Gamma(t \rightarrow \gamma q)/\Gamma(t \rightarrow W b)$ .
- [d] This limit is for  $\Gamma(t \rightarrow Z q)/\Gamma(t \rightarrow W b)$ .

# LIGHT UNFLAVORED MESONS ( $S = C = B = 0$ )

For  $l = 1$  ( $\pi, b, \rho, a$ ):  $u\bar{d}, (u\bar{u}-d\bar{d})/\sqrt{2}, d\bar{u}$ ;  
for  $l = 0$  ( $\eta, \eta', h, h', \omega, \phi, f, f'$ ):  $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

$\pi^\pm$

$$I^G(J^P) = 1^-(0^-)$$

Mass  $m = 139.57039 \pm 0.00018$  MeV ( $S = 1.8$ )

Mean life  $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$  s ( $S = 1.2$ )

$c\tau = 7.8045$  m

$\pi^\pm \rightarrow \ell^\pm \nu \gamma$  form factors [a]

$F_V = 0.0254 \pm 0.0017$

$F_A = 0.0119 \pm 0.0001$

$F_V$  slope parameter  $a = 0.10 \pm 0.06$

$R = 0.059^{+0.009}_{-0.008}$

$\pi^-$  modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

$\pi^\pm$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\mu^+ \nu_\mu$	[b] (99.98770 $\pm$ 0.00004) %		30
$\mu^+ \nu_\mu \gamma$	[c] ( 2.00 $\pm$ 0.25 ) $\times 10^{-4}$		30
$e^+ \nu_e$	[b] ( 1.230 $\pm$ 0.004 ) $\times 10^{-4}$		70
$e^+ \nu_e \gamma$	[c] ( 7.39 $\pm$ 0.05 ) $\times 10^{-7}$		70
$e^+ \nu_e \pi^0$	( 1.036 $\pm$ 0.006 ) $\times 10^{-8}$		4
$e^+ \nu_e e^+ e^-$	( 3.2 $\pm$ 0.5 ) $\times 10^{-9}$		70
$\mu^+ \nu_\mu \nu \bar{\nu}$	< 9 $\times 10^{-6}$	90%	30
$e^+ \nu_e \nu \bar{\nu}$	< 1.6 $\times 10^{-7}$	90%	70
<b>Lepton Family number (LF) or Lepton number (L) violating modes</b>			
$\mu^+ \bar{\nu}_e$	L [d] < 1.5 $\times 10^{-3}$	90%	30
$\mu^+ \nu_e$	LF [d] < 8.0 $\times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	LF < 1.6 $\times 10^{-6}$	90%	30

$\pi^0$

$$I^G(J^{PC}) = 1^-(0^{-+})$$

Mass  $m = 134.9768 \pm 0.0005$  MeV ( $S = 1.1$ )

$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$  MeV

Mean life  $\tau = (8.43 \pm 0.13) \times 10^{-17}$  s ( $S = 1.2$ )

$c\tau = 25.3$  nm

For decay limits to particles which are not established, see the appropriate Search sections ( $A^0$  (axion) and Other Light Boson ( $X^0$ ) Searches, etc.).

$\pi^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$2\gamma$	(98.823 $\pm$ 0.034) %	S=1.5	67
$e^+ e^- \gamma$	( 1.174 $\pm$ 0.035 ) %	S=1.5	67
$\gamma$ positronium	( 1.82 $\pm$ 0.29 ) $\times 10^{-9}$		67

$e^+ e^+ e^- e^-$		$(3.34 \pm 0.16) \times 10^{-5}$		67
$e^+ e^-$		$(6.46 \pm 0.33) \times 10^{-8}$		67
$4\gamma$		$< 2$	$\times 10^{-8}$	CL=90% 67
invisible		$< 4.4$	$\times 10^{-9}$	CL=90% -
$\nu_e \bar{\nu}_e$		$< 1.7$	$\times 10^{-6}$	CL=90% 67
$\nu_\mu \bar{\nu}_\mu$		$< 1.6$	$\times 10^{-6}$	CL=90% 67
$\nu_\tau \bar{\nu}_\tau$		$< 2.1$	$\times 10^{-6}$	CL=90% 67
$\gamma \nu \bar{\nu}$		$< 1.9$	$\times 10^{-7}$	CL=90% 67

**Charge conjugation (C) or Lepton Family number (LF) violating modes**

$3\gamma$	C	$< 3.1$	$\times 10^{-8}$	CL=90% 67
$\mu^+ e^-$	LF	$< 3.8$	$\times 10^{-10}$	CL=90% 26
$\mu^- e^+$	LF	$< 3.2$	$\times 10^{-10}$	CL=90% 26
$\mu^+ e^- + \mu^- e^+$	LF	$< 3.6$	$\times 10^{-10}$	CL=90% 26

 **$\eta$** 

$$J^{PC} = 0^+(0^-+)$$

Mass  $m = 547.862 \pm 0.017$  MeVFull width  $\Gamma = 1.31 \pm 0.05$  keV**C-nonconserving decay parameters**

$\pi^+ \pi^- \pi^0$	left-right asymmetry	$= (0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+ \pi^- \pi^0$	sextant asymmetry	$= (0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+ \pi^- \pi^0$	quadrant asymmetry	$= (-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+ \pi^- \gamma$	left-right asymmetry	$= (0.9 \pm 0.4) \times 10^{-2}$
$\pi^+ \pi^- \gamma$	$\beta$ (D-wave)	$= -0.02 \pm 0.07$ (S = 1.3)

**CP-nonconserving decay parameters**

$$\pi^+ \pi^- e^+ e^- \text{ decay-plane asymmetry } A_\phi = (-0.6 \pm 3.1) \times 10^{-2}$$

**Other decay parameters**

$\pi^0 \pi^0 \pi^0$	Dalitz plot $\alpha$	$= -0.0296 \pm 0.0016$ (S = 1.7)
Parameter $\Lambda$ in $\eta \rightarrow \ell^+ \ell^- \gamma$ decay		$= 0.716 \pm 0.011$ GeV/ $c^2$

$\eta$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/ $c$ )
<b>Neutral modes</b>			
neutral modes	$(71.96 \pm 0.30) \%$	S=1.3	-
$2\gamma$	$(39.36 \pm 0.18) \%$	S=1.1	274
$3\pi^0$	$(32.57 \pm 0.21) \%$	S=1.2	179
$\pi^0 2\gamma$	$(2.55 \pm 0.22) \times 10^{-4}$		257
$2\pi^0 2\gamma$	$< 1.2$	$\times 10^{-3}$	CL=90% 238
$4\gamma$	$< 2.8$	$\times 10^{-4}$	CL=90% 274
invisible	$< 1.0$	$\times 10^{-4}$	CL=90% -
<b>Charged modes</b>			
charged modes	$(28.04 \pm 0.30) \%$	S=1.3	-
$\pi^+ \pi^- \pi^0$	$(23.02 \pm 0.25) \%$	S=1.2	174
$\pi^+ \pi^- \gamma$	$(4.28 \pm 0.07) \%$	S=1.1	236
$e^+ e^- \gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	S=1.2	274
$\mu^+ \mu^- \gamma$	$(3.1 \pm 0.4) \times 10^{-4}$		253
$e^+ e^-$	$< 7$	$\times 10^{-7}$	CL=90% 274
$\mu^+ \mu^-$	$(5.8 \pm 0.8) \times 10^{-6}$		253
$2e^+ 2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$		274
$\pi^+ \pi^- e^+ e^- (\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$		235
$e^+ e^- \mu^+ \mu^-$	$< 1.6$	$\times 10^{-4}$	CL=90% 253
$2\mu^+ 2\mu^-$	$(5.0 \pm 1.3) \times 10^{-9}$		161

$\mu^+ \mu^- \pi^+ \pi^-$	< 3.6	$\times 10^{-4}$	CL=90%	113
$\pi^+ e^- \bar{\nu}_e + \text{c.c.}$	< 1.7	$\times 10^{-4}$	CL=90%	256
$\pi^+ \pi^- 2\gamma$	< 2.1	$\times 10^{-3}$		236
$\pi^+ \pi^- \pi^0 \gamma$	< 6	$\times 10^{-4}$	CL=90%	174
$\pi^0 \mu^+ \mu^- \gamma$	< 3	$\times 10^{-6}$	CL=90%	210

**Charge conjugation (C), Parity (P),  
Charge conjugation  $\times$  Parity (CP), or  
Lepton Family number (LF) violating modes**

$\pi^0 \gamma$	C	[e] < 9	$\times 10^{-5}$	CL=90%	257
$\pi^+ \pi^-$	P,CP	< 4.4	$\times 10^{-6}$	CL=90%	236
$2\pi^0$	P,CP	< 3.5	$\times 10^{-4}$	CL=90%	238
$2\pi^0 \gamma$	C	< 5	$\times 10^{-4}$	CL=90%	238
$3\pi^0 \gamma$	C	< 6	$\times 10^{-5}$	CL=90%	179
$3\gamma$	C	< 1.6	$\times 10^{-5}$	CL=90%	274
$4\pi^0$	P,CP	< 6.9	$\times 10^{-7}$	CL=90%	40
$\pi^0 e^+ e^-$	C	[f] < 8	$\times 10^{-6}$	CL=90%	257
$\pi^0 \mu^+ \mu^-$	C	[f] < 5	$\times 10^{-6}$	CL=90%	210
$\mu^+ e^- + \mu^- e^+$	LF	< 6	$\times 10^{-6}$	CL=90%	264

**$f_0(500)$**

$$I^G(J^{PC}) = 0^+(0^{++})$$

also known as  $\sigma$ ; was  $f_0(600)$ ,  $f_0(400-1200)$

See the review on "Scalar Mesons below 1 GeV."

Mass (T-Matrix Pole  $\sqrt{s}$ ) = (400-550) -  $i$ (200-350) MeV

Mass (Breit-Wigner) = 400 to 800 MeV

Full width (Breit-Wigner) = 100 to 800 MeV

**$\rho(770)$**

$$I^G(J^{PC}) = 1^+(1^{--})$$

See the review on "Spectroscopy of Light Meson Resonances."

T-Matrix Pole  $\sqrt{s}$  = (761-765) -  $i$ (71-74) MeV

$\rho^0$  mass (Breit-Wigner) =  $775.26 \pm 0.23$  MeV [g]

$\rho^0$  full width (Breit-Wigner) =  $147.4 \pm 0.8$  MeV [g] (S = 2.0)

$\rho(770)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$\pi\pi$	$\sim 100$	%	363
<b><math>\rho(770)^\pm</math> decays</b>			
$\pi^\pm \gamma$	( $4.5 \pm 0.5$ )	$\times 10^{-4}$	S=2.2 375
$\pi^\pm \eta$	< 6	$\times 10^{-3}$	CL=84% 152
$\pi^\pm \pi^+ \pi^- \pi^0$	< 2.0	$\times 10^{-3}$	CL=84% 254
<b><math>\rho(770)^0</math> decays</b>			
$\pi^+ \pi^- \gamma$	( $9.9 \pm 1.6$ )	$\times 10^{-3}$	362
$\pi^0 \gamma$	( $4.7 \pm 0.8$ )	$\times 10^{-4}$	S=1.7 376
$\eta \gamma$	( $3.00 \pm 0.21$ )	$\times 10^{-4}$	194
$\pi^0 \pi^0 \gamma$	( $4.5 \pm 0.8$ )	$\times 10^{-5}$	363
$\mu^+ \mu^-$	[h] ( $4.55 \pm 0.28$ )	$\times 10^{-5}$	373
$e^+ e^-$	[h] ( $4.72 \pm 0.05$ )	$\times 10^{-5}$	388
$\pi^+ \pi^- \pi^0$	( $1.01^{+0.54}_{-0.36} \pm 0.34$ )	$\times 10^{-4}$	323
$\pi^+ \pi^- \pi^+ \pi^-$	( $1.8 \pm 0.9$ )	$\times 10^{-5}$	251
$\pi^+ \pi^- \pi^0 \pi^0$	( $1.6 \pm 0.8$ )	$\times 10^{-5}$	257
$\pi^0 e^+ e^-$	< 1.2	$\times 10^{-5}$	CL=90% 376



**$\omega(782)$** 

$$J^{PC} = 0^{-}(1^{-}-)$$

Mass  $m = 782.66 \pm 0.13$  MeV ( $S = 2.0$ )Full width  $\Gamma = 8.68 \pm 0.13$  MeV

$\omega(782)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$\pi^+ \pi^- \pi^0$	$(89.2 \pm 0.7) \%$		327
$\pi^0 \gamma$	$(8.35 \pm 0.27) \%$	S=2.2	380
$\pi^+ \pi^-$	$(1.53 \pm 0.12) \%$	S=1.2	366
neutrals (excluding $\pi^0 \gamma$ )	$(7 \pm 8_{-4}) \times 10^{-3}$	S=1.1	—
$\eta \gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	S=1.1	200
$\pi^0 e^+ e^-$	$(7.7 \pm 0.6) \times 10^{-4}$		380
$\pi^0 \mu^+ \mu^-$	$(1.34 \pm 0.18) \times 10^{-4}$	S=1.5	349
$e^+ e^-$	$(7.38 \pm 0.22) \times 10^{-5}$	S=1.9	391
$\pi^+ \pi^- \pi^0 \pi^0$	$< 2 \times 10^{-4}$	CL=90%	262
$\pi^+ \pi^- \gamma$	$< 3.6 \times 10^{-3}$	CL=95%	366
$\pi^+ \pi^- \pi^+ \pi^-$	$< 1 \times 10^{-3}$	CL=90%	256
$\pi^0 \pi^0 \gamma$	$(6.7 \pm 1.1) \times 10^{-5}$		367
$\eta \pi^0 \gamma$	$< 3.3 \times 10^{-5}$	CL=90%	162
$\mu^+ \mu^-$	$(7.4 \pm 1.8) \times 10^{-5}$		377
$3\gamma$	$< 1.9 \times 10^{-4}$	CL=95%	391

**Charge conjugation (C) violating modes**

$\eta \pi^0$	C	$< 2.1 \times 10^{-4}$	CL=90%	162
$2\pi^0$	C	$< 2.2 \times 10^{-4}$	CL=90%	367
$3\pi^0$	C	$< 2.3 \times 10^{-4}$	CL=90%	330
invisible		$< 7 \times 10^{-5}$	CL=90%	—

 **$\eta'(958)$** 

$$J^{PC} = 0^{+}(0^{-}+)$$

Mass  $m = 957.78 \pm 0.06$  MeVFull width  $\Gamma = 0.188 \pm 0.006$  MeV

$\eta'(958)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\pi^+ \pi^- \eta$	$(42.5 \pm 0.5) \%$		232
$\rho^0 \gamma$ (including non-resonant $\pi^+ \pi^- \gamma$ )	$(29.5 \pm 0.4) \%$		165
$\pi^0 \pi^0 \eta$	$(22.4 \pm 0.5) \%$		239
$\omega \gamma$	$(2.52 \pm 0.07) \%$		159
$\omega e^+ e^-$	$(2.0 \pm 0.4) \times 10^{-4}$		159
$\gamma \gamma$	$(2.307 \pm 0.033) \%$		479
$3\pi^0$	$(2.50 \pm 0.17) \times 10^{-3}$		430
$\mu^+ \mu^- \gamma$	$(1.13 \pm 0.28) \times 10^{-4}$		467
$\pi^+ \pi^- \mu^+ \mu^-$	$(1.9 \pm 0.4) \times 10^{-5}$		401
$\pi^+ \pi^- \pi^0$	$(3.61 \pm 0.17) \times 10^{-3}$		428
$(\pi^+ \pi^- \pi^0)$ S-wave	$(3.8 \pm 0.5) \times 10^{-3}$		428
$\pi^{\mp} \rho^{\pm}$	$(7.4 \pm 2.3) \times 10^{-4}$		106
$2(\pi^+ \pi^-)$	$(8.3 \pm 0.9) \times 10^{-5}$		372
$\pi^+ \pi^- 2\pi^0$	$(1.8 \pm 0.4) \times 10^{-4}$		376
$2(\pi^+ \pi^-)$ neutrals	$< 1 \%$	95%	—
$2(\pi^+ \pi^-) \pi^0$	$< 1.8 \times 10^{-3}$	90%	298
$2(\pi^+ \pi^-) 2\pi^0$	$< 1 \%$	95%	197
$3(\pi^+ \pi^-)$	$< 3.1 \times 10^{-5}$	90%	189

$K^\pm \pi^\mp$	< 4	$\times 10^{-5}$	90%	334
$\pi^+ \pi^- e^+ e^-$	( 2.42 $\pm$ 0.10 )	$\times 10^{-3}$		458
$\pi^+ e^- \nu_e + \text{c.c.}$	< 2.1	$\times 10^{-4}$	90%	469
$\gamma e^+ e^-$	( 4.91 $\pm$ 0.27 )	$\times 10^{-4}$		479
$\pi^0 \gamma \gamma$	( 3.20 $\pm$ 0.24 )	$\times 10^{-3}$		469
$\pi^0 \gamma \gamma$ (non resonant)	( 6.2 $\pm$ 0.9 )	$\times 10^{-4}$		—
$\eta \gamma \gamma$	< 1.33	$\times 10^{-4}$	90%	322
$4\pi^0$	< 4.94	$\times 10^{-5}$	90%	380
$e^+ e^-$	< 5.6	$\times 10^{-9}$	90%	479
$e^+ e^- e^+ e^-$	( 4.5 $\pm$ 1.1 )	$\times 10^{-6}$		479
invisible	< 6	$\times 10^{-4}$	90%	—

**Charge conjugation (C), Parity (P),  
Lepton family number (LF) violating modes**

$\pi^+ \pi^-$	$P, CP$	< 1.8	$\times 10^{-5}$	90%	458
$\pi^0 \pi^0$	$P, CP$	< 4	$\times 10^{-4}$	90%	459
$\pi^0 e^+ e^-$	$C$	[f] < 1.4	$\times 10^{-3}$	90%	469
$\pi^0 \rho^0$	$C$	< 4	%	90%	111
$\eta e^+ e^-$	$C$	[f] < 2.4	$\times 10^{-3}$	90%	322
$3\gamma$	$C$	< 1.0	$\times 10^{-4}$	90%	479
$\mu^+ \mu^- \pi^0$	$C$	[f] < 6.0	$\times 10^{-5}$	90%	445
$\mu^+ \mu^- \eta$	$C$	[f] < 1.5	$\times 10^{-5}$	90%	273
$e\mu$	$LF$	< 4.7	$\times 10^{-4}$	90%	473

**$f_0(980)$**

$$I^G(J^{PC}) = 0^+(0^{++})$$

See the review on "Scalar Mesons below 1 GeV."

T-matrix pole  $\sqrt{s} = (980-1010) - i(20-35)$  MeV [7]

Mass (Breit-Wigner) =  $990 \pm 20$  MeV [7]

Full width (Breit-Wigner) = 10 to 100 MeV [7]

**$a_0(980)$**

$$I^G(J^{PC}) = 1^-(0^{++})$$

See the review on "Scalar Mesons below 1 GeV."

T-matrix pole  $\sqrt{s} = (970-1020) - i(30-70)$  MeV [7]

Mass  $m = 980 \pm 20$  MeV [7]

Full width  $\Gamma = 50$  to 100 MeV [7]

**$\phi(1020)$**

$$I^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 1019.461 \pm 0.016$  MeV

Full width  $\Gamma = 4.249 \pm 0.013$  MeV ( $S = 1.1$ )

$\phi(1020)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$K^+ K^-$	(49.1 $\pm$ 0.5 ) %	S=1.3	127
$K_L^0 K_S^0$	(33.9 $\pm$ 0.4 ) %	S=1.2	110
$\rho\pi + \pi^+ \pi^- \pi^0$	(15.4 $\pm$ 0.4 ) %	S=1.2	—
$\eta \gamma$	( 1.301 $\pm$ 0.024 ) %	S=1.2	363
$\pi^0 \gamma$	( 1.32 $\pm$ 0.05 ) $\times 10^{-3}$		501
$\ell^+ \ell^-$	—		510
$e^+ e^-$	( 2.979 $\pm$ 0.033 ) $\times 10^{-4}$	S=1.2	510
$\mu^+ \mu^-$	( 2.85 $\pm$ 0.22 ) $\times 10^{-4}$	S=1.2	499

$\eta e^+ e^-$	$(1.08 \pm 0.04) \times 10^{-4}$		363
$\pi^+ \pi^-$	$(7.3 \pm 1.3) \times 10^{-5}$		490
$\omega \pi^0$	$(4.7 \pm 0.5) \times 10^{-5}$		171
$\omega \gamma$	$< 5$	%	CL=84% 209
$\rho \gamma$	$< 1.2$	$\times 10^{-5}$	CL=90% 215
$\pi^+ \pi^- \gamma$	$(4.1 \pm 1.3) \times 10^{-5}$		490
$f_0(980) \gamma$	$(3.22 \pm 0.19) \times 10^{-4}$	S=1.1	29
$\pi^0 \pi^0 \gamma$	$(1.12 \pm 0.06) \times 10^{-4}$		492
$\pi^+ \pi^- \pi^+ \pi^-$	$(3.9 \pm_{-2.2}^{+2.8}) \times 10^{-6}$		410
$\pi^+ \pi^+ \pi^- \pi^- \pi^0$	$< 4.6$	$\times 10^{-6}$	CL=90% 342
$\pi^0 e^+ e^-$	$(1.33 \pm_{-0.10}^{+0.07}) \times 10^{-5}$		501
$\pi^0 \eta \gamma$	$(7.27 \pm 0.30) \times 10^{-5}$	S=1.5	346
$a_0(980) \gamma$	$(7.6 \pm 0.6) \times 10^{-5}$		39
$K^0 \bar{K}^0 \gamma$	$< 1.9$	$\times 10^{-8}$	CL=90% 110
$\eta'(958) \gamma$	$(6.21 \pm 0.20) \times 10^{-5}$		60
$\eta \pi^0 \pi^0 \gamma$	$< 2$	$\times 10^{-5}$	CL=90% 293
$\mu^+ \mu^- \gamma$	$(1.4 \pm 0.5) \times 10^{-5}$		499
$\rho \gamma \gamma$	$< 1.2$	$\times 10^{-4}$	CL=90% 215
$\eta \pi^+ \pi^-$	$< 1.8$	$\times 10^{-5}$	CL=90% 288
$\eta \mu^+ \mu^-$	$< 9.4$	$\times 10^{-6}$	CL=90% 321
$\eta U \rightarrow \eta e^+ e^-$	$< 1$	$\times 10^{-6}$	CL=90% -
invisible	$< 1.7$	$\times 10^{-4}$	CL=90% -

## Lepton Family number (LF) violating modes

$e^\pm \mu^\mp$	LF	$< 2$	$\times 10^{-6}$	CL=90%	504
-----------------	----	-------	------------------	--------	-----

 **$h_1(1170)$** 

$$I^G(J^{PC}) = 0^-(1^+ -)$$

Mass  $m = 1166 \pm 6$  MeVFull width  $\Gamma = 375 \pm 35$  MeV **$b_1(1235)$** 

$$I^G(J^{PC}) = 1^+(1^+ -)$$

Mass  $m = 1229.5 \pm 3.2$  MeV (S = 1.6)Full width  $\Gamma = 142 \pm 9$  MeV (S = 1.2)

<b><math>b_1(1235)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\frac{p}{(\text{MeV}/c)}$
$\pi^\pm \gamma$	$(1.6 \pm 0.4) \times 10^{-3}$		607
$\pi^+ \pi^+ \pi^- \pi^0$	$< 50$	%	84% 535
$(K\bar{K})^\pm \pi^0$	$< 8$	%	90% 248
$K_S^0 K_L^0 \pi^\pm$	$< 6$	%	90% 235
$K_S^0 K_S^0 \pi^\pm$	$< 2$	%	90% 235
$\phi \pi$	$< 1.5$	%	84% 147

See Particle Listings for 3 decay modes that have been seen / not seen.

 **$a_1(1260)$  [J]**

$$I^G(J^{PC}) = 1^-(1^+ +)$$

T-Matrix Pole  $\sqrt{s} = (1209 \pm_{-10}^{+13}) - i(288 \pm_{-12}^{+45})$  MeVMass (Breit-Wigner) =  $1230 \pm 40$  MeV [J]

Full width (Breit-Wigner) = 250 to 600 MeV [J]

**$f_2(1270)$** 

$$I^G(J^{PC}) = 0^+(2^{++})$$

T-Matrix Pole  $\sqrt{s} = (1260-1283) - i(90-110)$  MeVMass (Breit-Wigner) =  $1275.4 \pm 0.8$  MeV ( $S = 1.1$ )Full width (Breit-Wigner) =  $186.6^{+2.8}_{-2.2}$  MeV ( $S = 1.5$ )

<b><math>f_2(1270)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$\pi\pi$	$(84.3^{+2.8}_{-1.0})\%$	$S=1.2$	623
$\pi^+\pi^-2\pi^0$	$(7.7^{+1.2}_{-3.1})\%$	$S=1.2$	563
$K\bar{K}$	$(4.6 \pm 0.4)\%$	$S=2.7$	404
$2\pi^+2\pi^-$	$(2.8 \pm 0.4)\%$	$S=1.2$	559
$\eta\eta$	$(4.0 \pm 0.8) \times 10^{-3}$	$S=2.1$	326
$4\pi^0$	$(3.0 \pm 1.0) \times 10^{-3}$		565
$\gamma\gamma$	$(1.42 \pm 0.24) \times 10^{-5}$	$S=1.4$	638
$\eta\pi\pi$	$< 8 \times 10^{-3}$	CL=95%	478
$K^0K^-\pi^+ + \text{c.c.}$	$< 3.4 \times 10^{-3}$	CL=95%	293
$e^+e^-$	$< 6 \times 10^{-10}$	CL=90%	638

 **$f_1(1285)$** 

$$I^G(J^{PC}) = 0^+(1^{++})$$

Mass  $m = 1281.8 \pm 0.5$  MeV ( $S = 1.7$ )Full width  $\Gamma = 23.0 \pm 1.1$  MeV ( $S = 1.6$ )

<b><math>f_1(1285)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$4\pi$	$(32.7 \pm 1.8)\%$	$S=1.2$	568
$\pi^0\pi^0\pi^+\pi^-$	$(21.8 \pm 1.2)\%$	$S=1.2$	566
$2\pi^+2\pi^-$	$(10.9 \pm 0.6)\%$	$S=1.2$	563
$\rho^0\pi^+\pi^-$	$(10.9 \pm 0.6)\%$	$S=1.2$	336
$4\pi^0$	$< 7 \times 10^{-4}$	CL=90%	568
$\eta\pi^+\pi^-$	$(35 \pm 15)\%$		479
$\eta\pi\pi$	$(52.2 \pm 1.9)\%$	$S=1.2$	482
$a_0(980)\pi$ [ignoring $a_0(980) \rightarrow K\bar{K}$ ]	$(38 \pm 4)\%$		238
$\eta\pi\pi$ [excluding $a_0(980)\pi$ ]	$(14 \pm 4)\%$		482
$K\bar{K}\pi$	$(9.0 \pm 0.4)\%$	$S=1.1$	308
$\pi^+\pi^-\pi^0$	$(3.0 \pm 0.9) \times 10^{-3}$		603
$\rho^\pm\pi^\mp$	$< 3.1 \times 10^{-3}$	CL=95%	390
$\gamma\rho^0$	$(6.1 \pm 1.0)\%$	$S=1.7$	406
$\phi\gamma$	$(7.4 \pm 2.6) \times 10^{-4}$		235
$e^+e^-$	$< 9.4 \times 10^{-9}$	CL=90%	641

See Particle Listings for 2 decay modes that have been seen / not seen.

 **$\eta(1295)$** 

$$I^G(J^{PC}) = 0^+(0^{-+})$$

See the review on "Spectroscopy of Light Meson Resonances."

Mass  $m = 1294 \pm 4$  MeV ( $S = 1.6$ )Full width  $\Gamma = 55 \pm 5$  MeV

**$\pi(1300)$** 

$$I^G(J^{PC}) = 1^-(0^-+)$$

Mass  $m = 1300 \pm 100$  MeV [1]Full width  $\Gamma = 200$  to  $600$  MeV [1] **$a_2(1320)$** 

$$I^G(J^{PC}) = 1^-(2^{++})$$

T-Matrix Pole  $\sqrt{s} = (1305-1321)-i(52-58)$  MeVMass (Breit-Wigner) =  $1318.2 \pm 0.6$  MeV ( $S = 1.2$ )Full width  $\Gamma = 107 \pm 5$  MeV

<b><math>a_2(1320)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$3\pi$	(70.1 $\pm$ 2.7 ) %	S=1.2	624
$\eta\pi$	(14.5 $\pm$ 1.2 ) %		535
$\omega\pi\pi$	(10.6 $\pm$ 3.2 ) %	S=1.3	366
$K\bar{K}$	( 4.9 $\pm$ 0.8 ) %		437
$\eta'(958)\pi$	( 5.5 $\pm$ 0.9 ) $\times 10^{-3}$		288
$\pi^\pm\gamma$	( 2.91 $\pm$ 0.27 ) $\times 10^{-3}$		652
$\gamma\gamma$	( 9.4 $\pm$ 0.7 ) $\times 10^{-6}$		659
$e^+e^-$	< 5 $\times 10^{-9}$	CL=90%	659

 **$f_0(1370)$** 

$$I^G(J^{PC}) = 0^+(0^{++})$$

See the review on "Spectroscopy of Light Meson Resonances."

T-Matrix Pole  $\sqrt{s} = (1250-1440) -i(60-300)$  MeVMass (Breit-Wigner) =  $1200$  to  $1500$  MeVFull width (Breit-Wigner) =  $200$  to  $500$  MeV **$\eta(1405)$** 

$$I^G(J^{PC}) = 0^+(0^-+)$$

See the review on "Spectroscopy of Light Meson Resonances." See also  $\eta(1475)$ .Mass  $m = 1408.7^{+2.0}_{-1.2}$  MeV ( $S = 2.2$ )Full width  $\Gamma = 50.3 \pm 2.5$  MeV ( $S = 1.6$ )

<b><math>\eta(1405)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\rho\rho$	< 58 %	99.85%	†

See Particle Listings for 9 decay modes that have been seen / not seen.

 **$h_1(1415)$** 

$$I^G(J^{PC}) = 0^-(1^{+-})$$

Mass  $m = 1409^{+9}_{-8}$  MeV ( $S = 1.9$ )Full width  $\Gamma = 78 \pm 11$  MeV

**$f_1(1420)$** 

$$I^G(J^{PC}) = 0^+(1^{++})$$

See the review on "Spectroscopy of Light Meson Resonances."

Mass  $m = 1428.4_{-1.3}^{+1.5}$  MeV ( $S = 1.8$ )

Full width  $\Gamma = 56.7 \pm 3.3$  MeV ( $S = 1.3$ )

 **$\omega(1420)^{[k]}$** 

$$I^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 1410 \pm 60$  MeV <sup>[l]</sup>

Full width  $\Gamma = 290 \pm 190$  MeV <sup>[l]</sup>

 **$a_0(1450)$** 

$$I^G(J^{PC}) = 1^-(0^{++})$$

See the review on "Spectroscopy of Light Meson Resonances."

T-Matrix Pole  $\sqrt{s} = (1290-1500) - i$  (30-140) MeV

Mass (Breit-Wigner) =  $1439 \pm 34$  MeV ( $S = 1.8$ )

Full width (Breit-Wigner) =  $258 \pm 14$  MeV

Branching fractions are given relative to the one **DEFINED AS 1**. **$a_0(1450)$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ ) $\rho$  (MeV/c) $\pi \eta$ 

0.093 ± 0.020

607

 $\pi \eta'(958)$ 

0.033 ± 0.017

384

 $K \bar{K}$ 

0.082 ± 0.028

523

 $\omega \pi \pi$ **DEFINED AS 1**

458

See Particle Listings for 2 decay modes that have been seen / not seen.

 **$\rho(1450)$** 

$$I^G(J^{PC}) = 1^+(1^{--})$$

See the review on "Spectroscopy of Light Meson Resonances."

Mass  $m = 1465 \pm 25$  MeV <sup>[l]</sup>

Full width  $\Gamma = 400 \pm 60$  MeV <sup>[l]</sup>

 **$\eta(1475)$** 

$$I^G(J^{PC}) = 0^+(0^{-+})$$

See the review on "Spectroscopy of Light Meson Resonances." See also  $\eta(1405)$ .

Mass  $m = 1476 \pm 4$  MeV ( $S = 1.4$ )

Full width  $\Gamma = 96 \pm 9$  MeV ( $S = 1.7$ )

 **$f_0(1500)$** 

$$I^G(J^{PC}) = 0^+(0^{++})$$

See the review on "Spectroscopy of Light Meson Resonances."

T-Matrix Pole  $\sqrt{s} = (1430-1530) - i$  (40-90) MeV

Mass (Breit-Wigner) =  $1522 \pm 25$  MeV

Full width (Breit-Wigner) =  $108 \pm 33$  MeV

$f_0(1500)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor	$\rho$ (MeV/c)
$\pi\pi$	(34.5±2.2) %	1.2	749
$4\pi$	(48.9±3.3) %	1.2	700
$\eta\eta$	( 6.0±0.9) %	1.1	528
$\eta\eta'(958)$	( 2.2±0.8) %	1.4	107
$K\bar{K}$	( 8.5±1.0) %	1.1	579

See Particle Listings for 9 decay modes that have been seen / not seen.

 **$f'_2(1525)$** 

$$I^G(J^{PC}) = 0^+(2^{++})$$

Mass  $m = 1517.3 \pm 2.4$  MeV (S = 2.8)

Full width  $\Gamma = 72^{+7}_{-6}$  MeV

 **$f'_2(1525)$  DECAY MODES**

	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$K\bar{K}$	(88.8 ±2.2) %	576
$\eta\eta$	(10.3 ±2.2) %	525
$\pi\pi$	( 8.2 ±1.5) × 10 <sup>-3</sup>	747
$\gamma\gamma$	( 1.12±0.15) × 10 <sup>-6</sup>	759

 **$f_2(1565)$** 

$$I^G(J^{PC}) = 0^+(2^{++})$$

See the review on "Spectroscopy of Light Meson Resonances."

T-Matrix Pole  $\sqrt{s} = (1495-1560) - i(40-110)$  MeV

Mass (Breit-Wigner) = 1571 ± 13 MeV

Full width (Breit-Wigner) = 132 ± 23 MeV (S = 1.1)

 **$\pi_1(1600)$** 

$$I^G(J^{PC}) = 1^-(1^{-+})$$

See the review on "Spectroscopy of Light Meson Resonances."

Mass (T-Matrix Pole  $\sqrt{s}$ ) = (1480-1680) -  $i(150-300)$  MeV

Mass (Breit-Wigner,  $\eta\pi$  mode) = 1354 ± 25 MeV (S = 1.8)

Mass (Breit-Wigner, non- $\eta\pi$  mode) = 1645<sup>+40</sup><sub>-17</sub> MeV (S = 1.3)

Full width (Breit-Wigner,  $\eta\pi$  mode) = 330 ± 35 MeV

Full width (Breit-Wigner, non- $\eta\pi$  mode) = 370<sup>+50</sup><sub>-60</sub> MeV

 **$a_1(1640)$** 

$$I^G(J^{PC}) = 1^-(1^{++})$$

Mass  $m = 1655 \pm 16$  MeV (S = 1.2)

Full width  $\Gamma = 250 \pm 40$  MeV (S = 1.8)

 **$\eta_2(1645)$** 

$$I^G(J^{PC}) = 0^+(2^{-+})$$

Mass  $m = 1617 \pm 5$  MeV

Full width  $\Gamma = 181 \pm 11$  MeV

**$\omega(1650)$**  [1]

$$J^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 1670 \pm 30$  MeV [1]Full width  $\Gamma = 315 \pm 35$  MeV [1] **$\omega_3(1670)$** 

$$J^G(J^{PC}) = 0^-(3^{--})$$

Mass  $m = 1667 \pm 4$  MeVFull width  $\Gamma = 168 \pm 10$  MeV **$\pi_2(1670)$** 

$$J^G(J^{PC}) = 1^-(2^{-+})$$

Mass  $m = 1670.6^{+2.9}_{-1.2}$  MeV (S = 1.3)Full width  $\Gamma = 258^{+8}_{-9}$  MeV (S = 1.2)

$\pi_2(1670)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$3\pi$	(95.8 ± 1.4) %		808
$f_2(1270)\pi$	(56.3 ± 3.2) %		327
$\rho\pi$	(31 ± 4) %		647
$\sigma\pi$	(10 ± 4) %		—
$\pi(\pi\pi)$ S-wave	(8.7 ± 3.4) %		—
$\pi^\pm\pi^+\pi^-$	(53 ± 4) %		806
$K\bar{K}^*(892) + \text{c.c.}$	(4.2 ± 1.4) %		453
$\omega\rho$	(2.7 ± 1.1) %		302
$\pi^\pm\gamma$	(7.0 ± 1.2) × 10 <sup>-4</sup>		829
$\gamma\gamma$	< 2.8 × 10 <sup>-7</sup>	90%	835
$\eta\pi$	< 5 %		739
$\pi^\pm 2\pi^+ 2\pi^-$	< 5 %		735
$\rho(1450)\pi$	< 3.6 × 10 <sup>-3</sup>	97.7%	145
$b_1(1235)\pi$	< 1.9 × 10 <sup>-3</sup>	97.7%	364

See Particle Listings for 2 decay modes that have been seen / not seen.

 **$\phi(1680)$** 

$$J^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 1680 \pm 20$  MeV [1]Full width  $\Gamma = 150 \pm 50$  MeV [1] **$\rho_3(1690)$** 

$$J^G(J^{PC}) = 1^+(3^{--})$$

Mass  $m = 1688.8 \pm 2.1$  MeVFull width  $\Gamma = 161 \pm 10$  MeV (S = 1.5)

$\rho_3(1690)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor	$\rho$ (MeV/c)
$4\pi$	(71.1 ± 1.9) %		790
$\pi^\pm\pi^+\pi^-\pi^0$	(67 ± 22) %		787
$\omega\pi$	(16 ± 6) %		655
$\pi\pi$	(23.6 ± 1.3) %		834
$K\bar{K}\pi$	(3.8 ± 1.2) %		629
$K\bar{K}$	(1.58 ± 0.26) %	1.2	685

See Particle Listings for 5 decay modes that have been seen / not seen.



**$\rho(1700)$** 

$$I^G(J^{PC}) = 1^+(1^{--})$$

See the review on "Spectroscopy of Light Meson Resonances."

Mass  $m = 1720 \pm 20$  MeV <sup>[i]</sup> ( $\eta\rho^0$  and  $\pi^+\pi^-$  modes)

Full width  $\Gamma = 250 \pm 100$  MeV <sup>[i]</sup> ( $\eta\rho^0$  and  $\pi^+\pi^-$  modes)

 **$a_2(1700)$** 

$$I^G(J^{PC}) = 1^-(2^{++})$$

T-Matrix Pole  $\sqrt{s} = (1630-1780) - i(60-250)$  MeV

Mass  $m = 1706 \pm 14$  MeV ( $S = 1.2$ )

Full width  $\Gamma = 380^{+60}_{-50}$  MeV ( $S = 3.9$ )

 **$a_2(1700)$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ ) $\rho$  (MeV/c)

$\eta\pi$	(2.5±0.6) %	758
$\gamma\gamma$	$(7.9\pm 1.7) \times 10^{-7}$	853
$K\bar{K}$	(1.3±0.8) %	695

See Particle Listings for 5 decay modes that have been seen / not seen.

 **$f_0(1710)$** 

$$I^G(J^{PC}) = 0^+(0^{++})$$

See the review on "Spectroscopy of Light Meson Resonances."

T-matrix pole  $\sqrt{s} = (1680-1820) - i(50-180)$  MeV

Mass (Breit-Wigner) =  $1733^{+8}_{-7}$  MeV ( $S = 1.5$ )

Full width (Breit-Wigner) =  $150^{+12}_{-10}$  MeV ( $S = 1.3$ )

 **$\pi(1800)$** 

$$I^G(J^{PC}) = 1^-(0^{-+})$$

See the review on "Spectroscopy of Light Meson Resonances."

Mass  $m = 1810^{+9}_{-11}$  MeV ( $S = 2.2$ )

Full width  $\Gamma = 215^{+7}_{-8}$  MeV

 **$\phi_3(1850)$** 

$$I^G(J^{PC}) = 0^-(3^{--})$$

Mass  $m = 1854 \pm 7$  MeV

Full width  $\Gamma = 87^{+28}_{-23}$  MeV ( $S = 1.2$ )

 **$\eta_2(1870)$** 

$$I^G(J^{PC}) = 0^+(2^{-+})$$

Mass  $m = 1842 \pm 8$  MeV

Full width  $\Gamma = 225 \pm 14$  MeV

 **$\pi_2(1880)$** 

$$I^G(J^{PC}) = 1^-(2^{-+})$$

Mass  $m = 1874^{+26}_{-5}$  MeV ( $S = 1.6$ )

Full width  $\Gamma = 237^{+33}_{-30}$  MeV ( $S = 1.2$ )

**$f_2(1950)$**

$$I^G(J^{PC}) = 0^+(2^{++})$$

T-Matrix Pole  $\sqrt{s} = (1830-2020) - i(110-220)$  MeV  
 Mass (Breit-Wigner) =  $1936 \pm 12$  MeV ( $S = 1.3$ )  
 Full width (Breit-Wigner) =  $464 \pm 24$  MeV

**$a_4(1970)$**

$$I^G(J^{PC}) = 1^-(4^{++})$$

Mass  $m = 1967 \pm 16$  MeV ( $S = 2.1$ )  
 Full width  $\Gamma = 324^{+15}_{-18}$  MeV

**$f_2(2010)$**

$$I^G(J^{PC}) = 0^+(2^{++})$$

Mass  $m = 2010^{+60}_{-80}$  MeV  
 Full width  $\Gamma = 200 \pm 60$  MeV

**$f_0(2020)$**

$$I^G(J^{PC}) = 0^+(0^{++})$$

T-Matrix Pole  $\sqrt{s} = (1870-2080) - i(120-240)$  MeV  
 Mass (Breit-Wigner) =  $1982^{+54.1}_{-3.0}$  MeV  
 Full width (Breit-Wigner) =  $440 \pm 50$  MeV

**$f_4(2050)$**

$$I^G(J^{PC}) = 0^+(4^{++})$$

Mass  $m = 2018 \pm 11$  MeV ( $S = 2.1$ )  
 Full width  $\Gamma = 237 \pm 18$  MeV ( $S = 1.9$ )

**$f_4(2050)$  DECAY MODES**

	Fraction ( $\Gamma_j/\Gamma$ )	$\rho$ (MeV/c)
$\pi\pi$	$(17.0 \pm 1.5)\%$	1000
$K\bar{K}$	$(6.8^{+3.4}_{-1.8}) \times 10^{-3}$	880
$\eta\eta$	$(2.1 \pm 0.8) \times 10^{-3}$	848
$4\pi^0$	$< 1.2\%$	964

See Particle Listings for 3 decay modes that have been seen / not seen.

**$\phi(2170)$**

$$I^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 2164 \pm 6$  MeV  
 Full width  $\Gamma = 106^{+24}_{-18}$  MeV ( $S = 2.0$ )

**$f_2(2300)$**

$$I^G(J^{PC}) = 0^+(2^{++})$$

Mass  $m = 2297 \pm 28$  MeV  
 Full width  $\Gamma = 150 \pm 40$  MeV

**$f_2(2340)$**

$$I^G(J^{PC}) = 0^+(2^{++})$$

Mass  $m = 2346^{+21}_{-10}$  MeV  
 Full width  $\Gamma = 331^{+27}_{-18}$  MeV

# STRANGE MESONS

## ( $S = \pm 1, C = B = 0$ )

$$K^+ = u\bar{s}, K^0 = d\bar{s}, \bar{K}^0 = \bar{d}s, K^- = \bar{u}s, \text{ similarly for } K^{*s}$$

 **$K^\pm$** 

$$I(J^P) = \frac{1}{2}(0^-)$$

$$\text{Mass } m = 493.677 \pm 0.015 \text{ MeV }^{[n]} \quad (S = 2.8)$$

$$\text{Mean life } \tau = (1.2380 \pm 0.0020) \times 10^{-8} \text{ s} \quad (S = 1.8)$$

$$c\tau = 3.711 \text{ m}$$

**CPT violation parameters ( $\Delta = \text{rate difference/sum}$ )**

$$\Delta(K^\pm \rightarrow \mu^\pm \nu_\mu) = (-0.27 \pm 0.21)\%$$

$$\Delta(K^\pm \rightarrow \pi^\pm \pi^0) = (0.4 \pm 0.6)\% \text{ }^{[o]}$$

**CP violation parameters ( $\Delta = \text{rate difference/sum}$ )**

$$\Delta(K^\pm \rightarrow \pi^\pm e^+ e^-) = (-2.2 \pm 1.6) \times 10^{-2}$$

$$\Delta(K^\pm \rightarrow \pi^\pm \mu^+ \mu^-) = 0.010 \pm 0.023$$

$$\Delta(K^\pm \rightarrow \pi^\pm \pi^0 \gamma) = (0.0 \pm 1.2) \times 10^{-3}$$

$$\Delta(K^\pm \rightarrow \pi^\pm \pi^+ \pi^-) = (0.04 \pm 0.06)\%$$

$$\Delta(K^\pm \rightarrow \pi^\pm \pi^0 \pi^0) = (-0.02 \pm 0.28)\%$$

**T violation parameters**

$$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu \quad P_T = (-1.7 \pm 2.5) \times 10^{-3}$$

$$K^+ \rightarrow \mu^+ \nu_\mu \gamma \quad P_T = (-0.6 \pm 1.9) \times 10^{-2}$$

$$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu \quad \text{Im}(\xi) = -0.006 \pm 0.008$$

**Slope parameter  $g$  <sup>[p]</sup>**

(See Particle Listings for quadratic coefficients and alternative parametrization related to  $\pi\pi$  scattering)

$$K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \quad g = -0.21134 \pm 0.00017$$

$$(g_+ - g_-) / (g_+ + g_-) = (-1.5 \pm 2.2) \times 10^{-4}$$

$$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \quad g = 0.626 \pm 0.007$$

$$(g_+ - g_-) / (g_+ + g_-) = (1.8 \pm 1.8) \times 10^{-4}$$

 **$K^\pm$  decay form factors <sup>[a,q]</sup>**

Assuming  $\mu$ -e universality

$$\lambda_+(K_{\mu 3}^+) = \lambda_+(K_{e 3}^+) = (2.959 \pm 0.025) \times 10^{-2}$$

$$\lambda_0(K_{\mu 3}^+) = (1.76 \pm 0.25) \times 10^{-2} \quad (S = 2.7)$$

Not assuming  $\mu$ -e universality

$$\lambda_+(K_{e 3}^+) = (2.956 \pm 0.025) \times 10^{-2}$$

$$\lambda_+(K_{\mu 3}^+) = (3.09 \pm 0.25) \times 10^{-2} \quad (S = 1.5)$$

$$\lambda_0(K_{\mu 3}^+) = (1.73 \pm 0.27) \times 10^{-2} \quad (S = 2.6)$$

$K_{e 3}$  form factor quadratic fit

$$\lambda'_+(K_{e 3}^\pm) \text{ linear coeff.} = (2.59 \pm 0.04) \times 10^{-2}$$

$$\lambda''_+(K_{e 3}^\pm) \text{ quadratic coeff.} = (0.186 \pm 0.021) \times 10^{-2}$$

$$\lambda'_+ \text{ (LINEAR } K_{\mu 3}^\pm \text{ FORM FACTOR FROM QUADRATIC FIT)} = (24 \pm 4) \times 10^{-3}$$

$$\lambda''_+ \text{ (QUADRATIC } K_{\mu 3}^{\pm} \text{ FORM FACTOR)} = (1.8 \pm 1.5) \times 10^{-3}$$

$$M_V \text{ (VECTOR POLE MASS FOR } K_{e 3}^{\pm} \text{ DECAY)} = 890.3 \pm 2.8 \text{ MeV}$$

$$M_V \text{ (VECTOR POLE MASS FOR } K_{\mu 3}^{\pm} \text{ DECAY)} = 878 \pm 12 \text{ MeV}$$

$$M_S \text{ (SCALAR POLE MASS FOR } K_{\mu 3}^{\pm} \text{ DECAY)} = 1210 \pm 50 \text{ MeV}$$

$$\Lambda_+ \text{ (DISPERSIVE VECTOR FORM FACTOR IN } K_{e 3}^{\pm} \text{ DECAY)} = (2.460 \pm 0.017) \times 10^{-2}$$

$$\Lambda_+ \text{ (DISPERSIVE VECTOR FORM FACTOR IN } K_{\mu 3}^{\pm} \text{ DECAY)} = (25.4 \pm 0.9) \times 10^{-3}$$

$$\ln(C) \text{ (DISPERSIVE SCALAR FORM FACTOR in } K_{\mu 3}^{\pm} \text{ decays)} = (182 \pm 16) \times 10^{-3}$$

$$K_{e 3}^+ \quad |f_S/f_+| = (-0.08_{-0.40}^{+0.34}) \times 10^{-2}$$

$$K_{e 3}^+ \quad |f_T/f_+| = (-1.2_{-1.1}^{+1.3}) \times 10^{-2}$$

$$K_{\mu 3}^+ \quad |f_S/f_+| = (0.2 \pm 0.6) \times 10^{-2}$$

$$K_{\mu 3}^+ \quad |f_T/f_+| = (-0.1 \pm 0.7) \times 10^{-2}$$

$$K^+ \rightarrow e^+ \nu_e \gamma \quad |F_A + F_V| = 0.133 \pm 0.008 \quad (S = 1.3)$$

$$K^+ \rightarrow \mu^+ \nu_\mu \gamma \quad |F_A + F_V| = 0.165 \pm 0.013$$

$$K^+ \rightarrow e^+ \nu_e \gamma \quad |F_A - F_V| < 0.49, \text{ CL} = 90\%$$

$$K^+ \rightarrow \mu^+ \nu_\mu \gamma \quad |F_A - F_V| = -0.153 \pm 0.033 \quad (S = 1.1)$$

**Charge radius**

$$\langle r \rangle = 0.560 \pm 0.031 \text{ fm}$$

**Forward-backward asymmetry**

$$A_{FB}(K_{\pi\mu\mu}^{\pm}) = \frac{\Gamma(\cos(\theta_{K\mu}) > 0) - \Gamma(\cos(\theta_{K\mu}) < 0)}{\Gamma(\cos(\theta_{K\mu}) > 0) + \Gamma(\cos(\theta_{K\mu}) < 0)} < 0.9 \times 10^{-2}, \text{ CL} = 90\%$$

$K^-$  modes are charge conjugates of the modes below.

$K^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level (MeV/c)	$p$
<b>Leptonic and semileptonic modes</b>			
$e^+ \nu_e$	$(1.582 \pm 0.007) \times 10^{-5}$		247
$\mu^+ \nu_\mu$	$(63.56 \pm 0.11) \%$	S=1.2	236
$\pi^0 e^+ \nu_e$	$(5.07 \pm 0.04) \%$	S=2.1	228
Called $K_{e 3}^+$ .			
$\pi^0 \mu^+ \nu_\mu$	$(3.352 \pm 0.034) \%$	S=1.9	215
Called $K_{\mu 3}^+$ .			
$\pi^0 \pi^0 e^+ \nu_e$	$(2.55 \pm 0.04) \times 10^{-5}$	S=1.1	206
$\pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$		203
$\pi^+ \pi^- \mu^+ \nu_\mu$	$(1.4 \pm 0.9) \times 10^{-5}$		151
$\pi^0 \pi^0 \pi^0 e^+ \nu_e$	$< 3.5 \times 10^{-6}$	CL=90%	135
<b>Hadronic modes</b>			
$\pi^+ \pi^0$	$(20.67 \pm 0.08) \%$	S=1.2	205
$\pi^+ \pi^0 \pi^0$	$(1.760 \pm 0.023) \%$	S=1.1	133
$\pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024) \%$		125
<b>Leptonic and semileptonic modes with photons</b>			
$\mu^+ \nu_\mu \gamma$	$[r,s] (6.2 \pm 0.8) \times 10^{-3}$		236
$\mu^+ \nu_\mu \gamma (SD^+)$	$[a,t] (1.33 \pm 0.22) \times 10^{-5}$		-
$\mu^+ \nu_\mu \gamma (SD^+INT)$	$[a,t] < 2.7 \times 10^{-5}$	CL=90%	-
$\mu^+ \nu_\mu \gamma (SD^- + SD^-INT)$	$[a,t] < 2.6 \times 10^{-4}$	CL=90%	-

$e^+ \nu_e \gamma$		( 1.03 ± 0.14 ) × 10 <sup>-5</sup>		247
$\pi^0 e^+ \nu_e \gamma$	[r,s]	( 2.698 ± 0.033 ) × 10 <sup>-4</sup>		228
$\pi^0 e^+ \nu_e \gamma$ (SD)	[a,t]	< 5.3	× 10 <sup>-5</sup>	CL=90% 228
$\pi^0 \mu^+ \nu_\mu \gamma$	[r,s]	( 1.25 ± 0.25 ) × 10 <sup>-5</sup>		215
$\pi^0 \pi^0 e^+ \nu_e \gamma$	<	5	× 10 <sup>-6</sup>	CL=90% 206

### Hadronic modes with photons or $\ell\bar{\ell}$ pairs

$\pi^+ \pi^0 \gamma$ (INT)		( - 4.2 ± 0.9 ) × 10 <sup>-6</sup>		—
$\pi^+ \pi^0 \gamma$ (DE)	[r,u]	( 6.0 ± 0.4 ) × 10 <sup>-6</sup>		205
$\pi^+ \pi^0 e^+ e^-$		( 4.24 ± 0.14 ) × 10 <sup>-6</sup>		205
$\pi^+ \pi^0 \pi^0 \gamma$	[r,s]	( 7.6 $\begin{smallmatrix} +6.0 \\ -3.0 \end{smallmatrix}$ ) × 10 <sup>-6</sup>		133
$\pi^+ \pi^+ \pi^- \gamma$	[r,s]	( 7.1 ± 0.5 ) × 10 <sup>-6</sup>		125
$\pi^+ \gamma \gamma$	[r]	( 1.01 ± 0.06 ) × 10 <sup>-6</sup>		227
$\pi^+ 3\gamma$	[r]	< 1.0	× 10 <sup>-4</sup>	CL=90% 227
$\pi^+ e^+ e^- \gamma$		( 1.19 ± 0.13 ) × 10 <sup>-8</sup>		227

### Leptonic modes with $\ell\bar{\ell}$ pairs

$e^+ \nu_e \nu \bar{\nu}$	<	6	× 10 <sup>-5</sup>	CL=90% 247
$\mu^+ \nu_\mu \nu \bar{\nu}$	<	1.0	× 10 <sup>-6</sup>	CL=90% 236
$e^+ \nu_e e^+ e^-$		( 2.48 ± 0.20 ) × 10 <sup>-8</sup>		247
$\mu^+ \nu_\mu e^+ e^-$		( 7.06 ± 0.31 ) × 10 <sup>-8</sup>		236
$e^+ \nu_e \mu^+ \mu^-$		( 1.7 ± 0.5 ) × 10 <sup>-8</sup>		223
$\mu^+ \nu_\mu \mu^+ \mu^-$	<	4.1	× 10 <sup>-7</sup>	CL=90% 185

### Lepton family number (LF), Lepton number (L), $\Delta S = \Delta Q$ (SQ) violating modes, or $\Delta S = 1$ weak neutral current (SI) modes

$\pi^+ \pi^+ e^- \bar{\nu}_e$	SQ	<	1.3	× 10 <sup>-8</sup>	CL=90%	203	
$\pi^+ \pi^+ \mu^- \bar{\nu}_\mu$	SQ	<	3.0	× 10 <sup>-6</sup>	CL=95%	151	
$\pi^+ e^+ e^-$	SI		( 3.00 ± 0.09 ) × 10 <sup>-7</sup>			227	
$\pi^+ \mu^+ \mu^-$	SI		( 9.17 ± 0.14 ) × 10 <sup>-8</sup>		S=1.8	172	
$\pi^+ e^+ e^- e^+ e^-$		<	1.4	× 10 <sup>-8</sup>	CL=90%	227	
$\pi^+ \nu \bar{\nu}$	SI		( 1.14 $\begin{smallmatrix} +0.40 \\ -0.33 \end{smallmatrix}$ ) × 10 <sup>-10</sup>			227	
$\pi^+ \pi^0 \nu \bar{\nu}$	SI	<	4.3	× 10 <sup>-5</sup>	CL=90%	205	
$\mu^- \nu e^+ e^+$	LF	<	8.1	× 10 <sup>-11</sup>	CL=90%	236	
$\mu^+ \nu_e$	LF	[d]	<	4	× 10 <sup>-3</sup>	CL=90%	236
$\pi^+ \mu^+ e^-$	LF	<	1.3	× 10 <sup>-11</sup>	CL=90%	214	
$\pi^+ \mu^- e^+$	LF	<	6.6	× 10 <sup>-11</sup>	CL=90%	214	
$\pi^- \mu^+ e^+$	L	<	4.2	× 10 <sup>-11</sup>	CL=90%	214	
$\pi^- e^+ e^+$	L	<	5.3	× 10 <sup>-11</sup>	CL=90%	227	
$\pi^- \mu^+ \mu^+$	L	<	4.2	× 10 <sup>-11</sup>	CL=90%	172	
$\pi^- \pi^0 e^+ e^+$	L	<	8.5	× 10 <sup>-10</sup>	CL=90%	205	
$\mu^+ \bar{\nu}_e$	L	[d]	<	3.3	× 10 <sup>-3</sup>	CL=90%	236
$\pi^0 e^+ \bar{\nu}_e$	L	<	3	× 10 <sup>-3</sup>	CL=90%	228	
$\pi^+ \gamma$	[v]	<	2.3	× 10 <sup>-9</sup>	CL=90%	227	

$K^0$

$$I(J^P) = \frac{1}{2}(0^-)$$

50%  $K_S$ , 50%  $K_L$

$$\text{Mass } m = 497.611 \pm 0.013 \text{ MeV} \quad (S = 1.2)$$

$$m_{K^0} - m_{K^\pm} = 3.934 \pm 0.020 \text{ MeV} \quad (S = 1.6)$$

Mean square charge radius

$$\langle r^2 \rangle = -0.077 \pm 0.010 \text{ fm}^2$$

**T-violation parameters in  $K^0-\bar{K}^0$  mixing** <sup>[q]</sup>

$$\text{Asymmetry } A_T \text{ in } K^0-\bar{K}^0 \text{ mixing} = (6.6 \pm 1.6) \times 10^{-3}$$

**CP-violation parameters**

$$\text{Re}(\epsilon) = (1.596 \pm 0.013) \times 10^{-3}$$

**CPT-violation parameters** <sup>[q]</sup>

$$\text{Re } \delta = (2.5 \pm 2.3) \times 10^{-4}$$

$$\text{Im } \delta = (-1.5 \pm 1.6) \times 10^{-5}$$

$$\text{Re}(y), K_{e3} \text{ parameter} = (0.4 \pm 2.5) \times 10^{-3}$$

$$\text{Re}(x_-), K_{e3} \text{ parameter} = (-2.9 \pm 2.0) \times 10^{-3}$$

$$|m_{K^0} - m_{\bar{K}^0}| / m_{\text{average}} < 6 \times 10^{-19}, \text{ CL} = 90\% \text{ [x]}$$

$$(\Gamma_{K^0} - \Gamma_{\bar{K}^0}) / m_{\text{average}} = (8 \pm 8) \times 10^{-18}$$

**Tests of  $\Delta S = \Delta Q$** 

$$\text{Re}(x_+), K_{e3} \text{ parameter} = (-0.9 \pm 3.0) \times 10^{-3}$$

 **$K_S^0$** 

$$I(J^P) = \frac{1}{2}(0^-)$$

$$\text{Mean life } \tau = (0.8954 \pm 0.0004) \times 10^{-10} \text{ s} \quad (S = 1.1) \quad \text{Assuming } CPT$$

$$\text{Mean life } \tau = (0.89564 \pm 0.00033) \times 10^{-10} \text{ s} \quad \text{Not assuming } CPT$$

$$c\tau = 2.6844 \text{ cm} \quad \text{Assuming } CPT$$

**CP-violation parameters** <sup>[y]</sup>

$$\text{Im}(\eta_{+-0}) = -0.002 \pm 0.009$$

$$\text{Im}(\eta_{000}) = -0.001 \pm 0.016$$

$$|\eta_{000}| = |A(K_S^0 \rightarrow 3\pi^0) / A(K_L^0 \rightarrow 3\pi^0)| < 0.0088, \text{ CL} = 90\%$$

$$CP \text{ asymmetry } A \text{ in } \pi^+ \pi^- e^+ e^- = (-0.4 \pm 0.8)\%$$

$K_S^0$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Hadronic modes</b>			
$\pi^0 \pi^0$	$(30.69 \pm 0.05)\%$		209
$\pi^+ \pi^-$	$(69.20 \pm 0.05)\%$		206
$\pi^+ \pi^- \pi^0$	$(3.5 \pm_{-0.9}^{+1.1}) \times 10^{-7}$		133
<b>Modes with photons or <math>\ell\bar{\ell}</math> pairs</b>			
$\pi^+ \pi^- \gamma$	[s,z] $(1.79 \pm 0.05) \times 10^{-3}$		206
$\pi^+ \pi^- e^+ e^-$	$(4.79 \pm 0.15) \times 10^{-5}$		206
$\pi^0 \gamma \gamma$	[z] $(4.9 \pm 1.8) \times 10^{-8}$		230
$\gamma \gamma$	$(2.63 \pm 0.17) \times 10^{-6}$	S=3.1	249
$\mu^+ \mu^- \mu^+ \mu^-$	$< 5.1 \times 10^{-12}$	CL=90%	119
<b>Semileptonic modes</b>			
$\pi^\pm e^\mp \nu_e$	[a $\bar{a}$ ] $(7.14 \pm 0.06) \times 10^{-4}$		229
<b>CP violating (CP) and <math>\Delta S = 1</math> weak neutral current (SI) modes</b>			
$3\pi^0$	CP $< 2.6 \times 10^{-8}$	CL=90%	139
$\mu^+ \mu^-$	SI $< 2.1 \times 10^{-10}$	CL=90%	225
$e^+ e^-$	SI $< 9 \times 10^{-9}$	CL=90%	249
$\pi^0 e^+ e^-$	SI [z] $(3.0 \pm_{-1.2}^{+1.5}) \times 10^{-9}$		230
$\pi^0 \mu^+ \mu^-$	SI $(2.9 \pm_{-1.2}^{+1.5}) \times 10^{-9}$		177

$K_L^0$ 

$$I(J^P) = \frac{1}{2}(0^-)$$

$$\begin{aligned} m_{K_L} - m_{K_S} &= (0.5293 \pm 0.0009) \times 10^{10} \hbar s^{-1} \quad (S = 1.3) \quad \text{Assuming } CPT \\ &= (3.484 \pm 0.006) \times 10^{-12} \text{ MeV} \quad \text{Assuming } CPT \\ &= (0.5289 \pm 0.0010) \times 10^{10} \hbar s^{-1} \quad \text{Not assuming } CPT \\ \text{Mean life } \tau &= (5.116 \pm 0.021) \times 10^{-8} \text{ s} \quad (S = 1.1) \\ c\tau &= 15.34 \text{ m} \end{aligned}$$

**Slope parameters** <sup>[p]</sup>

(See Particle Listings for other linear and quadratic coefficients)

$$\begin{aligned} K_L^0 \rightarrow \pi^+ \pi^- \pi^0: g &= 0.678 \pm 0.008 \quad (S = 1.5) \\ K_L^0 \rightarrow \pi^+ \pi^- \pi^0: h &= 0.076 \pm 0.006 \\ K_L^0 \rightarrow \pi^+ \pi^- \pi^0: k &= 0.0099 \pm 0.0015 \\ K_L^0 \rightarrow \pi^0 \pi^0 \pi^0: h &= (0.6 \pm 1.2) \times 10^{-3} \end{aligned}$$

 **$K_L$  decay form factors** <sup>[q]</sup>Linear parametrization assuming  $\mu$ - $e$  universality

$$\begin{aligned} \lambda_+(K_{\mu 3}^0) &= \lambda_+(K_{e 3}^0) = (2.82 \pm 0.04) \times 10^{-2} \quad (S = 1.1) \\ \lambda_0(K_{\mu 3}^0) &= (1.38 \pm 0.18) \times 10^{-2} \quad (S = 2.2) \end{aligned}$$

Quadratic parametrization assuming  $\mu$ - $e$  universality

$$\begin{aligned} \lambda'_+(K_{\mu 3}^0) &= \lambda'_+(K_{e 3}^0) = (2.40 \pm 0.12) \times 10^{-2} \quad (S = 1.2) \\ \lambda''_+(K_{\mu 3}^0) &= \lambda''_+(K_{e 3}^0) = (0.20 \pm 0.05) \times 10^{-2} \quad (S = 1.2) \\ \lambda_0(K_{\mu 3}^0) &= (1.16 \pm 0.09) \times 10^{-2} \quad (S = 1.2) \end{aligned}$$

Pole parametrization assuming  $\mu$ - $e$  universality

$$\begin{aligned} M_V^\mu(K_{\mu 3}^0) &= M_V^e(K_{e 3}^0) = 878 \pm 6 \text{ MeV} \quad (S = 1.1) \\ M_S^\mu(K_{\mu 3}^0) &= 1252 \pm 90 \text{ MeV} \quad (S = 2.6) \end{aligned}$$

Dispersive parametrization assuming  $\mu$ - $e$  universality

$$\begin{aligned} \Lambda_+ &= (2.51 \pm 0.06) \times 10^{-2} \quad (S = 1.5) \\ \ln(C) &= (1.75 \pm 0.18) \times 10^{-1} \quad (S = 2.0) \\ K_{e 3}^0 \quad |f_S/f_+| &= (1.5_{-1.6}^{+1.4}) \times 10^{-2} \\ K_{e 3}^0 \quad |f_T/f_+| &= (5_{-5}^{+4}) \times 10^{-2} \\ K_{\mu 3}^0 \quad |f_T/f_+| &= (12 \pm 12) \times 10^{-2} \\ K_L \rightarrow \ell^+ \ell^- \gamma, K_L \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-: \alpha_{K^*} &= -0.205 \pm 0.022 \quad (S = 1.8) \\ K_L^0 \rightarrow \ell^+ \ell^- \gamma, K_L^0 \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-: \alpha_{DIP} &= -1.69 \pm 0.08 \quad (S = 1.7) \\ K_L \rightarrow \pi^+ \pi^- e^+ e^-: a_1/a_2 &= -0.737 \pm 0.014 \text{ GeV}^2 \\ K_L \rightarrow \pi^0 2\gamma: a_V &= -0.43 \pm 0.06 \quad (S = 1.5) \end{aligned}$$

**CP-violation parameters** <sup>[v]</sup>

$$\begin{aligned} A_L &= (0.332 \pm 0.006)\% \\ |\eta_{00}| &= (2.220 \pm 0.011) \times 10^{-3} \quad (S = 1.8) \\ |\eta_{+-}| &= (2.232 \pm 0.011) \times 10^{-3} \quad (S = 1.8) \\ |\epsilon| &= (2.228 \pm 0.011) \times 10^{-3} \quad (S = 1.8) \\ |\eta_{00}/\eta_{+-}| &= 0.9950 \pm 0.0007 \text{ }^{[bb]} \quad (S = 1.6) \end{aligned}$$

$$\text{Re}(\epsilon'/\epsilon) = (1.66 \pm 0.23) \times 10^{-3} [bb] \quad (S = 1.6)$$

Assuming *CPT*

$$\phi_{+-} = (43.51 \pm 0.05)^\circ \quad (S = 1.2)$$

$$\phi_{00} = (43.52 \pm 0.05)^\circ \quad (S = 1.2)$$

$$\phi_\epsilon = \phi_{SW} = (43.52 \pm 0.04)^\circ \quad (S = 1.2)$$

$$\text{Im}(\epsilon'/\epsilon) = -(\phi_{00} - \phi_{+-})/3 = (-0.002 \pm 0.005)^\circ \quad (S = 1.7)$$

Not assuming *CPT*

$$\phi_{+-} = (43.4 \pm 0.5)^\circ \quad (S = 1.2)$$

$$\phi_{00} = (43.7 \pm 0.6)^\circ \quad (S = 1.2)$$

$$\phi_\epsilon = (43.5 \pm 0.5)^\circ \quad (S = 1.3)$$

$$CP \text{ asymmetry } A \text{ in } K_L^0 \rightarrow \pi^+ \pi^- e^+ e^- = (13.7 \pm 1.5)\%$$

$$\beta_{CP} \text{ from } K_L^0 \rightarrow e^+ e^- e^+ e^- = -0.19 \pm 0.07$$

$$\gamma_{CP} \text{ from } K_L^0 \rightarrow e^+ e^- e^+ e^- = 0.01 \pm 0.11 \quad (S = 1.6)$$

$$j \text{ for } K_L^0 \rightarrow \pi^+ \pi^- \pi^0 = 0.0012 \pm 0.0008$$

$$f \text{ for } K_L^0 \rightarrow \pi^+ \pi^- \pi^0 = 0.004 \pm 0.006$$

$$|\eta_{+-\gamma}| = (2.35 \pm 0.07) \times 10^{-3}$$

$$\phi_{+-\gamma} = (44 \pm 4)^\circ$$

$$|\epsilon'_{+-\gamma}|/\epsilon < 0.3, \text{ CL} = 90\%$$

$$|g_{E1}| \text{ for } K_L^0 \rightarrow \pi^+ \pi^- \gamma < 0.21, \text{ CL} = 90\%$$

**T-violation parameters**

$$\text{Im}(\xi) \text{ in } K_{\mu 3}^0 = -0.007 \pm 0.026$$

**CPT invariance tests**

$$\phi_{00} - \phi_{+-} = (0.34 \pm 0.32)^\circ$$

$$\text{Re}(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}) - \frac{A_L}{2} = (-3 \pm 35) \times 10^{-6}$$

**$\Delta S = -\Delta Q$  in  $K_{\ell 3}^0$  decay**

$$\text{Re } x = -0.002 \pm 0.006$$

$$\text{Im } x = 0.0012 \pm 0.0021$$

$K_L^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level (MeV/c)	$p$
<b>Semileptonic modes</b>			
$\pi^\pm e^\mp \nu_e$ Called $K_{e3}^0$ .	[ <i>aa</i> ] (40.55 $\pm$ 0.11) %	S=1.7	229
$\pi^\pm \mu^\mp \nu_\mu$ Called $K_{\mu 3}^0$ .	[ <i>aa</i> ] (27.04 $\pm$ 0.07) %	S=1.1	216
$(\pi \mu \text{ atom}) \nu$	(1.05 $\pm$ 0.11) $\times 10^{-7}$		188
$\pi^0 \pi^\pm e^\mp \nu$	[ <i>aa</i> ] (5.20 $\pm$ 0.11) $\times 10^{-5}$		207
$\pi^\pm e^\mp \nu e^\pm e^-$	[ <i>aa</i> ] (1.26 $\pm$ 0.04) $\times 10^{-5}$		229
<b>Hadronic modes, including Charge conjugation <math>\times</math> Parity Violating (CPV) modes</b>			
$3\pi^0$	(19.52 $\pm$ 0.12) %	S=1.6	139
$\pi^+ \pi^- \pi^0$	(12.54 $\pm$ 0.05) %		133
$\pi^+ \pi^-$	CPV [ <i>cc</i> ] (1.967 $\pm$ 0.010) $\times 10^{-3}$	S=1.5	206
$\pi^0 \pi^0$	CPV (8.64 $\pm$ 0.06) $\times 10^{-4}$	S=1.8	209
<b>Semileptonic modes with photons</b>			
$\pi^\pm e^\mp \nu_e \gamma$	[ <i>s,aa,dd</i> ] (3.79 $\pm$ 0.06) $\times 10^{-3}$		229
$\pi^\pm \mu^\mp \nu_\mu \gamma$	(5.65 $\pm$ 0.23) $\times 10^{-4}$		216



**Hadronic modes with photons or  $\ell\bar{\ell}$  pairs**

$\pi^0\pi^0\gamma$	< 2.43	$\times 10^{-7}$	CL=90%	209
$\pi^+\pi^-\gamma$	[s,dd] ( 4.15 $\pm$ 0.15 )	$\times 10^{-5}$	S=2.8	206
$\pi^+\pi^-\gamma$ (DE)	( 2.84 $\pm$ 0.11 )	$\times 10^{-5}$	S=2.0	206
$\pi^0 2\gamma$	[dd] ( 1.273 $\pm$ 0.033 )	$\times 10^{-6}$		230
$\pi^0\gamma e^+e^-$	( 1.62 $\pm$ 0.17 )	$\times 10^{-8}$		230

**Other modes with photons or  $\ell\bar{\ell}$  pairs**

$2\gamma$	( 5.47 $\pm$ 0.04 )	$\times 10^{-4}$	S=1.1	249
$3\gamma$	< 7.4	$\times 10^{-8}$	CL=90%	249
$e^+e^-\gamma$	( 9.4 $\pm$ 0.4 )	$\times 10^{-6}$	S=2.0	249
$\mu^+\mu^-\gamma$	( 3.59 $\pm$ 0.11 )	$\times 10^{-7}$	S=1.3	225
$\mu^+\mu^-\mu^+\mu^-$	< 2.3	$\times 10^{-9}$	CL=90%	119
$e^+e^-\gamma\gamma$	[dd] ( 5.95 $\pm$ 0.33 )	$\times 10^{-7}$		249
$\mu^+\mu^-\gamma\gamma$	[dd] ( 1.0 $\pm_{-0.6}^{+0.8}$ )	$\times 10^{-8}$		225

**Charge conjugation  $\times$  Parity (CP) or Lepton Family number (LF) violating modes, or  $\Delta S = 1$  weak neutral current (SI) modes**

$\mu^+\mu^-$	SI	( 6.84 $\pm$ 0.11 )	$\times 10^{-9}$		225
$e^+e^-$	SI	( 9 $\pm_{-4}^{+6}$ )	$\times 10^{-12}$		249
$\pi^+\pi^-e^+e^-$	SI [dd]	( 3.11 $\pm$ 0.19 )	$\times 10^{-7}$		206
$\pi^0\pi^0e^+e^-$	SI	< 6.6	$\times 10^{-9}$	CL=90%	209
$\pi^0\pi^0\mu^+\mu^-$	SI	< 9.2	$\times 10^{-11}$	CL=90%	57
$\mu^+\mu^-e^+e^-$	SI	( 2.69 $\pm$ 0.27 )	$\times 10^{-9}$		225
$e^+e^-e^+e^-$	SI	( 3.56 $\pm$ 0.21 )	$\times 10^{-8}$		249
$\pi^0\mu^+\mu^-$	CP,SI [ee]	< 3.8	$\times 10^{-10}$	CL=90%	177
$\pi^0e^+e^-$	CP,SI [ee]	< 2.8	$\times 10^{-10}$	CL=90%	230
$\pi^0\nu\bar{\nu}$	CP,SI [ff]	< 3.0	$\times 10^{-9}$	CL=90%	230
$\pi^0\pi^0\nu\bar{\nu}$	SI	< 8.1	$\times 10^{-7}$	CL=90%	209
$e^\pm\mu^\mp$	LF [aa]	< 4.7	$\times 10^{-12}$	CL=90%	238
$e^\pm e^\pm\mu^\mp\mu^\mp$	LF [aa]	< 4.12	$\times 10^{-11}$	CL=90%	225
$\pi^0\mu^\pm e^\mp$	LF [aa]	< 7.6	$\times 10^{-11}$	CL=90%	217
$\pi^0\pi^0\mu^\pm e^\mp$	LF	< 1.7	$\times 10^{-10}$	CL=90%	159

**Lorentz invariance violating modes**

$\pi^0\gamma$	< 1.7	$\times 10^{-7}$	CL=90%	230
---------------	-------	------------------	--------	-----

 **$K_0^*(700)$** 

$$I(J^P) = \frac{1}{2}(0^+)$$

also known as  $\kappa$ ; was  $K_0^*(800)$ 

See the review on "Scalar Mesons below 1 GeV."

Mass (T-Matrix Pole  $\sqrt{s}$ ) = (630–730) –  $i$  (260–340) MeVMass (Breit-Wigner) = 845  $\pm$  17 MeVFull width (Breit-Wigner) = 468  $\pm$  30 MeV **$K_0^*(700)$  DECAY MODES**

	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	100 %	256

**$K^*(892)$** 

$$I(J^P) = \frac{1}{2}(1^-)$$

Mass (T-Matrix Pole  $\sqrt{s}$ ) =  $(890 \pm 14) - i(26 \pm 6)$  MeV $K^*(892)^\pm$  hadroproduced mass  $m = 891.67 \pm 0.26$  MeV $K^*(892)^\pm$  in  $\tau$  decays mass  $m = 895.5 \pm 0.8$  MeV $K^*(892)^0$  mass  $m = 895.55 \pm 0.20$  MeV ( $S = 1.7$ ) $K^*(892)^\pm$  hadroproduced full width  $\Gamma = 51.4 \pm 0.8$  MeV $K^*(892)^\pm$  in  $\tau$  decays full width  $\Gamma = 46.2 \pm 1.3$  MeV $K^*(892)^0$  full width  $\Gamma = 47.3 \pm 0.5$  MeV ( $S = 2.0$ )

<b><math>K^*(892)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$K\pi$	$\sim 100$	%	289
$K^0\gamma$	$(2.46 \pm 0.21) \times 10^{-3}$		307
$K^\pm\gamma$	$(9.8 \pm 0.9) \times 10^{-4}$		309
$K\pi\pi$	$< 7$	$\times 10^{-4}$	95% 223

 **$K_1(1270)$** 

$$I(J^P) = \frac{1}{2}(1^+)$$

Mass  $m = 1253 \pm 7$  MeV ( $S = 2.2$ )Full width  $\Gamma = 90 \pm 20$  MeV <sup>[1]</sup>

<b><math>K_1(1270)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor	$\rho$ (MeV/c)
$K\rho$	$(38 \pm 13)$ %	2.2	†
$K_0^*(1430)\pi$	$(28 \pm 4)$ %		†
$K^*(892)\pi$	$(21 \pm 10)$ %	2.2	286
$K\omega$	$(11.0 \pm 2.0)$ %		†
$Kf_0(1370)$	$(3.0 \pm 2.0)$ %		†

See Particle Listings for 1 decay modes that have been seen / not seen.

 **$K_1(1400)$** 

$$I(J^P) = \frac{1}{2}(1^+)$$

Mass  $m = 1403 \pm 7$  MeVFull width  $\Gamma = 174 \pm 13$  MeV ( $S = 1.6$ )

<b><math>K_1(1400)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$K^*(892)\pi$	$(94 \pm 6)$ %	402
$K\rho$	$(3.0 \pm 3.0)$ %	293
$Kf_0(1370)$	$(2.0 \pm 2.0)$ %	†
$K\omega$	$(1.0 \pm 1.0)$ %	284

See Particle Listings for 3 decay modes that have been seen / not seen.

 **$K^*(1410)$** 

$$I(J^P) = \frac{1}{2}(1^-)$$

T-matrix pole  $\sqrt{s} = (1368 \pm 38) - i(106^{+48}_{-59})$  MeVMass  $m = 1414 \pm 15$  MeV ( $S = 1.3$ )Full width  $\Gamma = 232 \pm 21$  MeV ( $S = 1.1$ )

<b><math>K^*(1410)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$K^*(892)\pi$	$> 40$	%	95% 410
$K\pi$	$(6.6 \pm 1.3)$ %		612

$K\rho$	< 7	%	95%	305
$\gamma K^0$	< 2.3	$\times 10^{-4}$	90%	619

See Particle Listings for 1 decay modes that have been seen / not seen.

**$K_0^*(1430)$**

$$I(J^P) = \frac{1}{2}(0^+)$$

T-matrix pole  $\sqrt{s} = (1431 \pm 6) - i(110 \pm 19)$  MeV

Mass  $m = 1425 \pm 50$  MeV [7]

Full width  $\Gamma = 270 \pm 80$  MeV [7]

<b><math>K_0^*(1430)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	(93 $\pm 10$ ) %	619
$K\eta$	( 8.6 $^{+2.7}_{-3.4}$ ) %	486

See Particle Listings for 1 decay modes that have been seen / not seen.

**$K_2^*(1430)$**

$$I(J^P) = \frac{1}{2}(2^+)$$

T-matrix pole  $\sqrt{s} = (1424 \pm 4) - i(66 \pm 2)$  MeV

$K_2^*(1430)^\pm$  mass  $m = 1427.3 \pm 1.5$  MeV (S = 1.3)

$K_2^*(1430)^0$  mass  $m = 1432.4 \pm 1.3$  MeV

$K_2^*(1430)^\pm$  full width  $\Gamma = 100.0 \pm 2.2$  MeV (S = 1.1)

$K_2^*(1430)^0$  full width  $\Gamma = 109 \pm 5$  MeV (S = 1.9)

<b><math>K_2^*(1430)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$K\pi$	(49.9 $\pm 1.2$ ) %		620
$K^*(892)\pi$	(24.7 $\pm 1.5$ ) %		420
$K^*(892)\pi\pi$	(13.4 $\pm 2.2$ ) %		373
$K\rho$	( 8.7 $\pm 0.8$ ) %	S=1.2	320
$K\omega$	( 2.9 $\pm 0.8$ ) %		313
$K^+\gamma$	( 2.4 $\pm 0.5$ ) $\times 10^{-3}$	S=1.1	628
$K\eta$	( 1.5 $^{+3.4}_{-1.0}$ ) $\times 10^{-3}$	S=1.3	488
$K\omega\pi$	< 7.2 $\times 10^{-4}$	CL=95%	106
$K^0\gamma$	< 9 $\times 10^{-4}$	CL=90%	627

**$K(1460)$**

$$I(J^P) = \frac{1}{2}(0^-)$$

**$K_1(1650)$**

$$I(J^P) = \frac{1}{2}(1^+)$$

Mass  $m = 1650 \pm 50$  MeV

Full width  $\Gamma = 150 \pm 50$  MeV

**$K^*(1680)$**

$$I(J^P) = \frac{1}{2}(1^-)$$

Mass  $m = 1718 \pm 18$  MeV

Full width  $\Gamma = 320 \pm 110$  MeV (S = 4.2)

$K^*(1680)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$K\pi$	(38.7±2.5) %	782
$K\rho$	(31.4 $^{+5.0}_{-2.1}$ ) %	571
$K^*(892)\pi$	(29.9 $^{+2.2}_{-5.0}$ ) %	618
$K\eta$	( 1.4 $^{+1.0}_{-0.8}$ ) %	683

See Particle Listings for 1 decay modes that have been seen / not seen.

**$K_2(1770)$  [gg]**

$$I(J^P) = \frac{1}{2}(2^-)$$

Mass  $m = 1773 \pm 8$  MeV

Full width  $\Gamma = 186 \pm 14$  MeV

$K_2(1770)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$K\pi\pi$		794

See Particle Listings for 6 decay modes that have been seen / not seen.

**$K_3^*(1780)$**

$$I(J^P) = \frac{1}{2}(3^-)$$

T-matrix pole  $\sqrt{s} = (1754 \pm 13) - i(119 \pm 14)$  MeV

Mass  $m = 1779 \pm 8$  MeV (S = 1.2)

Full width  $\Gamma = 161 \pm 17$  MeV (S = 1.1)

$K_3^*(1780)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$K\rho$	(31 ± 9) %		616
$K^*(892)\pi$	(20 ± 5) %		657
$K\pi$	(18.8± 1.0) %		815
$K\eta$	(30 ±13) %		721
$K_2^*(1430)\pi$	< 16 %	95%	292

**$K_2(1820)$  [gg]**

$$I(J^P) = \frac{1}{2}(2^-)$$

Mass  $m = 1819 \pm 12$  MeV

Full width  $\Gamma = 264 \pm 34$  MeV

**$K_0^*(1950)$**

$$I(J^P) = \frac{1}{2}(0^+)$$

Mass  $m = 1957 \pm 14$  MeV

Full width  $\Gamma = 170 \pm 50$  MeV (S = 2.2)

$K_0^*(1950)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$K^-\pi^+$	(52±14) %	911

**$K_2^*(1980)$**

$$I(J^P) = \frac{1}{2}(2^+)$$

Mass  $m = 1990^{+60}_{-50}$  MeV (S = 2.8)

Full width  $\Gamma = 348^{+50}_{-30}$  MeV (S = 1.3)

**$K_4^*(2045)$** 

$$I(J^P) = \frac{1}{2}(4^+)$$

Mass  $m = 2048_{-9}^{+8}$  MeV (S = 1.1)

Full width  $\Gamma = 199_{-19}^{+27}$  MeV

<b><math>K_4^*(2045)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	(9.9±1.2) %	960
$K^*(892)\pi\pi$	(9 ± 5) %	804
$K^*(892)\pi\pi\pi$	(7 ± 5) %	770
$\rho K\pi$	(5.7±3.2) %	744
$\omega K\pi$	(5.0±3.0) %	740
$\phi K\pi$	(2.8±1.4) %	597
$\phi K^*(892)$	(1.4±0.7) %	368

## CHARMED MESONS ( $C = \pm 1$ )

$$D^+ = c\bar{d}, D^0 = c\bar{u}, \bar{D}^0 = \bar{c}u, D^- = \bar{c}d, \text{ similarly for } D^{*\prime}\text{'s}$$

 **$D^\pm$** 

$$I(J^P) = \frac{1}{2}(0^-)$$

Mass  $m = 1869.66 \pm 0.05$  MeV

Mean life  $\tau = (1033 \pm 5) \times 10^{-15}$  s

$c\tau = 309.8 \mu\text{m}$

**c-quark decays**

$$\Gamma(c \rightarrow \ell^+ \text{ anything})/\Gamma(c \rightarrow \text{ anything}) = 0.096 \pm 0.004 \text{ } [hh]$$

$$\Gamma(c \rightarrow D^*(2010)^+ \text{ anything})/\Gamma(c \rightarrow \text{ anything}) = 0.255 \pm 0.017$$

**CP-violation decay-rate asymmetries**

$$A_{CP}(\mu^\pm \nu) = (8 \pm 8)\%$$

$$A_{CP}(K_L^0 e^\pm \nu) = (-0.6 \pm 1.6)\%$$

$$A_{CP}(K_S^0 \pi^\pm) = (-0.41 \pm 0.09)\%$$

$$A_{CP}(K_L^0 K^\pm) \text{ in } D^\pm \rightarrow K_L^0 K^\pm = (-4.2 \pm 3.4) \times 10^{-2}$$

$$A_{CP}(K^\mp 2\pi^\pm) = (-0.18 \pm 0.16)\%$$

$$A_{CP}(K^\mp \pi^\pm \pi^\pm \pi^0) = (-0.3 \pm 0.7)\%$$

$$A_{CP}(K_S^0 \pi^\pm \pi^0) = (-0.1 \pm 0.7)\%$$

$$A_{CP}(K_S^0 \pi^\pm \eta) \text{ in } D^\pm \rightarrow K_S^0 \pi^\pm \eta = (-0.9 \pm 3.1) \times 10^{-2}$$

$$A_{CP}(K_S^0 \pi^\pm \pi^+ \pi^-) = (0.0 \pm 1.2)\%$$

$$A_{CP}(K^\pm \pi^+ \pi^- \pi^0) \text{ in } D^\pm \rightarrow K^\pm \pi^+ \pi^- \pi^0 = -0.04 \pm 0.06$$

$$A_{CP}(\pi^\pm \pi^0) = (0.4 \pm 1.3)\% \quad (S = 1.7)$$

$$A_{CP}(\pi^\pm \eta) = (0.3 \pm 0.5)\%$$

$$A_{CP}(\pi^\pm \pi^0 \eta) \text{ in } D^\pm \rightarrow \pi^\pm \pi^0 \eta = (-6 \pm 7) \times 10^{-2}$$

$$A_{CP}(\pi^\pm \eta \eta) \text{ in } D^\pm \rightarrow \pi^\pm \eta \eta = (8 \pm 9) \times 10^{-2}$$

$$A_{CP}(\pi^\pm \eta'(958)) = (0.41 \pm 0.23)\% \quad (S = 1.2)$$

$$A_{CP}(\bar{K}^0 / K^0 K^\pm) = (0.11 \pm 0.17)\%$$

$$A_{CP}(K_S^0 K^\pm) = (-0.01 \pm 0.07)\%$$

$$A_{CP}(K_S^0 K^\pm \pi^0) \text{ in } D^\pm \rightarrow K_S^0 K^\pm \pi^0 = (1 \pm 4) \times 10^{-2}$$

$$A_{CP}(K_L^0 K^\pm \pi^0) \text{ in } D^\pm \rightarrow K_L^0 K^\pm \pi^0 = (-1 \pm 4) \times 10^{-2}$$

$$A_{CP}(K^+ K^- \pi^\pm) = (0.37 \pm 0.29)\%$$

$$A_{CP}(K^\pm K^{*0}) = (-0.3 \pm 0.4)\%$$

$$\begin{aligned}
A_{CP}(\phi\pi^\pm) &= (0.01 \pm 0.09)\% \quad (S = 1.8) \\
A_{CP}(K^\pm K_0^*(1430)^0) &= (8_{-6}^{+7})\% \\
A_{CP}(K^\pm K_2^*(1430)^0) &= (43_{-26}^{+20})\% \\
A_{CP}(K^\pm K_0^*(700)) &= (-12_{-13}^{+18})\% \\
A_{CP}(a_0(1450)^0\pi^\pm) &= (-19_{-16}^{+14})\% \\
A_{CP}(\phi(1680)\pi^\pm) &= (-9 \pm 26)\% \\
A_{CP}(\pi^\pm 2\pi^0) \text{ in } D^\pm &\rightarrow \pi^\pm 2\pi^0 = (5.6 \pm 2.7)\% \\
A_{CP}(\pi^+\pi^-\pi^\pm) &= (0.5 \pm 2.0)\% \\
A_{CP}(2\pi^\pm\pi^\mp\pi^0) \text{ in } D^\pm &\rightarrow 2\pi^\pm\pi^\mp\pi^0 = (0.3 \pm 2.0)\% \\
A_{CP}(2\pi^\pm\pi^\mp 2\pi^0) \text{ in } D^\pm &\rightarrow 2\pi^\pm\pi^\mp 2\pi^0 = (-4 \pm 4)\% \\
A_{CP}(\pi^+\pi^-\pi^\pm\eta) \text{ in } D^\pm &\rightarrow \pi^+\pi^-\pi^\pm\eta = (3 \pm 5) \times 10^{-2} \\
A_{CP}(K_S^0 K^\pm\pi^+\pi^-) &= (-4 \pm 7)\% \\
A_{CP}(K^\pm\pi^0) &= (-3 \pm 5)\% \\
A_{CP}(K^\pm\eta) \text{ in } D^\pm &\rightarrow K^\pm\eta = (-6 \pm 11) \times 10^{-2}
\end{aligned}$$

### $\chi^2$ tests of CP-violation (CPV)

$$\begin{aligned}
\text{Local CPV in } D^\pm &\rightarrow \pi^+\pi^-\pi^\pm = 78.1\% \\
\text{Local CPV in } D^\pm &\rightarrow K^+K^-\pi^\pm = 31\% \\
\text{Local CPV in } D^\pm &\rightarrow K^+K^-K^\pm = 31.6\%
\end{aligned}$$

### CP violating asymmetries of P-odd (T-odd) moments

$$\begin{aligned}
A_T(K_S^0 K^\pm\pi^+\pi^-) &= (-3 \pm 8) \times 10^{-3} \text{ [ii]} \quad (S = 1.1) \\
A_{Tviol}(K^+K^-K_S^0\pi^\pm) \text{ in } D^\pm &\rightarrow K^+K^-K_S^0\pi^\pm = (-3.3 \pm 2.7)\%
\end{aligned}$$

### $D^+$ form factors

$$\begin{aligned}
f_+(0)|V_{cs}| \text{ in } \overline{K}^0\ell^+\nu_\ell &= 0.719 \pm 0.011 \quad (S = 1.6) \\
r_1 \equiv a_1/a_0 \text{ in } \overline{K}^0\ell^+\nu_\ell &= -2.13 \pm 0.14 \\
r_2 \equiv a_2/a_0 \text{ in } \overline{K}^0\ell^+\nu_\ell &= -3 \pm 12 \quad (S = 1.5) \\
f_+(0)|V_{cd}| \text{ in } \pi^0\ell^+\nu_\ell &= 0.1407 \pm 0.0025 \\
r_1 \equiv a_1/a_0 \text{ in } \pi^0\ell^+\nu_\ell &= -2.00 \pm 0.13 \\
r_2 \equiv a_2/a_0 \text{ in } \pi^0\ell^+\nu_\ell &= -4 \pm 5 \\
f_+(0)|V_{cd}| \text{ in } D^+ &\rightarrow \eta\ell^+\nu_\ell (\ell = e \text{ or } \nu) = (8.4 \pm 0.4) \times 10^{-2} \\
r_1 \equiv a_1/a_0 \text{ in } D^+ &\rightarrow \eta e^+\nu_e = -5.3 \pm 2.7 \quad (S = 1.9) \\
r_\nu \equiv V(0)/A_1(0) \text{ in } D^+ &\rightarrow \omega e^+\nu_e = 1.24 \pm 0.11 \\
r_2 \equiv A_2(0)/A_1(0) \text{ in } D^+ &\rightarrow \omega e^+\nu_e = 1.06 \pm 0.16 \\
r_\nu \equiv V(0)/A_1(0) \text{ in } D^+, D^0 &\rightarrow \rho e^+\nu_e = 1.64 \pm 0.10 \quad (S = 1.2) \\
r_2 \equiv A_2(0)/A_1(0) \text{ in } D^+, D^0 &\rightarrow \rho e^+\nu_e = 0.84 \pm 0.06 \\
r_\nu \equiv V(0)/A_1(0) \text{ in } \overline{K}^*(892)^0\ell^+\nu_\ell &= 1.49 \pm 0.05 \quad (S = 2.1) \\
r_2 \equiv A_2(0)/A_1(0) \text{ in } \overline{K}^*(892)^0\ell^+\nu_\ell &= 0.802 \pm 0.021 \\
r_3 \equiv A_3(0)/A_1(0) \text{ in } \overline{K}^*(892)^0\ell^+\nu_\ell &= 0.0 \pm 0.4 \\
\Gamma_L/\Gamma_T \text{ in } \overline{K}^*(892)^0\ell^+\nu_\ell &= 1.13 \pm 0.08 \\
\Gamma_+/ \Gamma_- \text{ in } \overline{K}^*(892)^0\ell^+\nu_\ell &= 0.22 \pm 0.06 \quad (S = 1.6)
\end{aligned}$$

Most decay modes (other than the semileptonic modes) that involve a neutral  $K$  meson are now given as  $K_S^0$  modes, not as  $\overline{K}^0$  modes. Nearly always it is a  $K_S^0$  that is measured, and interference between Cabibbo-allowed and doubly Cabibbo-suppressed modes can invalidate the assumption that  $2\Gamma(K_S^0) = \Gamma(\overline{K}^0)$ .

$D^+$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Inclusive modes</b>			
$e^+$ semileptonic	$(16.07 \pm 0.30) \%$		—
$\mu^+$ anything	$(17.6 \pm 3.2) \%$		—

$K^-$ anything	(25.7 ± 1.4 )%		–
$K_S^0$ anything	(33.1 ± 0.4 )%		–
$K^+$ anything	( 5.9 ± 0.8 )%		–
$K^*(892)^-$ anything	( 6 ± 5 )%		–
$\bar{K}^*(892)^0$ anything	(23 ± 5 )%		–
$K^*(892)^0$ anything	< 6.6	%	CL=90% –
$\eta$ anything	( 6.3 ± 0.7 )%		–
$\eta'$ anything	( 1.04 ± 0.18 )%		–
$\phi$ anything	( 1.12 ± 0.04 )%		–
$\pi^+ \pi^+ \pi^-$ anything	(15.25 ± 0.20 )%		–

### Leptonic and semileptonic modes

$e^+ \nu_e$	< 8.8	$\times 10^{-6}$	CL=90%	935
$\gamma e^+ \nu_e$	< 3.0	$\times 10^{-5}$	CL=90%	935
$\mu^+ \nu_\mu$	( 3.74 ± 0.17 )	$\times 10^{-4}$		932
$\tau^+ \nu_\tau$	( 1.20 ± 0.27 )	$\times 10^{-3}$		90
$\bar{K}^0 e^+ \nu_e$	( 8.72 ± 0.09 )%			869
$\bar{K}^0 \mu^+ \nu_\mu$	( 8.76 ± 0.19 )%			865
$K^- \pi^+ e^+ \nu_e$	( 4.02 ± 0.18 )%		S=3.2	864
$\bar{K}^*(892)^0 e^+ \nu_e, \bar{K}^*(892)^0 \rightarrow$ $K^- \pi^+$	( 3.77 ± 0.17 )%			722
$(K^- \pi^+) [0.8-1.0] \text{GeV} e^+ \nu_e$	( 3.39 ± 0.09 )%			864
$(K^- \pi^+)_{S\text{-wave}} e^+ \nu_e$	( 2.28 ± 0.11 )	$\times 10^{-3}$		–
$\bar{K}^*(1410)^0 e^+ \nu_e,$ $\bar{K}^*(1410)^0 \rightarrow K^- \pi^+$	< 6	$\times 10^{-3}$	CL=90%	–
$\bar{K}_2^*(1430)^0 e^+ \nu_e,$ $\bar{K}_2^*(1430)^0 \rightarrow K^- \pi^+$	< 5	$\times 10^{-4}$	CL=90%	–
$K^- \pi^+ e^+ \nu_e$ nonresonant	< 7	$\times 10^{-3}$	CL=90%	864
$\bar{K}^*(892)^0 e^+ \nu_e$	( 5.40 ± 0.10 )%		S=1.1	722
$K^- \pi^+ \mu^+ \nu_\mu$	( 3.65 ± 0.34 )%			851
$\bar{K}^*(892)^0 \mu^+ \nu_\mu,$ $\bar{K}^*(892)^0 \rightarrow K^- \pi^+$	( 3.52 ± 0.10 )%			717
$K^- \pi^+ \mu^+ \nu_\mu$ nonresonant	( 1.9 ± 0.5 )	$\times 10^{-3}$		851
$\bar{K}^*(892)^0 \mu^+ \nu_\mu$	( 5.27 ± 0.15 )%			717
$K^- \pi^+ \pi^0 \mu^+ \nu_\mu$	< 1.5	$\times 10^{-3}$	CL=90%	825
$\bar{K}_1(1270)^0 e^+ \nu_e, \bar{K}_1^0 \rightarrow$ $K^- \pi^+ \pi^0$	( 1.06 ± 0.15 )	$\times 10^{-3}$		–
$\bar{K}_0^*(1430)^0 \mu^+ \nu_\mu$	< 2.3	$\times 10^{-4}$	CL=90%	380
$\bar{K}^*(1680)^0 \mu^+ \nu_\mu$	< 1.5	$\times 10^{-3}$	CL=90%	105
$\pi^0 e^+ \nu_e$	( 3.72 ± 0.17 )	$\times 10^{-3}$	S=2.0	930
$\pi^0 \mu^+ \nu_\mu$	( 3.50 ± 0.15 )	$\times 10^{-3}$		927
$\eta e^+ \nu_e$	( 1.11 ± 0.07 )	$\times 10^{-3}$		855
$\eta \mu^+ \nu_\mu$	( 1.04 ± 0.11 )	$\times 10^{-3}$		851
$\pi^- \pi^+ e^+ \nu_e$	( 2.49 ± 0.11 )	$\times 10^{-3}$	S=1.2	924
$f_0(500)^0 e^+ \nu_e, f_0(500)^0 \rightarrow$ $\pi^+ \pi^-$	( 6.4 ± 0.6 )	$\times 10^{-4}$		–
$\rho^0 e^+ \nu_e$	( 1.90 ± 0.10 )	$\times 10^{-3}$	S=1.2	774
$\rho^0 \mu^+ \nu_\mu$	( 2.4 ± 0.4 )	$\times 10^{-3}$		770
$\omega e^+ \nu_e$	( 1.69 ± 0.11 )	$\times 10^{-3}$		771
$\omega \mu^+ \nu_\mu$	( 1.77 ± 0.21 )	$\times 10^{-3}$		767
$\eta'(958) e^+ \nu_e$	( 2.0 ± 0.4 )	$\times 10^{-4}$		690
$a(980)^0 e^+ \nu_e, a(980)^0 \rightarrow \eta \pi^0$	( 1.7 ± 0.8 / 0.7 )	$\times 10^{-4}$		–
$b_1(1235)^0 e^+ \nu_e, b_1^0 \rightarrow \omega \pi^0$	< 1.75	$\times 10^{-4}$	CL=90%	–
$\phi e^+ \nu_e$	< 1.3	$\times 10^{-5}$	CL=90%	657

$D^0 e^+ \nu_e$	< 1.0	$\times 10^{-4}$	CL=90%	5
<b>Hadronic modes with a <math>\bar{K}</math> or <math>\bar{K}K\bar{K}</math></b>				
$K_S^0 \pi^+$	( 1.562 $\pm$ 0.031 ) %		S=1.7	863
$K_L^0 \pi^+$	( 1.46 $\pm$ 0.05 ) %			863
$K^- 2\pi^+$	[ $\eta$ ] ( 9.38 $\pm$ 0.16 ) %		S=1.6	846
$(K^- \pi^+)_{S\text{-wave}} \pi^+$	( 7.52 $\pm$ 0.17 ) %			846
$\bar{K}_0^*(1430)^0 \pi^+$ ,	[ $kk$ ] ( 1.25 $\pm$ 0.06 ) %			382
$\bar{K}_0^*(1430)^0 \rightarrow K^- \pi^+$				
$\bar{K}^*(892)^0 \pi^+$ ,	( 1.04 $\pm$ 0.12 ) %			714
$\bar{K}^*(892)^0 \rightarrow K^- \pi^+$				
$\bar{K}_2^*(1430)^0 \pi^+$ ,	[ $kk$ ] ( 2.3 $\pm$ 0.7 ) $\times 10^{-4}$			371
$\bar{K}_2^*(1430)^0 \rightarrow K^- \pi^+$				
$\bar{K}^*(1680)^0 \pi^+$ ,	[ $kk$ ] ( 2.2 $\pm$ 1.1 ) $\times 10^{-4}$			58
$\bar{K}^*(1680)^0 \rightarrow K^- \pi^+$				
$K^- (2\pi^+)_{I=2}$	( 1.45 $\pm$ 0.26 ) %			-
$K_S^0 \pi^+ \pi^0$	[ $\eta$ ] ( 7.36 $\pm$ 0.20 ) %			845
$K_S^0 \rho^+$	( 6.14 $\pm$ 0.60 / 0.35 ) %			677
$K_S^0 \rho(1450)^+$ , $\rho^+ \rightarrow \pi^+ \pi^0$	( 1.5 $\pm$ 1.2 / 1.4 ) $\times 10^{-3}$			-
$\bar{K}^*(892)^0 \pi^+$ ,	( 2.64 $\pm$ 0.32 ) $\times 10^{-3}$			714
$\bar{K}^*(892)^0 \rightarrow K_S^0 \pi^0$				
$\bar{K}_0^*(1430)^0 \pi^+$ , $\bar{K}_0^{*0} \rightarrow K_S^0 \pi^0$	( 2.7 $\pm$ 0.9 ) $\times 10^{-3}$			-
$\bar{K}_0^*(1680)^0 \pi^+$ , $\bar{K}_0^{*0} \rightarrow K_S^0 \pi^0$	( 10 $\pm$ 7 / 10 ) $\times 10^{-4}$			-
$\bar{\kappa}^0 \pi^+$ , $\bar{\kappa}^0 \rightarrow K_S^0 \pi^0$	( 6 $\pm$ 5 / 4 ) $\times 10^{-3}$			-
$K_S^0 \pi^+ \pi^0$ nonresonant	( 3 $\pm$ 4 ) $\times 10^{-3}$			845
$K_S^0 \pi^+ \pi^0$ nonresonant and $\bar{\kappa}^0 \pi^+$	( 1.37 $\pm$ 0.21 / 0.40 ) %			-
$(K_S^0 \pi^0)_{S\text{-wave}} \pi^+$	( 1.27 $\pm$ 0.27 / 0.33 ) %			845
$K_S^0 \pi^+ \omega$	( 7.1 $\pm$ 0.5 ) $\times 10^{-3}$			606
$K_S^0 \pi^+ \eta$	( 1.31 $\pm$ 0.05 ) %			722
$K_S^0 \pi^+ \eta'(958)$	( 1.90 $\pm$ 0.21 ) $\times 10^{-3}$			481
$K^- 2\pi^+ \pi^0$	[ $W$ ] ( 6.25 $\pm$ 0.18 ) %			817
$K_S^0 2\pi^+ \pi^-$	[ $W$ ] ( 3.10 $\pm$ 0.09 ) %			814
$K_S^0 \pi^+ 2\pi^0$	( 2.89 $\pm$ 0.09 ) %			817
$K_S^0 a_1(1260)^+$ , $a_1^+ \rightarrow \rho(770)^+ \pi^0$	( 8.7 $\pm$ 1.6 ) $\times 10^{-3}$			-
$K_S^0 a_1(1260)^+$ , $a_1^+ \rightarrow f_0(500) \pi^+$ , $f_0 \rightarrow \pi^0 \pi^0$	( 1.0 $\pm$ 0.6 ) $\times 10^{-3}$			-
$\bar{K}_1(1400)^0 \pi^+$ , $\bar{K}_1^0 \rightarrow \bar{K}^*(892)^0 \pi^0$ , $\bar{K}^{*0} \rightarrow K_S^0 \pi^0$	( 2.3 $\pm$ 0.4 ) $\times 10^{-3}$			-
$\bar{K}^*(892)^0 \rho^+$ , $\bar{K}^{*0} \rightarrow K_S^0 \pi^0$	( 9.7 $\pm$ 0.9 ) $\times 10^{-3}$			-
$\bar{K}^*(892)^0 \pi^+ \pi^0$ non-resonant, $\bar{K}^{*0} \rightarrow K_S^0 \pi^0$	( 2.6 $\pm$ 0.7 ) $\times 10^{-3}$			-
$K_S^0 \rho^+ \pi^0$ non-resonant	( 4.8 $\pm$ 0.5 ) $\times 10^{-3}$			-
$K^- 2\pi^+ \eta$	( 1.35 $\pm$ 0.12 ) $\times 10^{-3}$			657
$K_S^0 \pi^+ \pi^0 \eta$	( 1.22 $\pm$ 0.25 ) $\times 10^{-3}$			657
$K^- 3\pi^+ \pi^-$	[ $\eta$ ] ( 5.7 $\pm$ 0.5 ) $\times 10^{-3}$		S=1.1	772
$\bar{K}^*(892)^0 2\pi^+ \pi^-$ , $\bar{K}^*(892)^0 \rightarrow K^- \pi^+$	( 1.2 $\pm$ 0.4 ) $\times 10^{-3}$			645



$\bar{K}^*(892)^0 \rho^0 \pi^+$ ,	$(2.3 \pm 0.4) \times 10^{-3}$		239
$\bar{K}^*(892)^0 \rightarrow K^- \pi^+$			
$\bar{K}^*(892)^0 a_1(1260)^+$	$[nn] (9.3 \pm 1.9) \times 10^{-3}$		†
$K^- \rho^0 2\pi^+$	$(1.72 \pm 0.28) \times 10^{-3}$		524
$K^- 3\pi^+ \pi^-$ nonresonant	$(4.0 \pm 2.9) \times 10^{-4}$		772
$K_S^0 2\pi^+ \pi^- \pi^0$	$(1.53 \pm 0.08) \%$		773
$K_S^0 \pi^+ 3\pi^0$	$(5.5 \pm 0.5) \times 10^{-3}$		776
$K^- 2\pi^+ 2\pi^0$	$(4.95 \pm 0.32) \times 10^{-3}$		776
$K^+ 2K_S^0$	$(2.54 \pm 0.13) \times 10^{-3}$		545
$K^+ K^- K_S^0 \pi^+$	$(2.4 \pm 0.5) \times 10^{-4}$		436
<b>Pionic modes</b>			
$\pi^+ \pi^0$	$(1.247 \pm 0.033) \times 10^{-3}$		925
$2\pi^+ \pi^-$	$(3.27 \pm 0.09) \times 10^{-3}$		909
$\rho^0 \pi^+$	$(8.4 \pm 0.8) \times 10^{-4}$		767
$\pi^+ (\pi^+ \pi^-)_{S\text{-wave}}$	$(2.01 \pm 0.06) \times 10^{-3}$		909
$\sigma \pi^+, \sigma \rightarrow \pi^+ \pi^-$	$(1.38 \pm 0.10) \times 10^{-3}$		—
$f_0(980) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$(1.57 \pm 0.32) \times 10^{-4}$		669
$f_0(1370) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$(8 \pm 4) \times 10^{-5}$		—
$\omega \pi^+, \omega \rightarrow \pi^+ \pi^-$	$(3.4 \pm 0.5) \times 10^{-6}$		—
$f_2(1270) \pi^+, f_2 \rightarrow \pi^+ \pi^-$	$(4.58 \pm 0.28) \times 10^{-4}$		485
$\rho(1450)^0 \pi^+, \rho^0 \rightarrow \pi^+ \pi^-$	$(1.8 \pm 0.5) \times 10^{-4}$		338
$\rho(1700)^0 \pi^+, \rho^0 \rightarrow \pi^+ \pi^-$	$(1.9 \pm 0.5) \times 10^{-4}$		—
$f_0(1500) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$(1.1 \pm 0.4) \times 10^{-4}$		—
$f_0(1710) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$< 5 \times 10^{-5}$	CL=95%	—
$f_0(1790) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$< 7 \times 10^{-5}$	CL=95%	—
$(\pi^+ \pi^+)_{S\text{-wave}} \pi^-$	$< 1.2 \times 10^{-4}$	CL=95%	909
$2\pi^+ \pi^-$ nonresonant	$< 1.1 \times 10^{-4}$	CL=95%	909
$\pi^+ 2\pi^0$	$(4.61 \pm 0.15) \times 10^{-3}$		910
$2\pi^+ \pi^- \pi^0$	$(1.165 \pm 0.030) \%$		883
$\pi^+ 3\pi^0$	$(4.17 \pm 0.26) \times 10^{-3}$		885
$\pi^+ 4\pi^0$	$(1.9 \pm 0.4) \times 10^{-3}$		851
$2\pi^+ \pi^- 2\pi^0$	$(1.07 \pm 0.05) \%$		848
$3\pi^+ 2\pi^-$	$(1.66 \pm 0.16) \times 10^{-3}$	S=1.1	845
$2\pi^+ \pi^- 3\pi^0$	$(3.42 \pm 0.35) \times 10^{-3}$		803
$3\pi^+ 2\pi^- \pi^0$	$(2.34 \pm 0.27) \times 10^{-3}$		799
$\eta \pi^+$	$(3.77 \pm 0.09) \times 10^{-3}$		848
$\eta \pi^+ \pi^0$	$(2.05 \pm 0.35) \times 10^{-3}$	S=2.2	831
$\eta 2\pi^+ \pi^-$	$(3.41 \pm 0.20) \times 10^{-3}$		798
$\eta \pi^+ 2\pi^0$	$(3.20 \pm 0.33) \times 10^{-3}$		801
$\eta \pi^+ 3\pi^0$	$(2.9 \pm 0.5) \times 10^{-3}$		759
$\eta 2\pi^+ \pi^- \pi^0$	$(3.88 \pm 0.34) \times 10^{-3}$		755
$\eta \eta \pi^+$	$(2.96 \pm 0.26) \times 10^{-3}$		700
$\omega \pi^+$	$(2.8 \pm 0.6) \times 10^{-4}$		764
$\omega \pi^+ \pi^0$	$(3.9 \pm 0.9) \times 10^{-3}$		742
$\eta'(958) \pi^+$	$(4.97 \pm 0.19) \times 10^{-3}$		681
$\eta'(958) \pi^+ \pi^0$	$(1.6 \pm 0.5) \times 10^{-3}$		654
<b>Hadronic modes with a <math>K\bar{K}</math> pair</b>			
$K_S^0 K^+$	$(3.04 \pm 0.09) \times 10^{-3}$	S=2.2	793
$K_L^0 K^+$	$(3.21 \pm 0.16) \times 10^{-3}$		793
$K_S^0 K^+ \pi^0$	$(5.07 \pm 0.30) \times 10^{-3}$		744
$K^*(892)^+ K_S^0, K^{*+} \rightarrow K^+ \pi^0$	$(2.89 \pm 0.30) \times 10^{-3}$		612
$\bar{K}^*(892)^0 K^+, \bar{K}^{*0} \rightarrow K_S^0 \pi^0$	$(5.2 \pm 1.4) \times 10^{-4}$		613
$K_L^0 K^+ \pi^0$	$(5.24 \pm 0.31) \times 10^{-3}$		744

$K^+ K^- \pi^+$	$[\bar{u}]\bar{d}$ ( 9.68 ± 0.18 ) × 10 <sup>-3</sup>	744
$K^+ \bar{K}^*(892)^0$ ,	( 2.49 ± $\frac{0.08}{0.13}$ ) × 10 <sup>-3</sup>	613
$\bar{K}^*(892)^0 \rightarrow K^- \pi^+$		
$K^+ \bar{K}_0^*(1430)^0, \bar{K}_0^*(1430)^0 \rightarrow$	( 1.82 ± 0.35 ) × 10 <sup>-3</sup>	-
$K^- \pi^+$		
$K^+ \bar{K}_2^*(1430)^0, \bar{K}_2^* \rightarrow K^- \pi^+$	( 1.6 ± $\frac{1.2}{0.8}$ ) × 10 <sup>-4</sup>	-
$K^+ \bar{K}_0^*(700), \bar{K}_0^* \rightarrow K^- \pi^+$	( 6.8 ± $\frac{3.5}{2.1}$ ) × 10 <sup>-4</sup>	-
$a_0(1450)^0 \pi^+, a_0^0 \rightarrow K^+ K^-$	( 4.5 ± $\frac{7.0}{1.8}$ ) × 10 <sup>-4</sup>	-
$\phi(1680) \pi^+, \phi \rightarrow K^+ K^-$	( 4.9 ± $\frac{4.0}{1.9}$ ) × 10 <sup>-5</sup>	-
$\phi \pi^+, \phi \rightarrow K^+ K^-$	( 2.69 ± $\frac{0.07}{0.08}$ ) × 10 <sup>-3</sup>	647
$\phi \pi^+$	( 5.70 ± 0.14 ) × 10 <sup>-3</sup>	647
$K^+ K^- \pi^+ \pi^0$	( 6.62 ± 0.32 ) × 10 <sup>-3</sup>	682
$K_S^0 K_S^0 \pi^+$	( 2.70 ± 0.13 ) × 10 <sup>-3</sup>	741
$K_S^0 K_S^0 \pi^+ \pi^0$	( 1.34 ± 0.21 ) × 10 <sup>-3</sup>	679
$K_S^0 K^+ \eta$	( 1.8 ± 0.5 ) × 10 <sup>-4</sup>	516
$K^+ K_S^0 \pi^+ \pi^-$	( 1.89 ± 0.13 ) × 10 <sup>-3</sup>	678
$K_S^0 K^+ \pi^0 \pi^0$	( 5.8 ± 1.3 ) × 10 <sup>-4</sup>	683
$K_S^0 K^- 2\pi^+$	( 2.27 ± 0.13 ) × 10 <sup>-3</sup>	678
$K^+ K^- 2\pi^+ \pi^-$	( 2.3 ± 1.2 ) × 10 <sup>-4</sup>	601

A few poorly measured branching fractions:

$\phi \pi^+ \pi^0$	( 2.3 ± 1.0 ) %	619
$\phi \rho^+$	< 1.5 %	CL=90% 260
$K^+ K^- \pi^+ \pi^0$ non- $\phi$	( 1.5 ± $\frac{0.7}{0.6}$ ) %	682

**Doubly Cabibbo-suppressed modes**

$K^+ \pi^0$	( 2.08 ± 0.21 ) × 10 <sup>-4</sup>	S=1.4 864
$K^+ \eta$	( 1.25 ± 0.16 ) × 10 <sup>-4</sup>	S=1.1 776
$K^+ \eta'(958)$	( 1.85 ± 0.20 ) × 10 <sup>-4</sup>	571
$K^+ 2\pi^0$	( 2.1 ± 0.4 ) × 10 <sup>-4</sup>	847
$K^*(892)^+ \pi^0$	( 3.4 ± 1.4 ) × 10 <sup>-4</sup>	714
$K^+ \pi^+ \pi^-$	( 4.91 ± 0.09 ) × 10 <sup>-4</sup>	846
$K^+ \rho^0$	( 1.9 ± 0.5 ) × 10 <sup>-4</sup>	679
$K^+ \eta \pi^0$	( 2.1 ± 0.5 ) × 10 <sup>-4</sup>	726
$K^*(892)^+ \eta$	( 4.4 ± $\frac{1.8}{1.5}$ ) × 10 <sup>-4</sup>	586
$K^*(892)^0 \pi^+, K^*(892)^0 \rightarrow$	( 2.3 ± 0.4 ) × 10 <sup>-4</sup>	714
$K^+ \pi^-$		
$K^+ f_0(980), f_0(980) \rightarrow \pi^+ \pi^-$	( 4.4 ± 2.6 ) × 10 <sup>-5</sup>	-
$K_2^*(1430)^0 \pi^+, K_2^*(1430)^0 \rightarrow$	( 3.9 ± 2.7 ) × 10 <sup>-5</sup>	-
$K^+ \pi^-$		
$K^+ \pi^+ \pi^- \pi^0$	( 1.21 ± 0.09 ) × 10 <sup>-3</sup>	817
$K^+ \pi^+ \pi^- \pi^0$ nonresonant	( 1.10 ± 0.07 ) × 10 <sup>-3</sup>	817
$K^+ \omega$	( 5.7 ± $\frac{2.5}{2.1}$ ) × 10 <sup>-5</sup>	675
$2K^+ K^-$	( 6.14 ± 0.11 ) × 10 <sup>-5</sup>	550
$\phi(1020)^0 K^+$	< 2.1 × 10 <sup>-5</sup>	CL=90% -
$K^+ \phi(1020), \phi \rightarrow K^+ K^-$	( 4.4 ± 0.6 ) × 10 <sup>-6</sup>	-
$K^+ (K^+ K^-)_{S-wave}$	( 5.77 ± 0.12 ) × 10 <sup>-5</sup>	550

**$\Delta C = 1$  weak neutral current (C1) modes, or Lepton Family number (LF) , or Lepton number (L), or Baryon number (B) violating modes**

$\pi^+ e^+ e^-$	C1 < 1.1 × 10 <sup>-6</sup>	CL=90% 930
-----------------	-----------------------------	------------

$\pi^+ \pi^0 e^+ e^-$		< 1.4	$\times 10^{-5}$	CL=90%	925
$\pi^+ \phi, \phi \rightarrow e^+ e^-$		[00] ( 1.7 $\pm$ 1.4 $\pm$ 0.9 )	$\times 10^{-6}$		—
$\pi^+ \mu^+ \mu^-$	CI	< 6.7	$\times 10^{-8}$	CL=90%	918
$\pi^+ \phi, \phi \rightarrow \mu^+ \mu^-$		[00] ( 1.8 $\pm$ 0.8 )	$\times 10^{-6}$		—
$\rho^+ \mu^+ \mu^-$	CI	< 5.6	$\times 10^{-4}$	CL=90%	757
$K^+ e^+ e^-$		[pp] < 8.5	$\times 10^{-7}$	CL=90%	870
$K^+ \pi^0 e^+ e^-$		< 1.5	$\times 10^{-5}$	CL=90%	864
$K_S^0 \pi^+ e^+ e^-$		< 2.6	$\times 10^{-5}$	CL=90%	—
$K_S^0 K^+ e^+ e^-$		< 1.1	$\times 10^{-5}$	CL=90%	792
$K^+ \mu^+ \mu^-$		[pp] < 5.4	$\times 10^{-8}$	CL=90%	856
$\pi^+ e^+ \mu^-$	LF	< 2.1	$\times 10^{-7}$	CL=90%	927
$\pi^+ e^- \mu^+$	LF	< 2.2	$\times 10^{-7}$	CL=90%	927
$K^+ e^+ \mu^-$	LF	< 7.5	$\times 10^{-8}$	CL=90%	866
$K^+ e^- \mu^+$	LF	< 1.0	$\times 10^{-7}$	CL=90%	866
$\pi^- 2e^+$	L	< 5.3	$\times 10^{-7}$	CL=90%	930
$\pi^- 2\mu^+$	L	< 1.4	$\times 10^{-8}$	CL=90%	918
$\pi^- e^+ \mu^+$	L	< 1.3	$\times 10^{-7}$	CL=90%	927
$\rho^- 2\mu^+$	L	< 5.6	$\times 10^{-4}$	CL=90%	757
$K^- 2e^+$	L	< 9	$\times 10^{-7}$	CL=90%	870
$K_S^0 \pi^- 2e^+$		< 3.3	$\times 10^{-6}$	CL=90%	863
$K^- \pi^0 2e^+$		< 8.5	$\times 10^{-6}$	CL=90%	864
$K^- 2\mu^+$	L	< 1.0	$\times 10^{-5}$	CL=90%	856
$K^- e^+ \mu^+$	L	< 1.9	$\times 10^{-6}$	CL=90%	866
$K^*(892)^- 2\mu^+$	L	< 8.5	$\times 10^{-4}$	CL=90%	703
$\Lambda e^+$	L,B	< 1.1	$\times 10^{-6}$	CL=90%	602
$\bar{\Lambda} e^+$	L,B	< 6.5	$\times 10^{-7}$	CL=90%	602
$\Sigma^0 e^+$	L,B	< 1.7	$\times 10^{-6}$	CL=90%	554
$\bar{\Sigma}^0 e^+$	L,B	< 1.3	$\times 10^{-6}$	CL=90%	554
$\bar{n} e^+$		< 1.43	$\times 10^{-5}$	CL=90%	699
$n e^+$		< 2.91	$\times 10^{-5}$	CL=90%	699

See Particle Listings for 2 decay modes that have been seen / not seen.

**$D^0$**

$$I(J^P) = \frac{1}{2}(0^-)$$

Mass  $m = 1864.84 \pm 0.05$  MeV

$m_{D^\pm} - m_{D^0} = 4.822 \pm 0.015$  MeV

Mean life  $\tau = (410.3 \pm 1.0) \times 10^{-15}$  s

$c\tau = 123.01$   $\mu\text{m}$

### Mixing and related parameters

$$|m_{D_1^0} - m_{D_2^0}| = (0.997 \pm 0.116) \times 10^{10} \hbar \text{ s}^{-1}$$

$$(\Gamma_{D_1^0} - \Gamma_{D_2^0})/\Gamma = 2y = (1.394 \pm 0.056) \times 10^{-2}$$

$$|q/p| = 0.995 \pm 0.016$$

$$A_\Gamma = (0.089 \pm 0.113) \times 10^{-3}$$

$$\phi^{K_S^0 \pi \pi} = 0.02_{-0.05}^{+0.04}$$

$K^+ \pi^-$  relative strong phase:  $\cos \delta = 0.990 \pm 0.025$

$K^- \pi^+ \pi^0$  coherence factor  $R_{K \pi \pi^0} = 0.792 \pm 0.033$

$K^- \pi^+ \pi^0$  average relative strong phase  $\delta^{K \pi \pi^0} = (198 \pm 10)^\circ$

$K^- \pi^- 2\pi^+$  coherence factor  $R_{K 3\pi} = 0.52_{-0.09}^{+0.10}$

$K^- \pi^- 2\pi^+$  average relative strong phase  $\delta^{K 3\pi} =$

$$(149_{-16}^{+26})^\circ \quad (S = 1.4)$$

$$D^0 \rightarrow K^- \pi^- 2\pi^+, R_{K3\pi} (y \cos\delta^{K3\pi} - x \sin\delta^{K3\pi}) = (-3.0 \pm 0.7) \times 10^{-3} \text{ TeV}^{-1}$$

$$K_S^0 K^+ \pi^- \text{ coherence factor } R_{K_S^0 K\pi} = 0.70 \pm 0.08$$

$$K_S^0 K^+ \pi^- \text{ average relative strong phase } \delta^{K_S^0 K\pi} = (0 \pm 16)^\circ$$

$$K^* K \text{ coherence factor } R_{K^* K} = 0.94 \pm 0.12$$

$$K^* K \text{ average relative strong phase } \delta^{K^* K} = (-17 \pm 18)^\circ$$

### CP-even fractions (labeled by the $D^0$ decay)

$$CP\text{-even fraction in } D^0 \rightarrow K_S^0 \pi^+ \pi^- \pi^0 \text{ decays} = (23.6 \pm 0.9)\%$$

$$CP\text{-even fraction in } D^0 \rightarrow \pi^+ \pi^- \pi^0 \text{ decays} = (97.3 \pm 1.7)\%$$

$$CP\text{-even fraction in } D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^- \text{ decays} = (74.6 \pm 1.6)\% \quad (S = 1.2)$$

$$CP\text{-even fraction in } D^0 \rightarrow \pi^+ \pi^- 2\pi^0 \text{ decays} = 0.68 \pm 0.08$$

$$CP\text{-even fraction in } D^0 \rightarrow 2\pi^+ 2\pi^- \pi^0 \text{ decays} = 0.44 \pm 0.10$$

$$CP\text{-even fraction in } D^0 \rightarrow \pi^+ \pi^- 3\pi^0 \text{ decays} = 0.52_{-0.27}^{+0.34}$$

$$CP\text{-even fraction in } D^0 \rightarrow 2\pi^+ 2\pi^- 2\pi^0 \text{ decays} = 0.79 \pm 0.26$$

$$CP\text{-even fraction in } D^0 \rightarrow K^+ K^- \pi^0 \text{ decays} = (73 \pm 6)\%$$

$$CP\text{-even fraction in } D^0 \rightarrow K^+ K^- \pi^+ \pi^- \text{ decays} = (74.1 \pm 3.0)\%$$

### CP-violation decay-rate asymmetries (labeled by the $D^0$ decay)

$$A_{CP}(K^+ K^-) = (4 \pm 5) \times 10^{-4}$$

$$A_{CP}(2K_S^0) = (-1.9 \pm 1.1)\% \quad (S = 1.1)$$

$$A_{CP}(\pi^+ \pi^-) = (0.13 \pm 0.14)\%$$

$$A_{CP}(\pi^0 \pi^0) = (0.0 \pm 0.6)\%$$

$$A_{CP}(\rho\gamma) = (6 \pm 15) \times 10^{-2}$$

$$A_{CP}(\phi\gamma) = (-9 \pm 7) \times 10^{-2}$$

$$A_{CP}(K^*(892)^0 \gamma) = (-0.3 \pm 2.0) \times 10^{-2}$$

$$A_{CP}(\pi^+ \pi^- \pi^0) = (0.4 \pm 0.4)\%$$

$$A_{CP}(\eta\pi^+ \pi^-) \text{ in } D^0, \bar{D}^0 \rightarrow \eta\pi^+ \pi^- = (0.9 \pm 1.3) \times 10^{-2}$$

$$A_{CP}(\rho(770)^+ \pi^- \rightarrow \pi^+ \pi^- \pi^0) = (1.2 \pm 0.9)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(770)^0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (-3.1 \pm 3.0)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(770)^- \pi^+ \rightarrow \pi^+ \pi^- \pi^0) = (-1.0 \pm 1.7)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(1450)^+ \pi^- \rightarrow \pi^+ \pi^- \pi^0) = (0 \pm 70)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(1450)^0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (-20 \pm 40)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(1450)^- \pi^+ \rightarrow \pi^+ \pi^- \pi^0) = (6 \pm 9)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(1700)^+ \pi^- \rightarrow \pi^+ \pi^- \pi^0) = (-5 \pm 14)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(1700)^0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (13 \pm 9)\% \text{ [} qq \text{]}$$

$$A_{CP}(\rho(1700)^- \pi^+ \rightarrow \pi^+ \pi^- \pi^0) = (8 \pm 11)\% \text{ [} qq \text{]}$$

$$A_{CP}(f_0(980)\pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (0 \pm 35)\% \text{ [} qq \text{]}$$

$$A_{CP}(f_0(1370)\pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (25 \pm 18)\% \text{ [} qq \text{]}$$

$$A_{CP}(f_0(1500)\pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (0 \pm 18)\% \text{ [} qq \text{]}$$

$$A_{CP}(f_0(1710)\pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (0 \pm 24)\% \text{ [} qq \text{]}$$

$$A_{CP}(f_2(1270)\pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (-4 \pm 6)\% \text{ [} qq \text{]}$$

$$A_{CP}(\sigma(400)\pi^0 \rightarrow \pi^+ \pi^- \pi^0) = (6 \pm 8)\% \text{ [} qq \text{]}$$

$$A_{CP}(\text{nonresonant } \pi^+ \pi^- \pi^0) = (-13 \pm 23)\% \text{ [} qq \text{]}$$

$$A_{CP}(\pi^+ \pi^- 2\pi^0) \text{ in } D^0, \bar{D}^0 \rightarrow \pi^+ \pi^- 2\pi^0 = (-2.5 \pm 2.0)\%$$

$$A_{CP}(a_1(1260)^+ \pi^- \rightarrow 2\pi^+ 2\pi^-) = (5 \pm 6)\%$$

$$A_{CP}(a_1(1260)^- \pi^+ \rightarrow 2\pi^+ 2\pi^-) = (14 \pm 18)\%$$

$$A_{CP}(\pi(1300)^+ \pi^- \rightarrow 2\pi^+ 2\pi^-) = (-2 \pm 15)\%$$

$$A_{CP}(\pi(1300)^- \pi^+ \rightarrow 2\pi^+ 2\pi^-) = (-6 \pm 30)\%$$

$$A_{CP}(a_1(1640)^+ \pi^- \rightarrow 2\pi^+ 2\pi^-) = (9 \pm 26)\%$$

$$\begin{aligned}
A_{CP}(\pi_2(1670)^+ \pi^- \rightarrow 2\pi^+ 2\pi^-) &= (7 \pm 18)\% \\
A_{CP}(\sigma f_0(1370) \rightarrow 2\pi^+ 2\pi^-) &= (-15 \pm 19)\% \\
A_{CP}(\sigma \rho(770)^0 \rightarrow 2\pi^+ 2\pi^-) &= (3 \pm 27)\% \\
A_{CP}(2\rho(770)^0 \rightarrow 2\pi^+ 2\pi^-) &= (-6 \pm 6)\% \\
A_{CP}(2f_2(1270) \rightarrow 2\pi^+ 2\pi^-) &= (-28 \pm 24)\% \\
A_{CP}(\pi^+ \pi^- \pi^0 \eta) \text{ in } D^0, \bar{D}^0 \rightarrow \pi^+ \pi^- \pi^0 \eta &= (-6 \pm 6) \times 10^{-2} \\
A_{CP}(K^+ K^- \pi^0) &= (-1.0 \pm 1.7)\% \\
A_{CP}(K^*(892)^+ K^- \rightarrow K^+ K^- \pi^0) &= (-0.9 \pm 1.3)\% \text{ [qq]} \\
A_{CP}(K^*(1410)^+ K^- \rightarrow K^+ K^- \pi^0) &= (-21 \pm 24)\% \text{ [qq]} \\
A_{CP}((K^+ \pi^0)_{S\text{-wave}} K^- \rightarrow K^+ K^- \pi^0) &= (7 \pm 15)\% \text{ [qq]} \\
A_{CP}(\phi(1020) \pi^0 \rightarrow K^+ K^- \pi^0) &= (1.1 \pm 2.2)\% \text{ [qq]} \\
A_{CP}(f_0(980) \pi^0 \rightarrow K^+ K^- \pi^0) &= (-3 \pm 19)\% \text{ [qq]} \\
A_{CP}(a_0(980)^0 \pi^0 \rightarrow K^+ K^- \pi^0) &= (-5 \pm 16)\% \text{ [qq]} \\
A_{CP}(f'_2(1525) \pi^0 \rightarrow K^+ K^- \pi^0) &= (0 \pm 160)\% \text{ [qq]} \\
A_{CP}(K^*(892)^- K^+ \rightarrow K^+ K^- \pi^0) &= (-5 \pm 4)\% \text{ [qq]} \\
A_{CP}(K^*(1410)^- K^+ \rightarrow K^+ K^- \pi^0) &= (-17 \pm 29)\% \text{ [qq]} \\
A_{CP}((K^- \pi^0)_{S\text{-wave}} K^+ \rightarrow K^+ K^- \pi^0) &= (-10 \pm 40)\% \text{ [qq]} \\
A_{CP}(K^+ K^- \eta) \text{ in } D^0, \bar{D}^0 \rightarrow K^+ K^- \eta &= (-1.4 \pm 3.5) \times 10^{-2} \\
A_{CP}(\phi(1020) \eta \rightarrow K^+ K^- \eta) \text{ in } D^0, \bar{D}^0 \rightarrow \phi(1020) \eta &= (-2 \pm 4) \times 10^{-2} \\
A_{CP}(K_S^0 \pi^0) &= (-0.20 \pm 0.17)\% \\
A_{CP}(K_S^0 \eta) &= (0.5 \pm 0.5)\% \\
A_{CP}(K_S^0 \eta') &= (1.0 \pm 0.7)\% \\
A_{CP}(K_S^0 \phi) &= (-3 \pm 9)\% \\
A_{CP}(K^- \pi^+) &= (0.2 \pm 0.5)\% \\
A_{CP}(K^+ \pi^-) &= (-0.9 \pm 1.4)\% \\
A_{CP}(D_{CP(\pm 1)} \rightarrow K^\mp \pi^\pm) &= (13.1 \pm 1.0)\% \\
A_{CP}(K^- \pi^+ \pi^0) &= (0.1 \pm 0.5)\% \\
A_{CP}(K^+ \pi^- \pi^0) &= (0 \pm 5)\% \\
A_{CP}(K_S^0 \pi^+ \pi^-) &= (-0.1 \pm 0.8)\% \\
A_{CP}(K^\mp \pi^\pm \eta) \text{ in } D^0, \bar{D}^0 \rightarrow K^\mp \pi^\pm \eta &= (-1.9 \pm 1.6) \times 10^{-2} \\
A_{CP}(K_S^0 \pi^0 \eta) \text{ in } D^0, \bar{D}^0 \rightarrow K_S^0 \pi^0 \eta &= (-3.9 \pm 3.3) \times 10^{-2} \\
A_{CP}(K^\mp \pi^\pm \pi^0 \eta) \text{ in } D^0, \bar{D}^0 \rightarrow K^\mp \pi^\pm \pi^0 \eta &= (-8 \pm 5) \times 10^{-2} \\
A_{CP}(K^*(892)^- \pi^+ \rightarrow K_S^0 \pi^+ \pi^-) &= (0.4 \pm 0.5)\% \\
A_{CP}(K^*(892)^+ \pi^- \rightarrow K_S^0 \pi^+ \pi^-) &= (1 \pm 6)\% \\
A_{CP}(\bar{K}^0 \rho^0 \rightarrow K_S^0 \pi^+ \pi^-) &= (-0.1 \pm 0.5)\% \\
A_{CP}(\bar{K}^0 \omega \rightarrow K_S^0 \pi^+ \pi^-) &= (-13 \pm 7)\% \\
A_{CP}(\bar{K}^0 f_0(980) \rightarrow K_S^0 \pi^+ \pi^-) &= (-0.4 \pm 2.7)\% \\
A_{CP}(\bar{K}^0 f_2(1270) \rightarrow K_S^0 \pi^+ \pi^-) &= (-4 \pm 5)\% \\
A_{CP}(\bar{K}^0 f_0(1370) \rightarrow K_S^0 \pi^+ \pi^-) &= (-1 \pm 9)\% \\
A_{CP}(\bar{K}^0 \rho^0(1450) \rightarrow K_S^0 \pi^+ \pi^-) &= (-4 \pm 10)\% \\
A_{CP}(\bar{K}^0 f_0(600) \rightarrow K_S^0 \pi^+ \pi^-) &= (-3 \pm 5)\% \\
A_{CP}(K^*(1410)^- \pi^+ \rightarrow K_S^0 \pi^+ \pi^-) &= (-2 \pm 9)\% \\
A_{CP}(K_0^*(1430)^- \pi^+ \rightarrow K_S^0 \pi^+ \pi^-) &= (4 \pm 4)\% \\
A_{CP}(K_0^*(1430)^+ \pi^- \rightarrow K_S^0 \pi^+ \pi^-) &= (12 \pm 15)\% \\
A_{CP}(K_2^*(1430)^- \pi^+ \rightarrow K_S^0 \pi^+ \pi^-) &= (3 \pm 6)\% \\
A_{CP}(K_2^*(1430)^+ \pi^- \rightarrow K_S^0 \pi^+ \pi^-) &= (-10 \pm 32)\% \\
A_{CP}(K^- \pi^+ \pi^+ \pi^-) &= (0.2 \pm 0.5)\% \\
A_{CP}(K^+ \pi^- \pi^+ \pi^-) &= (-2 \pm 4)\% \\
A_{CP}(K^+ K^- \pi^+ \pi^-) &= (1.3 \pm 1.7)\% \\
A_{CP}(2K_S^0 \pi^+ \pi^-) \text{ in } D^0, \bar{D}^0 \rightarrow 2K_S^0 \pi^+ \pi^- &= (-2.5 \pm 1.4) \times 10^{-2}
\end{aligned}$$

$$\begin{aligned}
A_{CP}(K_1^*(1270)^+ K^- \rightarrow K^+ K^- \pi^+ \pi^-) &= (-2.3 \pm 1.7)\% \\
A_{CP}(K_1^*(1270)^+ K^- \rightarrow K^{*0} \pi^+ K^-) &= (-1 \pm 10)\% \\
A_{CP}(K_1^*(1270)^- K^+ \rightarrow \bar{K}^{*0} \pi^- K^+) &= (-10 \pm 32)\% \\
A_{CP}(K_1^*(1270)^- K^+ \rightarrow K^+ K^- \pi^+ \pi^-) &= (1.7 \pm 3.5)\% \\
A_{CP}(K_1^*(1270)^+ K^- \rightarrow \rho^0 K^+ K^-) &= (-7 \pm 17)\% \\
A_{CP}(K_1^*(1270)^- K^+ \rightarrow \rho^0 K^- K^+) &= (10 \pm 13)\% \\
A_{CP}(K_1(1400)^+ K^- \rightarrow K^+ K^- \pi^+ \pi^-) &= (-4.4 \pm 2.1)\% \\
A_{CP}(K^*(1410)^+ K^- \rightarrow K^{*0} \pi^+ K^-) &= (-20 \pm 17)\% \\
A_{CP}(K^*(1410)^- K^+ \rightarrow \bar{K}^{*0} \pi^- K^+) &= (-1 \pm 14)\% \\
A_{CP}(K^*(1680)^+ K^- \rightarrow K^+ K^- \pi^+ \pi^-) &= (-17 \pm 29)\% \\
A_{CP}(K^{*0} \bar{K}^{*0}) \text{ in } D^0, \bar{D}^0 \rightarrow K^{*0} \bar{K}^{*0} &= (-5 \pm 14)\% \\
A_{CP}(K^{*0} \bar{K}^{*0} \text{ S-wave}) &= (-3.9 \pm 2.2)\% \\
A_{CP}(\phi \rho^0) \text{ in } D^0, \bar{D}^0 \rightarrow \phi \rho^0 &= (1 \pm 9)\% \\
A_{CP}(\phi \rho^0 \text{ S-wave}) &= (-3 \pm 5)\% \\
A_{CP}(\phi \rho^0 \text{ D-wave}) &= (-37 \pm 19)\% \\
A_{CP}(\phi(\pi^+ \pi^-)_{\text{S-wave}}) &= (6 \pm 6)\% \\
A_{CP}(K^*(892)^0 (K^- \pi^+)_{\text{S-wave}}) &= (-10 \pm 40)\% \\
A_{CP}(K^+ K^- \pi^+ \pi^- \text{ non-resonant}) &= (8 \pm 20)\% \\
A_{CP}((K^- \pi^+)_{\text{P-wave}} (K^+ \pi^-)_{\text{S-wave}}) &= (3 \pm 11)\% \\
A_{CP}(K^+ K^- \mu^+ \mu^-) \text{ in } D^0, \bar{D}^0 \rightarrow K^+ K^- \mu^+ \mu^- &= (-2 \pm 6)\% \\
A_{CP}(\pi^+ \pi^- \mu^+ \mu^-) \text{ in } D^0, \bar{D}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^- &= (2.9 \pm 2.1)\%
\end{aligned}$$

### CP-violation asymmetry difference

$$\Delta A_{CP} = A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-) = (-0.154 \pm 0.029)\%$$

### $\chi^2$ tests of CP-violation (CPV) p-values

$$\begin{aligned}
\text{Local CPV in } D^0, \bar{D}^0 \rightarrow \pi^+ \pi^- \pi^0 &= 10.6\% \\
\text{Local CPV in } D^0, \bar{D}^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^- &= (0.6 \pm 0.2)\% \\
\text{Local CPV in } D^0, \bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^- &= 96\% \\
\text{Local CPV in } D^0, \bar{D}^0 \rightarrow K^+ K^- \pi^0 &= 16.6\% \\
\text{Local CPV in } D^0, \bar{D}^0 \rightarrow K^+ K^- \pi^+ \pi^- &= 9.1\%
\end{aligned}$$

### T-violation decay-rate asymmetry

$$\begin{aligned}
A_{\mathcal{T}}(K^+ K^- \pi^+ \pi^-) &= (2.9 \pm 2.2) \times 10^{-3} [ii] \\
A_{\mathcal{T}\text{viol}}(2K_S^0 \pi^+ \pi^-) \text{ in } D^0, \bar{D}^0 \rightarrow 2K_S^0 \pi^+ \pi^- &= (-1.9 \pm 1.4) \times 10^{-2} \\
A_{\mathcal{T}\text{viol}}(K_S^0 \pi^+ \pi^- \pi^0) \text{ in } D^0, \bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^- \pi^0 &= (-0.3_{-1.6}^{+1.4}) \times 10^{-3}
\end{aligned}$$

### CPT-violation decay-rate asymmetry

$$A_{CPT}(K^\mp \pi^\pm) = 0.008 \pm 0.008$$

### Form factors

$$\begin{aligned}
r_V \equiv V(0)/A_1(0) \text{ in } D^0 \rightarrow K^*(892)^- \ell^+ \nu_\ell &= 1.46 \pm 0.07 \\
r_2 \equiv A_2(0)/A_1(0) \text{ in } D^0 \rightarrow K^*(892)^- \ell^+ \nu_\ell &= 0.68 \pm 0.06 \\
f_+(0) \text{ in } D^0 \rightarrow K^- \ell^+ \nu_\ell &= 0.736 \pm 0.004 \\
f_+(0) |V_{cs}| \text{ in } D^0 \rightarrow K^- \ell^+ \nu_\ell &= 0.7166 \pm 0.0030 \\
r_1 \equiv a_1/a_0 \text{ in } D^0 \rightarrow K^- \ell^+ \nu_\ell &= -2.40 \pm 0.16 \\
r_2 \equiv a_2/a_0 \text{ in } D^0 \rightarrow K^- \ell^+ \nu_\ell &= 5 \pm 4 \\
f_+(0) \text{ in } D^0 \rightarrow \pi^- \ell^+ \nu_\ell &= 0.637 \pm 0.009 \\
f_+(0) |V_{cd}| \text{ in } D^0 \rightarrow \pi^- \ell^+ \nu_\ell &= 0.1436 \pm 0.0026 \quad (\text{S} = 1.5) \\
r_1 \equiv a_1/a_0 \text{ in } D^0 \rightarrow \pi^- \ell^+ \nu_\ell &= -1.97 \pm 0.28 \quad (\text{S} = 1.4) \\
r_2 \equiv a_1/a_0 \text{ in } D^0 \rightarrow \pi^- \ell^+ \nu_\ell &= -0.2 \pm 2.2 \quad (\text{S} = 1.7)
\end{aligned}$$

Most decay modes (other than the semileptonic modes) that involve a neutral  $K$  meson are now given as  $K_S^0$  modes, not as  $\bar{K}^0$  modes. Nearly always it is a  $K_S^0$  that is measured, and interference between Cabibbo-allowed and doubly Cabibbo-suppressed modes can invalidate the assumption that  $2\Gamma(K_S^0) = \Gamma(\bar{K}^0)$ .

<b>D<sup>0</sup> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Topological modes</b>			
0-prongs	[rr] (15 ± 6 ) %		—
2-prongs	(71 ± 6 ) %		—
4-prongs	[ss] (14.6 ± 0.5 ) %		—
6-prongs	[tt] ( 6.5 ± 1.3 ) × 10 <sup>-4</sup>		—
<b>Inclusive modes</b>			
$e^+$ anything	[uu] ( 6.49 ± 0.11 ) %		—
$\mu^+$ anything	( 6.8 ± 0.6 ) %		—
$K^-$ anything	(54.7 ± 2.8 ) %	S=1.3	—
$K_S^0$ anything	(20.75 ± 0.23 ) %		—
$K^+$ anything	( 3.4 ± 0.4 ) %		—
$K^*(892)^-$ anything	(15 ± 9 ) %		—
$\bar{K}^*(892)^0$ anything	( 9 ± 4 ) %		—
$K^*(892)^+$ anything	< 3.6 %	CL=90%	—
$K^*(892)^0$ anything	( 2.8 ± 1.3 ) %		—
$\eta$ anything	( 9.5 ± 0.9 ) %		—
$\eta'$ anything	( 2.48 ± 0.27 ) %		—
$\phi$ anything	( 1.08 ± 0.04 ) %		—
$\pi^+\pi^+\pi^-$ anything	(17.60 ± 0.25 ) %		—
invisibles	< 9.4 × 10 <sup>-5</sup>	CL=90%	—
<b>Semileptonic modes</b>			
$K^- e^+ \nu_e$	( 3.549 ± 0.026 ) %	S=1.2	867
$K^- \mu^+ \nu_\mu$	( 3.41 ± 0.04 ) %		864
$K^*(892)^- e^+ \nu_e$	( 2.15 ± 0.16 ) %		719
$K^*(892)^- \mu^+ \nu_\mu$	( 1.89 ± 0.24 ) %		714
$K^- \pi^0 e^+ \nu_e$	( 1.6 ± 1.3 / 0.5 ) %		861
$\bar{K}^0 \pi^- e^+ \nu_e$	( 1.44 ± 0.04 ) %		860
$(\bar{K}^0 \pi^-)_{S\text{-wave}} e^+ \nu_e$	( 7.9 ± 1.7 ) × 10 <sup>-4</sup>		860
$K^- \pi^+ \pi^- e^+ \nu_e$	( 2.8 ± 1.4 / 1.1 ) × 10 <sup>-4</sup>		843
$K_1(1270)^- e^+ \nu_e$	( 1.01 ± 0.18 ) × 10 <sup>-3</sup>		511
$K^- \pi^+ \pi^- \mu^+ \nu_\mu$	< 1.3 × 10 <sup>-3</sup>	CL=90%	821
$(\bar{K}^*(892)\pi)^- \mu^+ \nu_\mu$	< 1.5 × 10 <sup>-3</sup>	CL=90%	692
$\pi^- e^+ \nu_e$	( 2.91 ± 0.04 ) × 10 <sup>-3</sup>		927
$\pi^- \mu^+ \nu_\mu$	( 2.67 ± 0.12 ) × 10 <sup>-3</sup>	S=1.3	924
$\pi^- \pi^0 e^+ \nu_e$	( 1.45 ± 0.07 ) × 10 <sup>-3</sup>		922
$\rho^- e^+ \nu_e$	( 1.50 ± 0.12 ) × 10 <sup>-3</sup>	S=1.9	771
$\rho^- \mu^+ \nu_\mu$	( 1.35 ± 0.13 ) × 10 <sup>-3</sup>		767
$a(980)^- e^+ \nu_e, a^- \rightarrow \eta \pi^-$	( 1.33 ± 0.34 / 0.30 ) × 10 <sup>-4</sup>		—
$b_1(1235)^- e^+ \nu_e, b_1^- \rightarrow \omega \pi^-$	< 1.12 × 10 <sup>-4</sup>	CL=90%	—
<b>Hadronic modes with one <math>\bar{K}</math></b>			
$K^- \pi^+$	( 3.947 ± 0.030 ) %	S=1.2	861
$K_S^0 \pi^0$	( 1.240 ± 0.022 ) %		860
$K_L^0 \pi^0$	( 9.76 ± 0.32 ) × 10 <sup>-3</sup>		860

$K_L^0 \eta$		$(4.34 \pm 0.16) \times 10^{-3}$		772
$K_L^0 \eta'$		$(8.12 \pm 0.35) \times 10^{-3}$	S=1.3	565
$K_L^0 \omega$		$(1.16 \pm 0.04) \%$		670
$K_S^0 \pi^+ \pi^-$	[ij]	$(2.80 \pm 0.18) \%$	S=1.1	842
$K_S^0 \rho^0$		$(6.3 \pm_{-0.8}^{+0.6}) \times 10^{-3}$		674
$K_S^0 \omega, \omega \rightarrow \pi^+ \pi^-$		$(2.0 \pm 0.6) \times 10^{-4}$		670
$K_S^0 (\pi^+ \pi^-)_{S-wave}$		$(3.3 \pm 0.8) \times 10^{-3}$		842
$K_S^0 f_0(980), f_0 \rightarrow \pi^+ \pi^-$		$(1.20 \pm_{-0.23}^{+0.40}) \times 10^{-3}$		549
$K_S^0 f_0(1370), f_0 \rightarrow \pi^+ \pi^-$		$(2.8 \pm_{-1.3}^{+0.9}) \times 10^{-3}$		†
$K_S^0 f_2(1270), f_2 \rightarrow \pi^+ \pi^-$		$(9 \pm_{-6}^{+10}) \times 10^{-5}$		262
$K^*(892)^- \pi^+, K^{*-} \rightarrow K_S^0 \pi^-$		$(1.64 \pm_{-0.17}^{+0.14}) \%$		711
$K_0^*(1430)^- \pi^+, K_0^{*-} \rightarrow K_S^0 \pi^-$		$(2.67 \pm_{-0.32}^{+0.40}) \times 10^{-3}$		378
$K_2^*(1430)^- \pi^+, K_2^{*-} \rightarrow K_S^0 \pi^-$		$(3.4 \pm_{-1.0}^{+1.9}) \times 10^{-4}$		367
$K^*(1680)^- \pi^+, K^{*-} \rightarrow K_S^0 \pi^-$		$(4.4 \pm 3.5) \times 10^{-4}$		46
$K^*(892)^+ \pi^-, K^{*+} \rightarrow K_S^0 \pi^+$	[vv]	$(1.13 \pm_{-0.34}^{+0.60}) \times 10^{-4}$		711
$K_0^*(1430)^+ \pi^-, K_0^{*+} \rightarrow K_S^0 \pi^+$	[vv]	$< 1.4 \times 10^{-5}$	CL=95%	-
$K_2^*(1430)^+ \pi^-, K_2^{*+} \rightarrow K_S^0 \pi^+$	[vv]	$< 3.4 \times 10^{-5}$	CL=95%	-
$K_S^0 \pi^+ \pi^-$ nonresonant		$(2.5 \pm_{-1.6}^{+6.0}) \times 10^{-4}$		842
$K^- \pi^+ \pi^0$	[ij]	$(14.4 \pm 0.6) \%$	S=2.2	844
$K^- \rho^+$		$(11.2 \pm 0.7) \%$		675
$K^- \rho(1700)^+, \rho^+ \rightarrow \pi^+ \pi^0$		$(8.2 \pm 1.8) \times 10^{-3}$		†
$K^*(892)^- \pi^+, K^*(892)^- \rightarrow K^- \pi^0$		$(2.31 \pm_{-0.20}^{+0.40}) \%$		711
$\bar{K}^*(892)^0 \pi^0, \bar{K}^*(892)^0 \rightarrow K^- \pi^+$		$(1.95 \pm 0.25) \%$		711
$K_0^*(1430)^- \pi^+, K_0^{*-} \rightarrow K^- \pi^0$		$(4.8 \pm 2.2) \times 10^{-3}$		378
$\bar{K}_0^*(1430)^0 \pi^0, \bar{K}_0^{*0} \rightarrow K^- \pi^+$		$(5.9 \pm_{-1.6}^{+5.0}) \times 10^{-3}$		379
$K^*(1680)^- \pi^+, K^{*-} \rightarrow K^- \pi^0$		$(1.9 \pm 0.7) \times 10^{-3}$		46
$K^- \pi^+ \pi^0$ nonresonant		$(1.15 \pm_{-0.20}^{+0.60}) \%$		844
$K_S^0 2\pi^0$		$(9.1 \pm 1.1) \times 10^{-3}$	S=2.2	843
$K_L^0 \pi^0 \pi^0$		$(1.26 \pm 0.06) \%$		843
$K_S^0 (2\pi^0)_{S-wave}$		$(2.6 \pm 0.7) \times 10^{-3}$		-
$\bar{K}^*(892)^0 \pi^0, \bar{K}^{*0} \rightarrow K_S^0 \pi^0$		$(8.1 \pm 0.7) \times 10^{-3}$		711
$\bar{K}^*(1430)^0 \pi^0, \bar{K}^{*0} \rightarrow K_S^0 \pi^0$		$(4 \pm_{-23}^{+23}) \times 10^{-5}$		-
$\bar{K}^*(1680)^0 \pi^0, \bar{K}^{*0} \rightarrow K_S^0 \pi^0$		$(1.0 \pm 0.4) \times 10^{-3}$		-
$K_S^0 f_2(1270), f_2 \rightarrow 2\pi^0$		$(2.3 \pm 1.1) \times 10^{-4}$		-
$2K_S^0, \text{one } K_S^0 \rightarrow 2\pi^0$		$(3.2 \pm 1.1) \times 10^{-4}$		-
$K_S^0 3\pi^0$		$(7.6 \pm 0.4) \times 10^{-3}$		815



$K^- 2\pi^+ \pi^-$	[ij]	$( 8.22 \pm 0.14 ) \%$	813
$K^- \pi^+ \rho^0$ total		$( 6.87 \pm 0.31 ) \%$	609
$K^- \pi^+ \rho^0$ 3-body		$( 6.1 \pm 1.6 ) \times 10^{-3}$	609
$\overline{K}^*(892)^0 \rho^0, \overline{K}^{*0} \rightarrow$		$( 1.01 \pm 0.05 ) \%$	416
$\frac{K^- \pi^+}{\overline{K}^{*0}} \rho^0$ transverse,		$( 1.2 \pm 0.4 ) \%$	417
$\frac{K^- \pi^+}{\overline{K}^{*0}} \rightarrow K^- \pi^+$			
$K^- a_1(1260)^+, a_1^+ \rightarrow$		$( 4.32 \pm 0.32 ) \%$	327
$\rho^0 \pi^+$			
$K_1(1270)^- \pi^+, K_1^- \rightarrow$		$( 3.9 \pm 0.4 ) \times 10^{-3}$	-
$K^- \pi^+ \pi^-$ total			
$K_1(1270)^- \pi^+, K_1^- \rightarrow$		$( 6.6 \pm 2.3 ) \times 10^{-4}$	484
$\overline{K}^*(892)^0 \pi^-, \overline{K}^{*0} \rightarrow$			
$K^- \pi^+$			
$K^- 2\pi^+ \pi^-$ nonresonant		$( 1.81 \pm 0.07 ) \%$	813
$K_S^0 \pi^+ \pi^- \pi^0$	[xx]	$( 5.2 \pm 0.6 ) \%$	813
$K_S^0 \eta, \eta \rightarrow \pi^+ \pi^- \pi^0$		$( 1.17 \pm 0.03 ) \times 10^{-3}$	772
$K_S^0 \omega, \omega \rightarrow \pi^+ \pi^- \pi^0$		$( 9.9 \pm 0.6 ) \times 10^{-3}$	670
$K^- \pi^+ 2\pi^0$		$( 8.86 \pm 0.23 ) \%$	815
$K^- \pi^+ 3\pi^0$		$( 9.5 \pm 0.4 ) \times 10^{-3}$	774
$K_S^0 \pi^+ \pi^- 2\pi^0$		$( 1.27 \pm 0.06 ) \%$	773
$K^- 2\pi^+ \pi^- \pi^0$		$( 4.3 \pm 0.4 ) \%$	771
$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0, \overline{K}^{*0} \rightarrow$		$( 1.3 \pm 0.6 ) \%$	643
$\frac{K^- \pi^+}{\overline{K}^{*0}} \omega, \overline{K}^{*0} \rightarrow K^- \pi^+,$		$( 6.5 \pm 3.0 ) \times 10^{-3}$	410
$\omega \rightarrow \pi^+ \pi^- \pi^0$			
$K^- \pi^+ \omega$		$( 3.39 \pm 0.10 ) \%$	605
$\overline{K}^*(892)^0 \omega$		$( 1.1 \pm 0.5 ) \%$	410
$K_S^0 \pi^0 \omega$		$( 8.5 \pm 0.6 ) \times 10^{-3}$	605
$K_S^0 \eta \pi^0$		$( 1.01 \pm 0.05 ) \%$	721
$K_S^0 a_0(980), a_0 \rightarrow \eta \pi^0$		$( 1.20 \pm 0.28 ) \%$	-
$\overline{K}^*(892)^0 \eta, \overline{K}^{*0} \rightarrow K_S^0 \pi^0$		$( 2.9 \pm 0.7 ) \times 10^{-3}$	-
$K^- \pi^+ \eta$		$( 1.88 \pm 0.05 ) \%$	S=1.4 721
$K^*(892)^0 \eta, K^{*0} \rightarrow K^- \pi^+$		$( 8.9 \pm \begin{smallmatrix} 0.8 \\ 0.6 \end{smallmatrix} ) \times 10^{-3}$	-
$a_0(980)^+ K^-, a_0^+ \rightarrow \eta \pi^+$		$( 7.4 \pm \begin{smallmatrix} 0.9 \\ 0.7 \end{smallmatrix} ) \times 10^{-3}$	-
$K_2^*(1980)^- \pi^+, K_2^{*-} \rightarrow K^- \eta$		$( 2.2 \pm \begin{smallmatrix} 1.7 \\ 1.9 \end{smallmatrix} ) \times 10^{-4}$	-
$K^- \pi^+ \pi^0 \eta$		$( 4.49 \pm 0.27 ) \times 10^{-3}$	656
$K_S^0 \pi^+ \pi^- \eta$		$( 2.80 \pm 0.21 ) \times 10^{-3}$	651
$K_S^0 2\pi^0 \eta$		$( 1.76 \pm 0.26 ) \times 10^{-3}$	656
$K_S^0 2\pi^+ 2\pi^-$		$( 2.66 \pm 0.30 ) \times 10^{-3}$	768
$K_S^0 \rho^0 \pi^+ \pi^-, \text{no } K^*(892)^-$		$( 1.1 \pm 0.7 ) \times 10^{-3}$	-
$K^*(892)^- 2\pi^+ \pi^-,$		$( 5 \pm 7 ) \times 10^{-4}$	642
$K^*(892)^- \rightarrow K_S^0 \pi^-, \text{no}$			
$\rho^0$			
$K^*(892)^- \rho^0 \pi^+, K^*(892)^- \rightarrow$		$( 1.6 \pm 0.6 ) \times 10^{-3}$	230
$K_S^0 \pi^-$			
$K_S^0 2\pi^+ 2\pi^-$ nonresonant		$< 1.2 \times 10^{-3}$	CL=90% 768
$K^- 3\pi^+ 2\pi^-$		$( 2.2 \pm 0.6 ) \times 10^{-4}$	713

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes. These nine modes below are all corrected for unseen decays of the resonances.

$K_S^0 \eta$	$( 5.09 \pm 0.13 ) \times 10^{-3}$	772
$K_S^0 \omega$	$( 1.11 \pm 0.06 ) \%$	670

$K_S^0 \eta'(958)$	$( 9.49 \pm 0.32 ) \times 10^{-3}$	565
$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0$	$( 1.9 \pm 0.9 ) \%$	643
$\overline{K}^*(892)^0 \eta$	$( 1.41 \pm 0.12 ) \%$	583
$K^- \pi^+ \eta'(958)$	$( 6.43 \pm 0.34 ) \times 10^{-3}$	479
$K_S^0 \eta'(958) \pi^0$	$( 2.52 \pm 0.27 ) \times 10^{-3}$	479
$\overline{K}^*(892)^0 \eta'(958)$	$< 1.0 \times 10^{-3}$	CL=90% 119

**Hadronic modes with three K's**

$K_S^0 K^+ K^-$	$( 4.42 \pm 0.32 ) \times 10^{-3}$	544
$K_S^0 a_0(980)^0, a_0^0 \rightarrow K^+ K^-$	$( 2.9 \pm 0.4 ) \times 10^{-3}$	-
$K^- a_0(980)^+, a_0^+ \rightarrow K^+ K_S^0$	$( 5.9 \pm 1.8 ) \times 10^{-4}$	-
$K^+ a_0(980)^-, a_0^- \rightarrow K^- K_S^0$	$< 1.1 \times 10^{-4}$	CL=95% -
$K_S^0 f_0(980), f_0 \rightarrow K^+ K^-$	$< 9 \times 10^{-5}$	CL=95% -
$K_S^0 \phi, \phi \rightarrow K^+ K^-$	$( 2.03 \pm 0.15 ) \times 10^{-3}$	520
$K_L^0 \phi$	$( 4.14 \pm 0.23 ) \times 10^{-3}$	521
$K_S^0 f_0(1370), f_0 \rightarrow K^+ K^-$	$( 1.7 \pm 1.1 ) \times 10^{-4}$	-
$3K_S^0$	$( 7.5 \pm 0.7 ) \times 10^{-4}$	S=1.4 539
$K^+ 2K^- \pi^+$	$( 2.25 \pm 0.32 ) \times 10^{-4}$	434
$K^+ K^- \overline{K}^*(892)^0, \overline{K}^{*0} \rightarrow K^- \pi^+$	$( 4.5 \pm 1.8 ) \times 10^{-5}$	†
$K^- \pi^+ \phi, \phi \rightarrow K^+ K^-$	$( 4.0 \pm 1.7 ) \times 10^{-5}$	422
$\phi \overline{K}^*(892)^0, \phi \rightarrow K^+ K^-, \overline{K}^{*0} \rightarrow K^- \pi^+$	$( 1.08 \pm 0.21 ) \times 10^{-4}$	†
$K^+ 2K^- \pi^+$ nonresonant	$( 3.4 \pm 1.5 ) \times 10^{-5}$	434
$2K_S^0 K^\pm \pi^\mp$	$( 5.9 \pm 1.3 ) \times 10^{-4}$	427

**Pionic modes**

$\pi^+ \pi^-$	$( 1.454 \pm 0.024 ) \times 10^{-3}$	S=1.4 922
$2\pi^0$	$( 8.26 \pm 0.25 ) \times 10^{-4}$	923
$\pi^+ \pi^- \pi^0$	$( 1.49 \pm 0.07 ) \%$	S=2.3 907
$\rho^+ \pi^-$	$( 1.01 \pm 0.05 ) \%$	764
$\rho^0 \pi^0$	$( 3.86 \pm 0.24 ) \times 10^{-3}$	764
$\rho^- \pi^+$	$( 5.15 \pm 0.26 ) \times 10^{-3}$	764
$\rho(1450)^+ \pi^-, \rho^+ \rightarrow \pi^+ \pi^0$	$( 1.6 \pm 2.1 ) \times 10^{-5}$	-
$\rho(1450)^0 \pi^0, \rho^0 \rightarrow \pi^+ \pi^-$	$( 4.5 \pm 2.0 ) \times 10^{-5}$	-
$\rho(1450)^- \pi^+, \rho^- \rightarrow \pi^- \pi^0$	$( 2.7 \pm 0.4 ) \times 10^{-4}$	-
$\rho(1700)^+ \pi^-, \rho^+ \rightarrow \pi^+ \pi^0$	$( 6.1 \pm 1.5 ) \times 10^{-4}$	-
$\rho(1700)^0 \pi^0, \rho^0 \rightarrow \pi^+ \pi^-$	$( 7.4 \pm 1.8 ) \times 10^{-4}$	-
$\rho(1700)^- \pi^+, \rho^- \rightarrow \pi^- \pi^0$	$( 4.8 \pm 1.1 ) \times 10^{-4}$	-
$f_0(980) \pi^0, f_0 \rightarrow \pi^+ \pi^-$	$( 3.7 \pm 0.9 ) \times 10^{-5}$	-
$f_0(500) \pi^0, f_0 \rightarrow \pi^+ \pi^-$	$( 1.22 \pm 0.22 ) \times 10^{-4}$	-
$f_0(1370) \pi^0, f_0 \rightarrow \pi^+ \pi^-$	$( 5.5 \pm 2.1 ) \times 10^{-5}$	-
$f_0(1500) \pi^0, f_0 \rightarrow \pi^+ \pi^-$	$( 5.8 \pm 1.6 ) \times 10^{-5}$	-
$f_0(1710) \pi^0, f_0 \rightarrow \pi^+ \pi^-$	$( 4.6 \pm 1.6 ) \times 10^{-5}$	-
$f_2(1270) \pi^0, f_2 \rightarrow \pi^+ \pi^-$	$( 1.97 \pm 0.21 ) \times 10^{-4}$	-
$\pi^+ \pi^- \pi^0$ nonresonant	$( 1.3 \pm 0.4 ) \times 10^{-4}$	907
$3\pi^0$	$( 2.0 \pm 0.5 ) \times 10^{-4}$	908
$2\pi^+ 2\pi^-$	$( 7.56 \pm 0.20 ) \times 10^{-3}$	880
$a_1(1260)^+ \pi^-, a_1^+ \rightarrow 2\pi^+ \pi^-$ total	$( 4.53 \pm 0.31 ) \times 10^{-3}$	-
$a_1(1260)^+ \pi^-, a_1^+ \rightarrow \rho^0 \pi^+$ S-wave	$( 3.13 \pm 0.21 ) \times 10^{-3}$	-
$a_1(1260)^+ \pi^-, a_1^+ \rightarrow \rho^0 \pi^+$ D-wave	$( 1.9 \pm 0.5 ) \times 10^{-4}$	-
$a_1(1260)^+ \pi^-, a_1^+ \rightarrow \sigma \pi^+$	$( 6.4 \pm 0.7 ) \times 10^{-4}$	-

$a_1(1260)^- \pi^+, a_1^- \rightarrow$ $\rho^0 \pi^-$ <i>S</i> -wave	$(2.3 \pm 0.9) \times 10^{-4}$		—
$a_1(1260)^- \pi^+, a_1^- \rightarrow \sigma \pi^-$	$(6.0 \pm 3.4) \times 10^{-5}$		—
$\pi(1300)^+ \pi^-, \pi(1300)^+ \rightarrow$ $\sigma \pi^+$	$(5.1 \pm 2.7) \times 10^{-4}$		—
$\pi(1300)^- \pi^+, \pi(1300)^- \rightarrow$ $\sigma \pi^-$	$(2.3 \pm 2.2) \times 10^{-4}$		—
$a_1(1640)^+ \pi^-, a_1^+ \rightarrow$ $\rho^0 \pi^+$ <i>D</i> -wave	$(3.2 \pm 1.6) \times 10^{-4}$		—
$a_1(1640)^+ \pi^-, a_1^+ \rightarrow \sigma \pi^+$	$(1.8 \pm 1.4) \times 10^{-4}$		—
$\pi_2(1670)^+ \pi^-, \pi_2^+ \rightarrow$ $f_2(1270)^0 \pi^+, f_2^0 \rightarrow$ $\pi^+ \pi^-$	$(2.0 \pm 0.9) \times 10^{-4}$		—
$\pi_2(1670)^+ \pi^-, \pi_2^+ \rightarrow \sigma \pi^+$	$(2.6 \pm 1.0) \times 10^{-4}$		—
$2\rho^0$ total	$(1.85 \pm 0.13) \times 10^{-3}$		518
$2\rho^0$ , parallel helicities	$(8.3 \pm 3.2) \times 10^{-5}$		—
$2\rho^0$ , perpendicular helicities	$(4.8 \pm 0.6) \times 10^{-4}$		—
$2\rho^0$ , longitudinal helicities	$(1.27 \pm 0.10) \times 10^{-3}$		—
$2\rho(770)^0$ , <i>S</i> -wave	$(1.8 \pm 1.3) \times 10^{-4}$		—
$2\rho(770)^0$ , <i>P</i> -wave	$(5.3 \pm 1.3) \times 10^{-4}$		—
$2\rho(770)^0$ , <i>D</i> -wave	$(6.2 \pm 3.0) \times 10^{-4}$		—
Resonant $(\pi^+ \pi^-) \pi^+ \pi^-$	$(1.51 \pm 0.12) \times 10^{-3}$		—
3-body total			
$\sigma \pi^+ \pi^-$	$(6.2 \pm 0.9) \times 10^{-4}$		—
$\sigma \rho(770)^0$	$(5.0 \pm 2.5) \times 10^{-4}$		—
$f_0(980) \pi^+ \pi^-, f_0 \rightarrow \pi^+ \pi^-$	$(1.8 \pm 0.5) \times 10^{-4}$		—
$f_2(1270) \pi^+ \pi^-, f_2 \rightarrow$ $\pi^+ \pi^-$	$(3.7 \pm 0.6) \times 10^{-4}$		—
$2f_2(1270), f_2 \rightarrow \pi^+ \pi^-$	$(1.6 \pm 1.8) \times 10^{-4}$		—
$f_0(1370) \sigma, f_0 \rightarrow \pi^+ \pi^-$	$(1.6 \pm 0.5) \times 10^{-3}$		—
$\pi^+ \pi^- 2\pi^0$	$(1.002 \pm 0.031) \%$		882
$4\pi^0$	$(7.6 \pm 1.1) \times 10^{-4}$		883
$\eta \pi^0$	[ $\gamma\gamma$ ] $(6.3 \pm 0.6) \times 10^{-4}$	S=1.1	846
$\omega \pi^0$	[ $\gamma\gamma$ ] $(1.17 \pm 0.35) \times 10^{-4}$		761
$\omega \eta$	$(1.98 \pm 0.18) \times 10^{-3}$	S=1.1	648
$2\pi^+ 2\pi^- \pi^0$	$(3.46 \pm 0.21) \times 10^{-3}$		844
$\pi^+ \pi^- 3\pi^0$	$(1.53 \pm 0.21) \times 10^{-3}$		847
$2\pi^+ 2\pi^- 2\pi^0$	$(4.8 \pm 0.4) \times 10^{-3}$		798
$\eta \pi^+ \pi^-$	[ $\gamma\gamma$ ] $(1.16 \pm 0.07) \times 10^{-3}$		827
$\omega \pi^+ \pi^-$	[ $\gamma\gamma$ ] $(1.33 \pm 0.20) \times 10^{-3}$		738
$\omega \pi^0 \pi^0$	$< 1.10 \times 10^{-3}$	CL=90%	740
$\eta 2\pi^0$	$(3.8 \pm 1.3) \times 10^{-4}$		829
$\pi^+ \pi^- \pi^0 \eta$	$(3.23 \pm 0.22) \times 10^{-3}$		797
$\eta 3\pi^0$	$(2.36 \pm 0.28) \times 10^{-3}$		799
$\eta 2\pi^+ 2\pi^-$	$(6.0 \pm 1.2) \times 10^{-4}$		751
$3\pi^+ 3\pi^-$	$(4.3 \pm 1.2) \times 10^{-4}$		795
$\eta'(958) \pi^0$	$(9.2 \pm 1.0) \times 10^{-4}$		678
$\eta'(958) \pi^+ \pi^-$	$(4.5 \pm 1.7) \times 10^{-4}$		650
$2\eta$	$(2.11 \pm 0.19) \times 10^{-3}$	S=2.2	754
$2\eta \pi^0$	$(7.3 \pm 2.2) \times 10^{-4}$		699
$2\eta \pi^+ \pi^-$	$(8.5 \pm 1.4) \times 10^{-4}$		623
$3\eta$	$< 1.3 \times 10^{-4}$	CL=90%	421
$\eta \eta'(958)$	$(1.01 \pm 0.19) \times 10^{-3}$		537
<b>Hadronic modes with a <math>K\bar{K}</math> pair</b>			
$K^+ K^-$	$(4.08 \pm 0.06) \times 10^{-3}$	S=1.6	791

$2K_S^0$	$(1.41 \pm 0.05) \times 10^{-4}$	S=1.1	789
$K_S^0 K^- \pi^+$	$(3.3 \pm 0.5) \times 10^{-3}$	S=1.1	739
$\bar{K}^*(892)^0 K_S^0, \bar{K}^{*0} \rightarrow K^- \pi^+$	$(8.2 \pm 1.6) \times 10^{-5}$		608
$K^*(892)^+ K^-, K^{*+} \rightarrow K_S^0 \pi^+$	$(1.89 \pm 0.30) \times 10^{-3}$		-
$\bar{K}^*(1410)^0 K_S^0, \bar{K}^{*0} \rightarrow K^- \pi^+$	$(1.3 \pm 1.9) \times 10^{-4}$		-
$K^*(1410)^+ K^-, K^{*+} \rightarrow K_S^0 \pi^+$	$(3.2 \pm 1.9) \times 10^{-4}$		-
$(K^- \pi^+)_{S\text{-wave}} K_S^0$	$(6.0 \pm 2.9) \times 10^{-4}$		739
$(K_S^0 \pi^+)_{S\text{-wave}} K^-$	$(3.9 \pm 1.0) \times 10^{-4}$		739
$a_0(980)^- \pi^+, a_0^- \rightarrow K_S^0 K^-$	$(1.3 \pm 1.4) \times 10^{-4}$		-
$a_0(1450)^- \pi^+, a_0^- \rightarrow K_S^0 K^-$	$(2.5 \pm 2.0) \times 10^{-5}$		-
$a_2(1320)^- \pi^+, a_2^- \rightarrow K_S^0 K^-$	$(5 \pm 5) \times 10^{-6}$		-
$\rho(1450)^- \pi^+, \rho^- \rightarrow K_S^0 K^-$	$(4.6 \pm 2.5) \times 10^{-5}$		-
$K_S^0 K^+ \pi^-$	$(2.17 \pm 0.35) \times 10^{-3}$	S=1.1	739
$K^*(892)^0 K_S^0, K^{*0} \rightarrow K^+ \pi^-$	$(1.12 \pm 0.21) \times 10^{-4}$		608
$K^*(892)^- K^+, K^{*-} \rightarrow K_S^0 \pi^-$	$(6.2 \pm 1.1) \times 10^{-4}$		-
$K^*(1410)^0 K_S^0, K^{*0} \rightarrow K^+ \pi^+$	$(5 \pm 8) \times 10^{-5}$		-
$K^*(1410)^- K^+, K^{*-} \rightarrow K_S^0 \pi^-$	$(2.6 \pm 2.0) \times 10^{-4}$		-
$(K^+ \pi^-)_{S\text{-wave}} K_S^0$	$(3.7 \pm 1.9) \times 10^{-4}$		739
$(K_S^0 \pi^-)_{S\text{-wave}} K^+$	$(1.4 \pm 0.6) \times 10^{-4}$		739
$a_0(980)^+ \pi^-, a_0^+ \rightarrow K_S^0 K^+$	$(6 \pm 4) \times 10^{-4}$		-
$a_0(1450)^+ \pi^-, a_0^+ \rightarrow K_S^0 K^+$	$(3.2 \pm 2.5) \times 10^{-5}$		-
$\rho(1700)^+ \pi^-, \rho^+ \rightarrow K_S^0 K^+$	$(1.1 \pm 0.6) \times 10^{-5}$		-
$K^+ K^- \pi^0$	$(3.42 \pm 0.15) \times 10^{-3}$		743
$K^*(892)^+ K^-, K^*(892)^+ \rightarrow K^+ \pi^0$	$(1.52 \pm 0.08) \times 10^{-3}$		-
$K^*(892)^- K^+, K^*(892)^- \rightarrow K^- \pi^0$	$(5.4 \pm 0.4) \times 10^{-4}$		-
$(K^+ \pi^0)_{S\text{-wave}} K^-$	$(2.43 \pm 0.18) \times 10^{-3}$		743
$(K^- \pi^0)_{S\text{-wave}} K^+$	$(1.3 \pm 0.5) \times 10^{-4}$		743
$f_0(980) \pi^0, f_0 \rightarrow K^+ K^-$	$(3.6 \pm 0.6) \times 10^{-4}$		-
$\phi \pi^0, \phi \rightarrow K^+ K^-$	$(6.6 \pm 0.4) \times 10^{-4}$		-
$2K_S^0 \pi^0$	$< 1.45 \times 10^{-4}$	CL=90%	740
$K^+ K^- \eta$	$(5.9 \pm 1.9) \times 10^{-5}$		514
$\phi(1020) \eta$	$(1.84 \pm 0.12) \times 10^{-4}$		489
$K^+ K^- \eta$ nonresonant	$(9.9 \pm 0.9) \times 10^{-5}$		514
$2K_S^0 \eta$	$(1.3 \pm 0.6) \times 10^{-4}$		508
$K^+ K^- \pi^0 \pi^0$	$(6.9 \pm 0.8) \times 10^{-4}$		681
$K^+ K^- \pi^+ \pi^-$	$(2.47 \pm 0.11) \times 10^{-3}$		677
$\phi(\pi^+ \pi^-)_{S\text{-wave}}, \phi \rightarrow K^+ K^-$	$(10 \pm 5) \times 10^{-5}$		614
$(\phi \rho^0)_{S\text{-wave}}, \phi \rightarrow K^+ K^-$	$(6.9 \pm 0.6) \times 10^{-4}$		250
$(\phi \rho^0)_{P\text{-wave}}, \phi \rightarrow K^+ K^-$	$(4.0 \pm 1.9) \times 10^{-5}$		-
$(\phi \rho^0)_{D\text{-wave}}, \phi \rightarrow K^+ K^-$	$(4.2 \pm 1.4) \times 10^{-5}$		-
$(K^*(892)^0 \bar{K}^*(892)^0)_{S\text{-wave}}, K^{*0} \rightarrow K^\pm \pi^\mp$	$(2.24 \pm 0.13) \times 10^{-4}$		-
$(K^*(892)^0 \bar{K}^*(892)^0)_{P\text{-wave}}, K^* \rightarrow K^\pm \pi^\mp$	$(1.20 \pm 0.08) \times 10^{-4}$		-

$(K^*(892)^0 \bar{K}^*(892)^0)_{D\text{-wave}},$ $K^* \rightarrow K^\pm \pi^\mp$	$(4.7 \pm 0.4) \times 10^{-5}$	—
$K^*(892)^0 (K^- \pi^+)_{S\text{-wave}}$ 3- body, $K^{*0} \rightarrow K^+ \pi^-$	$(1.4 \pm 0.6) \times 10^{-4}$	—
$K_1(1270)^+ K^-, K_1^+ \rightarrow$ $K^{*0} \pi^+$	$(1.4 \pm 0.9) \times 10^{-4}$	—
$K_1(1270)^+ K^-, K_1^+ \rightarrow$ $K^*(1430)^0 \pi^+, K^{*0} \rightarrow$ $K^+ \pi^-$	$(1.5 \pm 0.5) \times 10^{-4}$	—
$K_1(1270)^+ K^-, K_1^+ \rightarrow \rho^0 K^+$	$(2.2 \pm 0.6) \times 10^{-4}$	—
$K_1(1270)^+ K^-, K_1^+ \rightarrow$ $\omega(782) K^+, \omega \rightarrow \pi^+ \pi^-$	$(1.5 \pm 1.2) \times 10^{-5}$	—
$K_1(1270)^- K^+, K_1^- \rightarrow \rho^0 K^-$	$(1.3 \pm 0.4) \times 10^{-4}$	—
$K_1(1400)^+ K^-, K_1^+ \rightarrow$ $K^*(892)^0 \pi^+, K^{*0} \rightarrow$ $K^+ \pi^-$	$(4.6 \pm 0.4) \times 10^{-4}$	—
$K^*(1410)^- K^+, K^{*-} \rightarrow$ $\bar{K}^{*0} \pi^-$	$(7.0 \pm 1.1) \times 10^{-5}$	—
$K_1(1680)^+ K^-, K_1^+ \rightarrow$ $K^{*0} \pi^+, K^{*0} \rightarrow K^+ \pi^-$	$(8.9 \pm 3.2) \times 10^{-5}$	—
$K^+ K^- \pi^+ \pi^-$ non-resonant	$(2.7 \pm 0.6) \times 10^{-4}$	—
$2K_S^0 \pi^+ \pi^-$	$(5.3 \pm 0.9) \times 10^{-4}$	673
$K_S^0 K^- \pi^+ \pi^0$	$(1.32 \pm 0.16) \times 10^{-3}$	677
$K_S^0 K^+ \pi^- \pi^0$	$(6.5 \pm 0.7) \times 10^{-4}$	677
$K_S^0 K^- 2\pi^+ \pi^-$	$< 1.4 \times 10^{-4}$	CL=90% 595
$K^+ K^- \pi^+ \pi^- \pi^0$	$(3.1 \pm 2.0) \times 10^{-3}$	600

Other  $K \bar{K} X$  modes. They include all decay modes of the  $\phi$ ,  $\eta$ , and  $\omega$ .

$\phi \pi^0$	$(1.17 \pm 0.04) \times 10^{-3}$	645
$\phi \eta$	$(1.8 \pm 0.5) \times 10^{-4}$	489
$\phi \omega$	$(6.5 \pm 1.0) \times 10^{-4}$	238

### Radiative modes

$\rho^0 \gamma$	$(1.82 \pm 0.32) \times 10^{-5}$	771
$\omega \gamma$	$< 2.4 \times 10^{-4}$	CL=90% 768
$\phi \gamma$	$(2.81 \pm 0.19) \times 10^{-5}$	654
$\bar{K}^*(892)^0 \gamma$	$(4.1 \pm 0.7) \times 10^{-4}$	719

### Doubly Cabibbo suppressed (DC) modes or $\Delta C = 2$ forbidden via mixing (C2M) modes

$K^+ \ell^- \bar{\nu}_\ell$ via $\bar{D}^0$	$[zz] < 2.2 \times 10^{-5}$	CL=90%	—
$K^+$ or $K^*(892)^+ e^- \bar{\nu}_e$ via $\bar{D}^0$	$< 6 \times 10^{-5}$	CL=90%	—
$K^+ \pi^-$ DC	$(1.50 \pm 0.07) \times 10^{-4}$	S=3.0	861
$K^+ \pi^-$ via DCS	$(1.363 \pm 0.025) \times 10^{-4}$		—
$K^+ \pi^-$ via $\bar{D}^0$	$< 1.6 \times 10^{-5}$	CL=95%	861
$K_S^0 \pi^+ \pi^-$ in $D^0 \rightarrow \bar{D}^0$	$< 1.8 \times 10^{-4}$	CL=95%	—
$K^*(892)^+ \pi^-, K^{*+} \rightarrow$ $K_S^0 \pi^+$ DC	$(1.13 \pm_{-0.34}^{0.60}) \times 10^{-4}$		711
$K_0^*(1430)^+ \pi^-, K_0^{*+} \rightarrow$ $K_S^0 \pi^+$ DC	$< 1.4 \times 10^{-5}$		—
$K_2^*(1430)^+ \pi^-, K_2^{*+} \rightarrow$ $K_S^0 \pi^+$ DC	$< 3.4 \times 10^{-5}$		—
$K^+ \pi^- \pi^0$ DC	$(3.06 \pm 0.16) \times 10^{-4}$	S=1.4	844
$K^+ \pi^- \pi^0$ via $\bar{D}^0$	$(7.6 \pm_{-0.6}^{0.5}) \times 10^{-4}$		—

$K^+ \pi^- 2\pi^0$		$< 3.6$	$\times 10^{-4}$	CL=90%	815
$K^+ \pi^+ 2\pi^-$ via DCS		$(2.49 \pm 0.07)$	$\times 10^{-4}$		—
$K^+ \pi^+ 2\pi^-$	DC	$(2.65 \pm 0.06)$	$\times 10^{-4}$		813
$K^+ \pi^+ 2\pi^-$ via $\bar{D}^0$		$(7.9 \pm 3.0)$	$\times 10^{-6}$		812
$\mu^-$ anything via $\bar{D}^0$		$< 4$	$\times 10^{-4}$	CL=90%	—

**$\Delta C = 1$  weak neutral current (C1) modes,  
Lepton Family number (LF) violating modes,  
Lepton (L) or Baryon (B) number violating modes**

$\gamma\gamma$	C1	$< 8.5$	$\times 10^{-7}$	CL=90%	932
$e^+ e^-$	C1	$< 7.9$	$\times 10^{-8}$	CL=90%	932
$\mu^+ \mu^-$	C1	$< 3.1$	$\times 10^{-9}$	CL=90%	926
$\pi^0 e^+ e^-$	C1	$< 4$	$\times 10^{-6}$	CL=90%	928
$\pi^0 \mu^+ \mu^-$	C1	$< 1.8$	$\times 10^{-4}$	CL=90%	915
$\pi^0 \nu \bar{\nu}$		$< 2.1$	$\times 10^{-4}$	CL=90%	928
$\eta e^+ e^-$	C1	$< 3$	$\times 10^{-6}$	CL=90%	852
$\eta \mu^+ \mu^-$	C1	$< 5.3$	$\times 10^{-4}$	CL=90%	838
$\pi^+ \pi^- e^+ e^-$	C1	$< 7$	$\times 10^{-6}$	CL=90%	922
$\rho^0 e^+ e^-$	C1	$< 1.0$	$\times 10^{-4}$	CL=90%	771
$\pi^+ \pi^- \mu^+ \mu^-$	C1	$(9.6 \pm 1.2)$	$\times 10^{-7}$		894
$\pi^+ \pi^- \mu^+ \mu^-$ (non-res)		$< 5.5$	$\times 10^{-7}$	CL=90%	—
$\rho^0 \mu^+ \mu^-$	C1	$< 2.2$	$\times 10^{-5}$	CL=90%	754
$\omega e^+ e^-$	C1	$< 6$	$\times 10^{-6}$	CL=90%	768
$\omega \mu^+ \mu^-$	C1	$< 8.3$	$\times 10^{-4}$	CL=90%	751
$K^- K^+ e^+ e^-$	C1	$< 1.1$	$\times 10^{-5}$	CL=90%	791
$\phi e^+ e^-$	C1	$< 5.2$	$\times 10^{-5}$	CL=90%	654
$K^- K^+ \mu^+ \mu^-$	C1	$(1.54 \pm 0.32)$	$\times 10^{-7}$		710
$K^- K^+ \mu^+ \mu^-$ (non-res)		$< 3.3$	$\times 10^{-5}$	CL=90%	—
$\phi \mu^+ \mu^-$	C1	$< 3.1$	$\times 10^{-5}$	CL=90%	631
$\bar{K}^0 e^+ e^-$	[pp]	$< 2.4$	$\times 10^{-5}$	CL=90%	866
$\bar{K}^0 \mu^+ \mu^-$	[pp]	$< 2.6$	$\times 10^{-4}$	CL=90%	852
$K^- \pi^+ e^+ e^-$ , $675 < m_{ee} < 875$ MeV		$(4.0 \pm 0.5)$	$\times 10^{-6}$		—
$K^- \pi^+ e^+ e^-$ , $1.005 < m_{ee} < 1.035$ GeV		$< 5$	$\times 10^{-7}$	CL=90%	—
$\bar{K}^*(892)^0 e^+ e^-$	[pp]	$< 4.7$	$\times 10^{-5}$	CL=90%	719
$K^- \pi^+ \mu^+ \mu^-$	C1	$< 3.59$	$\times 10^{-4}$	CL=90%	829
$K^- \pi^+ \mu^+ \mu^-$ , $675 < m_{\mu\mu} < 875$ MeV		$(4.2 \pm 0.4)$	$\times 10^{-6}$		—
$\bar{K}^*(892)^0 \mu^+ \mu^-$	[pp]	$< 2.4$	$\times 10^{-5}$	CL=90%	700
$\pi^+ \pi^- \pi^0 \mu^+ \mu^-$	C1	$< 8.1$	$\times 10^{-4}$	CL=90%	863
$\mu^\pm e^\mp$	LF	[aa] $< 1.3$	$\times 10^{-8}$	CL=90%	929
$\pi^0 e^\pm \mu^\mp$	LF	[aa] $< 8.0$	$\times 10^{-7}$	CL=90%	924
$\eta e^\pm \mu^\mp$	LF	[aa] $< 2.25$	$\times 10^{-6}$	CL=90%	848
$\pi^+ \pi^- e^\pm \mu^\mp$	LF	[aa] $< 1.71$	$\times 10^{-6}$	CL=90%	911
$\rho^0 e^\pm \mu^\mp$	LF	[aa] $< 5.0$	$\times 10^{-7}$	CL=90%	767
$\omega e^\pm \mu^\mp$	LF	[aa] $< 1.71$	$\times 10^{-6}$	CL=90%	764
$K^- K^+ e^\pm \mu^\mp$	LF	[aa] $< 1.00$	$\times 10^{-6}$	CL=90%	754
$\phi e^\pm \mu^\mp$	LF	[aa] $< 5.1$	$\times 10^{-7}$	CL=90%	648
$\bar{K}^0 e^\pm \mu^\mp$	LF	[aa] $< 1.74$	$\times 10^{-6}$	CL=90%	863
$K^- \pi^+ e^\pm \mu^\mp$	LF	[aa] $< 1.90$	$\times 10^{-6}$	CL=90%	848
$\bar{K}^*(892)^0 e^\pm \mu^\mp$	LF	[aa] $< 1.25$	$\times 10^{-6}$	CL=90%	714
$2\pi^- 2e^+$	L	$< 9.1$	$\times 10^{-7}$	CL=90%	922
$2\pi^- 2\mu^+$	L	$< 1.52$	$\times 10^{-6}$	CL=90%	894
$K^- \pi^- 2e^+$	L	$< 5.0$	$\times 10^{-7}$	CL=90%	861

$K^- \pi^- 2\mu^+$	$L$	$< 5.3$	$\times 10^{-7}$	CL=90%	829
$2K^- 2e^+$	$L$	$< 3.4$	$\times 10^{-7}$	CL=90%	791
$2K^- 2\mu^+$	$L$	$< 1.0$	$\times 10^{-7}$	CL=90%	710
$\pi^- \pi^- e^+ \mu^+$	$L$	$< 3.06$	$\times 10^{-6}$	CL=90%	911
$K^- \pi^- e^+ \mu^+$	$L$	$< 2.10$	$\times 10^{-6}$	CL=90%	848
$2K^- e^+ \mu^+$	$L$	$< 5.8$	$\times 10^{-7}$	CL=90%	754
$p e^-$	$L, B$	$< 2.2$	$\times 10^{-6}$	CL=90%	696
$\bar{p} e^+$	$L, B$	$< 1.2$	$\times 10^{-6}$	CL=90%	696

 **$D^*(2007)^0$** 

$$I(J^P) = \frac{1}{2}(1^-)$$

Mass  $m = 2006.85 \pm 0.05$  MeV ( $S = 1.1$ ) $m_{D^{*0}} - m_{D^0} = 142.014 \pm 0.030$  MeV ( $S = 1.5$ )Full width  $\Gamma < 2.1$  MeV, CL = 90% $\bar{D}^*(2007)^0$  modes are charge conjugates of modes below.

<b><math>D^*(2007)^0</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$D^0 \pi^0$	(64.7 $\pm$ 0.9) %		43
$D^0 \gamma$	(35.3 $\pm$ 0.9) %		137
$D^0 e^+ e^-$	( 3.91 $\pm$ 0.33) $\times 10^{-3}$		137
$\mu^+ \mu^-$	$< 2.5$ $\times 10^{-8}$	90%	998
$e^+ e^-$	$< 1.7$ $\times 10^{-6}$	90%	1003

 **$D^*(2010)^\pm$** 

$$I(J^P) = \frac{1}{2}(1^-)$$

Mass  $m = 2010.26 \pm 0.05$  MeV $m_{D^*(2010)^+} - m_{D^+} = 140.603 \pm 0.015$  MeV $m_{D^*(2010)^+} - m_{D^0} = 145.4258 \pm 0.0017$  MeVFull width  $\Gamma = 83.4 \pm 1.8$  keV $D^*(2010)^-$  modes are charge conjugates of the modes below.

<b><math>D^*(2010)^\pm</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$D^0 \pi^+$	(67.7 $\pm$ 0.5) %	39
$D^+ \pi^0$	(30.7 $\pm$ 0.5) %	38
$D^+ \gamma$	( 1.6 $\pm$ 0.4) %	136

 **$D_0^*(2300)$** 

$$I(J^P) = \frac{1}{2}(0^+)$$

was  $D_0^*(2400)$ Mass  $m = 2343 \pm 10$  MeV ( $S = 1.5$ )Full width  $\Gamma = 229 \pm 16$  MeV **$D_1(2420)$** 

$$I(J^P) = \frac{1}{2}(1^+)$$

Mass  $m = 2422.1 \pm 0.6$  MeV ( $S = 1.7$ ) $m_{D_1(2420)^0} - m_{D^{*+}} = 411.8 \pm 0.6$  MeV ( $S = 1.7$ ) $m_{D_1(2420)^\pm} - m_{D_1(2420)^0} = 4 \pm 4$  MeVFull width  $\Gamma = 31.3 \pm 1.9$  MeV ( $S = 2.8$ )

**$D_1(2430)^0$** 

$$I(J^P) = \frac{1}{2}(1^+)$$

Mass  $m = 2412 \pm 9$  MeVFull width  $\Gamma = 314 \pm 29$  MeV **$D_2^*(2460)$** 

$$I(J^P) = \frac{1}{2}(2^+)$$

Mass  $m = 2461.1 \pm 0.8$  MeV ( $S = 6.3$ ) $m_{D_2^*(2460)^0} - m_{D^+} = 591.5 \pm 0.8$  MeV ( $S = 6.0$ ) $m_{D_2^*(2460)^0} - m_{D^{*+}} = 450.9 \pm 0.8$  MeV ( $S = 6.0$ ) $m_{D_2^*(2460)^\pm} - m_{D_2^*(2460)^0} = 2.4 \pm 1.7$  MeVFull width  $\Gamma = 47.3 \pm 0.8$  MeV ( $S = 1.5$ ) **$D_3^*(2750)$** 

$$I(J^P) = \frac{1}{2}(3^-)$$

Mass  $m = 2763.1 \pm 3.2$  MeV ( $S = 2.1$ )Full width  $\Gamma = 66 \pm 5$  MeV

## CHARMED, STRANGE MESONS ( $C = \pm 1, S = \pm 1$ ) (including possibly non- $q\bar{q}$ states)

$$D_s^+ = c\bar{s}, D_s^- = \bar{c}s, \text{ similarly for } D_s^{*\prime}s$$

 **$D_s^\pm$** 

$$I(J^P) = 0(0^-)$$

Mass  $m = 1968.35 \pm 0.07$  MeV $m_{D_s^\pm} - m_{D^\pm} = 98.69 \pm 0.05$  MeVMean life  $\tau = (501.2 \pm 2.2) \times 10^{-15}$  s ( $S = 1.3$ ) $c\tau = 150.3 \mu\text{m}$  **$CP$ -violating decay-rate asymmetries**

$$A_{CP}(\mu^\pm\nu) = (-0.2 \pm 2.5)\%$$

$$A_{CP}(\tau^\pm\nu) \text{ in } D_s^+ \rightarrow \tau^+\nu_\tau, D_s^- \rightarrow \tau^-\bar{\nu}_\tau = (3 \pm 5)\%$$

$$A_{CP}(K^\pm K_S^0) = (0.09 \pm 0.26)\%$$

$$A_{CP}(K^\pm K_L^0) \text{ in } D_s^\pm \rightarrow K^\pm K_L^0 = (-1.1 \pm 2.7) \times 10^{-2}$$

$$A_{CP}(K^+ K^- \pi^\pm) = (-0.5 \pm 0.9)\%$$

$$A_{CP}(\phi\pi^\pm) = (-0.38 \pm 0.27)\%$$

$$A_{CP}(K^\pm K_S^0 \pi^0) = (-2 \pm 6)\%$$

$$A_{CP}(2K_S^0 \pi^\pm) = (3 \pm 5)\%$$

$$A_{CP}(K^+ K^- \pi^\pm \pi^0) = (0.0 \pm 3.0)\%$$

$$A_{CP}(K^\pm K_S^0 \pi^+ \pi^-) = (-6 \pm 5)\%$$

$$A_{CP}(K_S^0 K^\mp 2\pi^\pm) = (4.1 \pm 2.8)\%$$

$$A_{CP}(\pi^+ \pi^- \pi^\pm) = (-0.7 \pm 3.1)\%$$

$$A_{CP}(\pi^\pm \eta) = (0.32 \pm 0.31)\%$$

$$A_{CP}(\pi^\pm \eta') = (-0.06 \pm 0.22)\% \quad (S = 1.6)$$

$$A_{CP}(\eta\pi^\pm\pi^0) = (-1 \pm 4)\%$$



$$\begin{aligned}
A_{CP}(\eta' \pi^\pm \pi^0) &= (0 \pm 8)\% \\
A_{CP}(K^\pm \pi^0) &= (2 \pm 4)\% \quad (S = 1.2) \\
A_{CP}(\bar{K}^0 / K^0 \pi^\pm) &= (0.4 \pm 0.5)\% \\
A_{CP}(K_S^0 \pi^\pm) &= (0.20 \pm 0.18)\% \\
A_{CP}(K^\pm \pi^+ \pi^-) &= (3.7 \pm 2.7)\% \\
A_{CP}(K_S^0 \pi^+ \pi^0) \text{ in } D_S^\pm &\rightarrow K_S^0 \pi^\pm \pi^0 = (3 \pm 6)\% \\
A_{CP}(K^\pm \pi^+ \pi^- \pi^0) \text{ in } D_S^\pm &\rightarrow K^\pm \pi^+ \pi^- \pi^0 = (7 \pm 5) \times 10^{-2} \\
A_{CP}(K^\pm \eta) &= (1.8 \pm 1.9)\% \\
A_{CP}(K^\pm \eta'(958)) &= (6 \pm 19)\%
\end{aligned}$$

### CP violating asymmetries of P-odd (T-odd) moments

$$\begin{aligned}
\text{Local CPV in } D_S^\pm &\rightarrow K^+ K^- K^\pm = 0.133 \\
A_T(K_S^0 K^\pm \pi^+ \pi^-) &= (-8 \pm 6) \times 10^{-3} \text{ [} \bar{u} \text{]}
\end{aligned}$$

### $D_S^+ \rightarrow \phi \ell^+ \nu_\ell$ form factors

$$\begin{aligned}
r_2 &= 0.83 \pm 0.08 \quad (S = 1.8) \\
r_V &= 1.76 \pm 0.07 \quad (S = 1.1) \\
\Gamma_L / \Gamma_T &= 0.72 \pm 0.18 \\
f_+(0) |V_{cs}| \text{ in } D_S^+ &\rightarrow \eta e^+ \nu_e = 0.452 \pm 0.010 \\
f_+(0) |V_{cs}| \text{ in } D_S^+ &\rightarrow \eta' e^+ \nu_e = 0.525 \pm 0.026 \\
f_+(0) |V_{cd}| \text{ in } D_S^+ &\rightarrow K^0 e^+ \nu_e = 0.162 \pm 0.019 \\
r_V \equiv V(0) / A_1(0) \text{ in } D_S^+ &\rightarrow K^*(892)^0 e^+ \nu_e = 1.7 \pm 0.4 \\
r_2 \equiv A_2(0) / A_1(0) \text{ in } D_S^+ &\rightarrow K^*(892)^0 e^+ \nu_e = 0.77 \pm 0.29 \\
f_{D_S^+} |V_{cs}| \text{ in } D_S^+ &\rightarrow \mu^+ \nu_\mu = 241.8 \pm 3.3 \text{ MeV} \\
f_{D_S^+} |V_{cs}| \text{ in } D_S^+ &\rightarrow \tau^+ \nu_\tau = 246.6 \pm 2.5 \text{ MeV}
\end{aligned}$$

Unless otherwise noted, the branching fractions for modes with a resonance in the final state include all the decay modes of the resonance.  $D_S^-$  modes are charge conjugates of the modes below.

$D_S^+$ DECAY MODES	Fraction ( $\Gamma_j / \Gamma$ )	Scale factor / Confidence level	$p$ (MeV/c)
<b>Inclusive modes</b>			
$e^+$ semileptonic	[ $aaa$ ] ( 6.33 $\pm$ 0.15 ) %		—
$\pi^+$ anything	( 119.3 $\pm$ 1.4 ) %		—
$\pi^-$ anything	( 43.2 $\pm$ 0.9 ) %		—
$\pi^0$ anything	( 123 $\pm$ 7 ) %		—
$K^-$ anything	( 18.7 $\pm$ 0.5 ) %		—
$K^+$ anything	( 28.9 $\pm$ 0.7 ) %		—
$K_S^0$ anything	( 19.0 $\pm$ 1.1 ) %		—
$\eta$ anything	[ $bbb$ ] ( 29.9 $\pm$ 2.8 ) %		—
$\omega$ anything	( 6.1 $\pm$ 1.4 ) %		—
$\eta'$ anything	[ $ccc$ ] ( 10.3 $\pm$ 1.4 ) %	S=1.1	—
$f_0(980)$ anything, $f_0 \rightarrow \pi^+ \pi^-$	< 1.3 %	CL=90%	—
$\phi$ anything	( 15.7 $\pm$ 1.0 ) %		—
$K^+ K^-$ anything	( 15.8 $\pm$ 0.7 ) %		—
$K_S^0 K^+$ anything	( 5.8 $\pm$ 0.5 ) %		—
$K_S^0 K^-$ anything	( 1.9 $\pm$ 0.4 ) %		—
$2K_S^0$ anything	( 1.70 $\pm$ 0.32 ) %		—
$2K^+$ anything	< 2.6 $\times 10^{-3}$	CL=90%	—
$2K^-$ anything	< 6 $\times 10^{-4}$	CL=90%	—
$2\pi^+ \pi^-$ + anything	( 32.8 $\pm$ 0.7 ) %		—

Leptonic and semileptonic modes			
$e^+ \nu_e$	< 8.3	$\times 10^{-5}$	CL=90% 984
$\mu^+ \nu_\mu$	( 5.35 $\pm$ 0.12 )	$\times 10^{-3}$	981
$\tau^+ \nu_\tau$	( 5.36 $\pm$ 0.10 )	%	182
$\gamma e^+ \nu_e$	< 1.3	$\times 10^{-4}$	CL=90% 984
$K^+ K^- e^+ \nu_e$	—		851
$K_S^0 K_S^0 e^+ \nu_e$	< 3.8	$\times 10^{-4}$	CL=90% 849
$\phi e^+ \nu_e$	[ddd] ( 2.39 $\pm$ 0.16 )	%	S=1.3 720
$K_1(1270)^0 e^+ \nu_e$	< 4.1	$\times 10^{-4}$	CL=90% 585
$b_1(1235)^0 e^+ \nu_e, b_1^0 \rightarrow \omega \pi^0$	< 6.4	$\times 10^{-4}$	CL=90% —
$\phi \mu^+ \nu_\mu$	( 2.24 $\pm$ 0.11 )	%	715
$\eta e^+ \nu_e + \eta'(958) e^+ \nu_e$	[ddd] ( 3.03 $\pm$ 0.24 )	%	—
$\eta e^+ \nu_e$	[ddd] ( 2.26 $\pm$ 0.06 )	%	908
$\eta'(958) e^+ \nu_e$	[ddd] ( 8.0 $\pm$ 0.4 )	$\times 10^{-3}$	751
$\eta \mu^+ \nu_\mu$	( 2.4 $\pm$ 0.5 )	%	905
$\eta'(958) \mu^+ \nu_\mu$	( 1.1 $\pm$ 0.5 )	%	747
$\omega e^+ \nu_e$	[eee] < 2.0	$\times 10^{-3}$	CL=90% 829
$K^0 e^+ \nu_e$	( 3.4 $\pm$ 0.4 )	$\times 10^{-3}$	921
$K^*(892)^0 e^+ \nu_e$	[ddd] ( 2.15 $\pm$ 0.28 )	$\times 10^{-3}$	S=1.1 782
$f_0(500) e^+ \nu_e, f_0 \rightarrow \pi^0 \pi^0$	< 7.3	$\times 10^{-4}$	CL=90% —
$f_0(980) e^+ \nu_e, f_0 \rightarrow \pi^0 \pi^0$	( 7.9 $\pm$ 1.5 )	$\times 10^{-4}$	—
$f_0(980) \mu^+ \nu_\mu, f_0 \rightarrow K^+ K^-$	< 5.45	$\times 10^{-4}$	CL=90% —
$a_0(980)^0 e^+ \nu_e, a_0^0 \rightarrow \pi^0 \eta$	< 1.2	$\times 10^{-4}$	CL=90% —
$\pi^0 e^+ \nu_e$	< 6.4	$\times 10^{-5}$	CL=90% 980

### Hadronic modes with a $K\bar{K}$ pair

$K^+ K_S^0$	( 1.450 $\pm$ 0.035 )	%	850
$K^+ K^0$	( 1.49 $\pm$ 0.06 )	%	850
$K^+ \bar{K}^0$	( 2.95 $\pm$ 0.14 )	%	850
$K^+ K^- \pi^+$	[jj] ( 5.37 $\pm$ 0.10 )	%	S=1.1 805
$\phi \pi^+$	[ddd,fff] ( 4.5 $\pm$ 0.4 )	%	712
$\phi \pi^+, \phi \rightarrow K^+ K^-$	[fff] ( 2.21 $\pm$ 0.06 )	%	712
$K^+ \bar{K}^*(892)^0$	( 12.7 $\pm$ 4.0 / -3.1 )	%	685
$K^+ \bar{K}^*(892)^0, \bar{K}^{*0} \rightarrow K^- \pi^+$	( 2.58 $\pm$ 0.06 )	%	416
$K^+ \bar{K}^*(892)^0, \bar{K}^{*0} \rightarrow K_S^0 \pi^0$	( 4.8 $\pm$ 0.5 )	$\times 10^{-3}$	—
$f_0(980) \pi^+, f_0 \rightarrow K^+ K^-$	( 1.11 $\pm$ 0.19 )	%	732
$f_0(1370) \pi^+, f_0 \rightarrow K^+ K^-$	( 7.1 $\pm$ 2.9 )	$\times 10^{-4}$	—
$f_0(1710) \pi^+, f_0 \rightarrow K^+ K^-$	( 6.7 $\pm$ 2.8 )	$\times 10^{-4}$	198
$a_0(980)^+ \pi^0, a_0^+ \rightarrow K^+ K_S^0$	( 1.1 $\pm$ 0.4 )	$\times 10^{-3}$	—
$a_0(1710)^+ \pi^0, a_0^+ \rightarrow K^+ K_S^0$	( 3.5 $\pm$ 0.6 )	$\times 10^{-3}$	—
$K^+ \bar{K}_0^*(1430)^0, \bar{K}_0^{*0} \rightarrow K^- \pi^+$	( 1.76 $\pm$ 0.25 )	$\times 10^{-3}$	218
$K^+ \bar{K}^*(1410)^0, \bar{K}_0^{*0} \rightarrow K_S^0 \pi^0$	( 8.8 $\pm$ 2.8 )	$\times 10^{-4}$	—
$K^+ K_S^0 \pi^0$	( 1.47 $\pm$ 0.07 )	%	805
$K^*(892)^+ K_S^0, K^{*+} \rightarrow K^+ \pi^0$	( 2.04 $\pm$ 0.33 )	$\times 10^{-3}$	—
$2K_S^0 \pi^+$	( 7.1 $\pm$ 0.4 )	$\times 10^{-3}$	S=1.3 802
$f_0(980) \pi^+, f_0 \rightarrow K_S^0 K_S^0$	< 1.8	$\times 10^{-4}$	CL=90% —
$f_0(1710) \pi^+, f_0 \rightarrow K_S^0 K_S^0$	( 3.3 $\pm$ 0.4 )	$\times 10^{-3}$	—
$K^*(892)^+ K_S^0, K^{*+} \rightarrow$	( 3.09 $\pm$ 0.33 )	$\times 10^{-3}$	683
$K_S^0 \pi^+$	—		802
$K^0 \bar{K}^0 \pi^+$	—		802
$K^*(892)^+ \bar{K}^0$	[ddd] ( 5.4 $\pm$ 1.2 )	%	683
$K^+ K^- \pi^+ \pi^0$	( 5.50 $\pm$ 0.24 )	%	S=1.3 748
$\phi \rho^+$	[ddd] ( 5.59 $\pm$ 0.34 )	%	401

$\bar{K}_1(1270)^0 K^+, \bar{K}_1(1270)^0 \rightarrow K^- \rho^+$	( 5.7 ± 0.6 ) × 10 <sup>-3</sup>		-
$\bar{K}_1(1270)^0 K^+, \bar{K}_1(1270)^0 \rightarrow K^*(892)\pi$	( 1.31 ± 0.25 ) %		-
$\bar{K}_1(1400)^0 K^+, \bar{K}_1(1400)^0 \rightarrow K^*(892)\pi$	( 2.0 ± 0.4 ) %		-
$a_0(980)^0 \rho^+, a_0^0 \rightarrow K^+ K^-$	( 1.9 ± 0.4 ) × 10 <sup>-3</sup>		-
$f_1(1420)^0 \pi^+, f_1(1420)^0 \rightarrow K^*(892)^\mp K^\pm$	( 3.9 ± 0.7 ) × 10 <sup>-3</sup>		-
$f_1(1420)^0 \pi^+, f_1(1420)^0 \rightarrow a_0(980)^0 \pi^0, a_0(980)^0 \rightarrow K^+ K^-$	( 4.0 ± 1.4 ) × 10 <sup>-4</sup>		-
$\eta(1475)\pi^+, \eta(1475) \rightarrow a_0(980)^0 \pi^0, a_0(980)^0 \rightarrow K^+ K^-$	( 7.0 ± 2.8 ) × 10 <sup>-4</sup>		-
$K_S^0 K^- 2\pi^+$	( 1.53 ± 0.08 ) %	S=1.5	744
$K^+ K^- K_S^0 \pi^+$	( 1.29 ± 0.18 ) × 10 <sup>-4</sup>		527
$K^*(892)^+ \bar{K}^*(892)^0$	[ddd] ( 5.64 ± 0.35 ) %		417
$\eta(1475)K_S^0, \eta \rightarrow K^*(892)^0 \pi^+, K^{*0} \rightarrow K^- \pi^+$	( 3.4 ± 1.0 ) × 10 <sup>-4</sup>		-
$\eta(1475)\pi^+, \eta \rightarrow \bar{K}^*(892)^+ K^-, \bar{K}^{*+} \rightarrow K_S^0 \pi^+$	( 3.4 ± 1.0 ) × 10 <sup>-4</sup>		-
$\eta(1475)\pi^+, \eta \rightarrow a_0(980)^- \pi^+, a_0^- \rightarrow K_S^0 K^-$	( 1.7 ± 0.9 ) × 10 <sup>-3</sup>		-
$f_1(1285)\pi^+, f_1 \rightarrow a_0(980)^- \pi^+, a_0^- \rightarrow K_S^0 K^-$	( 3.4 ± 0.8 ) × 10 <sup>-4</sup>		-
$K^+ K_S^0 \pi^+ \pi^-$	( 9.5 ± 0.8 ) × 10 <sup>-3</sup>	S=1.1	744
$K^+ K^- 2\pi^+ \pi^-$	( 6.6 ± 0.6 ) × 10 <sup>-3</sup>		673
$\phi 2\pi^+ \pi^-$	[ddd] ( 1.21 ± 0.16 ) %		640
$\phi \rho^0 \pi^+, \phi \rightarrow K^+ K^-$	( 4.9 ± 0.7 ) × 10 <sup>-3</sup>		181
$\phi a_1(1260)^+, \phi \rightarrow K^+ K^-, a_1^+ \rightarrow \rho^0 \pi^+$	( 7.4 ± 1.2 ) × 10 <sup>-3</sup>		†
$\phi 2\pi^+ \pi^-$ non- $\rho, \phi \rightarrow K^+ K^-$	( 1.4 ± 0.5 ) × 10 <sup>-3</sup>		-
$K^+ K^- \rho^0 \pi^+$ non- $\phi$	< 2.0 × 10 <sup>-4</sup>	CL=90%	249
$K^+ K^- 2\pi^+ \pi^-$ nonresonant	( 1.0 ± 0.4 ) × 10 <sup>-3</sup>		673
$2K_S^0 2\pi^+ \pi^-$	( 7.8 ± 3.3 ) × 10 <sup>-4</sup>		669
<b>Hadronic modes without K's</b>			
$\pi^+ \pi^0$	< 1.2 × 10 <sup>-4</sup>	CL=90%	975
$2\pi^+ \pi^-$	( 1.08 ± 0.04 ) %		959
$\rho^0 \pi^+$	( 1.12 ± 0.17 ) × 10 <sup>-4</sup>		825
$\pi^+ (\pi^+ \pi^-)_{S\text{-wave}}$	[ggg] ( 9.12 ± 0.35 ) × 10 <sup>-3</sup>		959
$f_2(1270)\pi^+, f_2 \rightarrow \pi^+ \pi^-$	( 1.40 ± 0.11 ) × 10 <sup>-3</sup>		559
$f_2'(1525)^0 \pi^+, f_2' \rightarrow \pi^+ \pi^-$	( 5.7 ± 2.0 ) × 10 <sup>-6</sup>		-
$\rho(1450)^0 \pi^+, \rho^0 \rightarrow \pi^+ \pi^-$	( 1.8 ± 0.6 ) × 10 <sup>-4</sup>		421
$\rho(1700)^0 \pi^+, \rho^0 \rightarrow \pi^+ \pi^-$	( 4 ± 4 ) × 10 <sup>-5</sup>		-
$\pi^+ 2\pi^0$	( 5.2 ± 0.5 ) × 10 <sup>-3</sup>	S=1.1	961
$f_0(980)\pi^+, f_0 \rightarrow \pi^0 \pi^0$	( 2.9 ± 0.6 ) × 10 <sup>-3</sup>		-
$f_0(1370)\pi^+, f_0 \rightarrow \pi^0 \pi^0$	( 1.3 ± 0.6 ) × 10 <sup>-3</sup>		-
$f_2(1270)\pi^+, f_2 \rightarrow \pi^0 \pi^0$	( 5.0 ± 3.5 ) × 10 <sup>-4</sup>		-

$2\pi^+\pi^-\pi^0$	—		935
$\eta\pi^+$	[ddd]	( 1.67 ± 0.09 ) %	S=1.1 902
$\omega\pi^+$	[ddd]	( 1.92 ± 0.30 ) × 10 <sup>-3</sup>	822
$\omega\pi^+, \omega \rightarrow \pi^+\pi^-$		( 3.9 ± 0.5 ) × 10 <sup>-5</sup>	—
$3\pi^+2\pi^-$		( 7.8 ± 0.8 ) × 10 <sup>-3</sup>	899
$2\pi^+\pi^-2\pi^0$	—		902
$\eta\rho^+$	[ddd]	( 8.9 ± 0.8 ) %	724
$\eta\pi^+\pi^0$		( 9.5 ± 0.5 ) %	885
$\eta(\pi^+\pi^0)_{P\text{-wave}}$		( 5.1 ± 3.1 ) × 10 <sup>-3</sup>	885
$a_0(980)^{+0}\pi^{0+}, a_0(980)^{+0} \rightarrow$		( 2.2 ± 0.4 ) %	—
$\eta\pi^{+0}$			
$\omega\pi^+\pi^0$	[ddd]	( 2.8 ± 0.7 ) %	802
$2\pi^+\pi^-\eta$		( 3.12 ± 0.16 ) %	855
$a_1(1260)^+\eta, a_1^+ \rightarrow$		( 1.73 ± 0.16 ) %	—
$\rho(770)^0\pi^+, \rho^0 \rightarrow \pi^+\pi^-$			
$a_1(1260)^+\eta, a_1^+ \rightarrow$		( 2.5 ± 0.9 ) × 10 <sup>-3</sup>	—
$f_0(500)\pi^+, f_0 \rightarrow \pi^+\pi^-$			
$a_0(980)^+\rho(770)^0, a_0^+ \rightarrow$		( 2.1 ± 0.9 ) × 10 <sup>-3</sup>	—
$\eta\pi^+$			
$\eta(1405)\pi^+, \eta(1405) \rightarrow$		( 2.2 ± 0.7 ) × 10 <sup>-4</sup>	—
$a_0(980)^-\pi^+, a_0^- \rightarrow \eta\pi^-$			
$\eta(1405)\pi^+, \eta(1405) \rightarrow$		( 2.2 ± 0.7 ) × 10 <sup>-4</sup>	—
$a_0(980)^+\pi^-, a_0^+ \rightarrow \eta\pi^+$			
$f_1(1420)\pi^+, f_1 \rightarrow$		( 5.9 ± 1.8 ) × 10 <sup>-4</sup>	—
$a_0(980)^-\pi^+, a_0^- \rightarrow \eta\pi^-$			
$f_1(1420)\pi^+, f_1 \rightarrow$		( 5.3 ± 1.8 ) × 10 <sup>-4</sup>	—
$a_0(980)^+\pi^-, a_0^+ \rightarrow \eta\pi^+$			
$3\pi^+2\pi^-\pi^0$		( 4.9 ± 3.2 ) %	856
$\omega 2\pi^+\pi^-$	[ddd]	( 1.6 ± 0.5 ) %	766
$\eta'(958)\pi^+$	[ccc,ddd]	( 3.94 ± 0.25 ) %	743
$3\pi^+2\pi^-2\pi^0$	—		803
$\omega\eta\pi^+$	[ddd]	( 5.4 ± 1.3 ) × 10 <sup>-3</sup>	654
$\eta'(958)\rho^+$	[ccc,ddd]	( 5.8 ± 1.5 ) %	465
$\eta'(958)\pi^+\pi^0$		( 6.08 ± 0.29 ) %	720
$\eta'(958)\pi^+\pi^0$ nonresonant	<	5.1 %	CL=90% 720

## Modes with one or three K's

$K^+\pi^0$		( 7.4 ± 0.5 ) × 10 <sup>-4</sup>	917
$K_S^0\pi^+$		( 1.09 ± 0.05 ) × 10 <sup>-3</sup>	916
$K^+\eta$	[ddd]	( 1.73 ± 0.08 ) × 10 <sup>-3</sup>	835
$K^+\omega$	[ddd]	( 9.9 ± 1.5 ) × 10 <sup>-4</sup>	741
$K^+\eta'(958)$	[ddd]	( 2.64 ± 0.24 ) × 10 <sup>-3</sup>	646
$K^+\pi^+\pi^-$		( 6.20 ± 0.19 ) × 10 <sup>-3</sup>	900
$K^+\rho^0$		( 2.17 ± 0.25 ) × 10 <sup>-3</sup>	745
$K^+\rho(1450)^0, \rho^0 \rightarrow \pi^+\pi^-$		( 7.2 ± 1.7 ) × 10 <sup>-4</sup>	—
$K^+f_0(500), f_0 \rightarrow \pi^+\pi^-$		( 4.5 ± 3.0 ) × 10 <sup>-4</sup>	—
$K^+f_0(980), f_0 \rightarrow \pi^+\pi^-$		( 2.8 ± 1.1 ) × 10 <sup>-4</sup>	—
$K^+f_0(1370), f_0 \rightarrow \pi^+\pi^-$		( 1.2 ± 0.6 ) × 10 <sup>-3</sup>	—
$K^*(892)^0\pi^+, K^{*0} \rightarrow K^+\pi^-$		( 1.67 ± 0.26 ) × 10 <sup>-3</sup>	775
$K^*(1410)^0\pi^+, K^{*0} \rightarrow$		( 6 ± 4 ) × 10 <sup>-4</sup>	—
$K^+\pi^-$			
$K^*(1430)^0\pi^+, K^{*0} \rightarrow$		( 9.3 ± 3.1 ) × 10 <sup>-4</sup>	—
$K^+\pi^-$			
$K^+\pi^+\pi^-$ nonresonant		( 9.9 ± 3.2 ) × 10 <sup>-4</sup>	900
$K_S^0\pi^+\pi^0$		( 5.38 ± 0.32 ) × 10 <sup>-3</sup>	899

$K_S^0 \rho(770)^+, \rho^+ \rightarrow \pi^+ \pi^0$	( 2.7 ± 0.5 ) × 10 <sup>-3</sup>	-
$K_S^0 \rho(1450)^+, \rho^+ \rightarrow \pi^+ \pi^0$	( 1.10 ± 0.34 ) × 10 <sup>-3</sup>	-
$K^*(892)^0 \pi^+, K^{*0} \rightarrow K_S^0 \pi^0$	( 4.5 ± 1.3 ) × 10 <sup>-4</sup>	-
$K^*(892)^+ \pi^0, K^{*+} \rightarrow K_S^0 \pi^+$	( 2.5 ± 0.8 ) × 10 <sup>-4</sup>	-
$K^*(1410)^0 \pi^+, K^{*0} \rightarrow K_S^0 \pi^0$	( 1.8 ± 0.9 ) × 10 <sup>-4</sup>	-
$K_S^0 2\pi^+ \pi^-$	( 2.8 ± 1.0 ) × 10 <sup>-3</sup>	870
$K^+ \pi^+ \pi^- \pi^0$	( 9.7 ± 0.6 ) × 10 <sup>-3</sup>	873
$K^*(892)^0 \rho^+, K^{*0} \rightarrow K^+ \pi^-$	( 3.9 ± 0.4 ) × 10 <sup>-3</sup>	-
$K^*(892)^+ \rho^0, K^{*+} \rightarrow K^+ \pi^0$	( 4.2 ± 1.2 ) × 10 <sup>-4</sup>	-
$K_1(1270)^0 \pi^+, K_1^0 \rightarrow K^+ \rho^-$	( 3.9 ± 1.3 ) × 10 <sup>-4</sup>	†
$K_1(1400)^0 \pi^+, K_1^0 \rightarrow$	( 5.4 ± 0.9 ) × 10 <sup>-4</sup>	-
$K^*(890)^+ \pi^-, K^{*+} \rightarrow$		
$K^+ \pi^0$		
$K_1(1400)^0 \pi^+, K_1^0 \rightarrow$	( 5.9 ± 1.0 ) × 10 <sup>-4</sup>	-
$K^*(890)^0 \pi^0, K^{*0} \rightarrow$		
$K^+ \pi^-$		
$K^+ a_1(1260)^0, a_1 \rightarrow \rho^+ \pi^-$	( 1.8 ± 1.1 ) × 10 <sup>-4</sup>	-
$K^+ a_1(1260)^0, a_1 \rightarrow \rho^- \pi^+$	( 1.8 ± 1.1 ) × 10 <sup>-4</sup>	-
$K^+ \pi^+ \pi^- \pi^0$ nonresonant	( 9.2 ± 2.4 ) × 10 <sup>-4</sup>	873
( $K^+ \pi^0$ ) $P$ -wave $\rho^0$	( 1.01 ± 0.21 ) × 10 <sup>-3</sup>	688
$K^+ \omega \pi^0$	[ddd] < 8.2 × 10 <sup>-3</sup>	CL=90% 684
$K^+ \omega \pi^+ \pi^-$	[ddd] < 5.4 × 10 <sup>-3</sup>	CL=90% 603
$K^+ \omega \eta$	[ddd] < 7.9 × 10 <sup>-3</sup>	CL=90% 366
$2K^+ K^-$	( 2.15 ± 0.20 ) × 10 <sup>-4</sup>	628
$\phi K^+, \phi \rightarrow K^+ K^-$	( 8.8 ± 2.0 ) × 10 <sup>-5</sup>	-

### Doubly Cabibbo-suppressed modes

$2K^+ \pi^-$	( 1.274 ± 0.031 ) × 10 <sup>-4</sup>	805
$K^+ K^*(892)^0, K^{*0} \rightarrow K^+ \pi^-$	( 6.0 ± 3.4 ) × 10 <sup>-5</sup>	-

### Baryon-antibaryon mode

$p\bar{p}$	( 1.22 ± 0.11 ) × 10 <sup>-3</sup>	295
$p\bar{p}e^+ \nu_e$	< 2.0 × 10 <sup>-4</sup>	CL=90% 296

### $\Delta C = 1$ weak neutral current (C1) modes, Lepton family number (LF), or Lepton number (L) violating modes

$\pi^+ e^+ e^-$	[pp] < 5.5 × 10 <sup>-6</sup>	CL=90% 979
$\pi^+ \phi, \phi \rightarrow e^+ e^-$	[oo] ( 6 + <sub>-4</sub> <sup>8</sup> ) × 10 <sup>-6</sup>	-
$\pi^+ \mu^+ \mu^-$	[pp] < 1.8 × 10 <sup>-7</sup>	CL=90% 968
$K^+ e^+ e^-$	C1 < 3.7 × 10 <sup>-6</sup>	CL=90% 922
$K^+ \mu^+ \mu^-$	C1 < 1.4 × 10 <sup>-7</sup>	CL=90% 909
$K^*(892)^+ \mu^+ \mu^-$	C1 < 1.4 × 10 <sup>-3</sup>	CL=90% 765
$\pi^+ e^+ \mu^-$	LF < 1.1 × 10 <sup>-6</sup>	CL=90% 976
$\pi^+ e^- \mu^+$	LF < 9.4 × 10 <sup>-7</sup>	CL=90% 976
$K^+ e^+ \mu^-$	LF < 7.9 × 10 <sup>-7</sup>	CL=90% 919
$K^+ e^- \mu^+$	LF < 5.6 × 10 <sup>-7</sup>	CL=90% 919
$\pi^- 2e^+$	L < 1.4 × 10 <sup>-6</sup>	CL=90% 979
$\pi^- 2\mu^+$	L < 8.6 × 10 <sup>-8</sup>	CL=90% 968
$\pi^- e^+ \mu^+$	L < 6.3 × 10 <sup>-7</sup>	CL=90% 976
$K^- 2e^+$	L < 7.7 × 10 <sup>-7</sup>	CL=90% 922
$K^- 2\mu^+$	L < 2.6 × 10 <sup>-8</sup>	CL=90% 909
$K^- e^+ \mu^+$	L < 2.6 × 10 <sup>-7</sup>	CL=90% 919
$K^*(892)^- 2\mu^+$	L < 1.4 × 10 <sup>-3</sup>	CL=90% 765

**$D_s^{*\pm}$** 

$$I(J^P) = 0(1^-)$$

Mass  $m = 2112.2 \pm 0.4$  MeV

$$m_{D_s^{*\pm}} - m_{D_s^\pm} = 143.8 \pm 0.4$$
 MeV

Full width  $\Gamma < 1.9$  MeV, CL = 90% $D_s^{*-}$  modes are charge conjugates of the modes below. **$D_s^{*+}$  DECAY MODES**

$D_s^{*+}$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$D_s^+ \gamma$	(93.6 $\pm$ 0.4) %	139
$D_s^+ \pi^0$	( 5.77 $\pm$ 0.35) %	48
$D_s^+ e^+ e^-$	( 6.7 $\pm$ 1.6) $\times 10^{-3}$	139
$e^+ \nu_e$	( 2.1 $^{+1.2}_{-0.9}$ ) $\times 10^{-5}$	1056

 **$D_{s0}^{*}(2317)^\pm$** 

$$I(J^P) = 0(0^+)$$

 $J, P$  need confirmation. $J^P$  is natural, low mass consistent with  $0^+$ .See the review on "Heavy Non- $q\bar{q}$  Mesons."Mass  $m = 2317.8 \pm 0.5$  MeV

$$m_{D_{s0}^{*}(2317)^\pm} - m_{D_s^\pm} = 349.4 \pm 0.5$$
 MeV

Full width  $\Gamma < 3.8$  MeV, CL = 95% $D_{s0}^{*}(2317)^-$  modes are charge conjugates of modes below. **$D_{s0}^{*}(2317)^\pm$  DECAY MODES**

$D_{s0}^{*}(2317)^\pm$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$D_s^+ \pi^0$	(100 $^{+0}_{-20}$ ) %		298
$D_s^+ \gamma$	< 5 %	90%	323
$D_s^{*}(2112)^+ \gamma$	< 6 %	90%	—
$D_s^+ \gamma \gamma$	< 18 %	95%	323
$D_s^{*}(2112)^+ \pi^0$	< 11 %	90%	—
$D_s^+ \pi^+ \pi^-$	< 4 $\times 10^{-3}$	90%	194

See Particle Listings for 1 decay modes that have been seen / not seen.

 **$D_{s1}(2460)^\pm$** 

$$I(J^P) = 0(1^+)$$

See the review on "Heavy Non- $q\bar{q}$  Mesons."Mass  $m = 2459.5 \pm 0.6$  MeV ( $S = 1.1$ )

$$m_{D_{s1}(2460)^\pm} - m_{D_s^{*\pm}} = 347.3 \pm 0.7$$
 MeV ( $S = 1.2$ )

$$m_{D_{s1}(2460)^\pm} - m_{D_s^\pm} = 491.1 \pm 0.6$$
 MeV ( $S = 1.1$ )

Full width  $\Gamma < 3.5$  MeV, CL = 95% $D_{s1}(2460)^-$  modes are charge conjugates of the modes below. **$D_{s1}(2460)^+$  DECAY MODES**

$D_{s1}(2460)^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$D_s^{*+} \pi^0$	(48 $\pm$ 11) %		297
$D_s^+ \gamma$	(18 $\pm$ 4) %		442

$D_S^+ \pi^+ \pi^-$	( $4.3 \pm 1.3$ ) %	S=1.1	363
$D_S^{*+} \gamma$	< 8 %	CL=90%	323
$D_{S0}^*(2317)^+ \gamma$	( $3.7^+_{-2.4}$ ) %		138

 **$D_{S1}(2536)^\pm$** 

$$I(J^P) = 0(1^+)$$

$J, P$  need confirmation.

Mass  $m = 2535.11 \pm 0.06$  MeV

$$m_{D_{S1}(2536)^\pm} - m_{D_S^*(2111)} = 422.9 \pm 0.4 \text{ MeV}$$

$$m_{D_{S1}(2536)^\pm} - m_{D^*(2010)^\pm} = 524.85 \pm 0.04 \text{ MeV}$$

$$m_{D_{S1}(2536)^\pm} - m_{D^*(2007)^0} = 528.26 \pm 0.05 \text{ MeV} \quad (S = 1.1)$$

Full width  $\Gamma = 0.92 \pm 0.05$  MeV

Branching fractions are given relative to the one **DEFINED AS 1**.  $D_{S1}(2536)^-$  modes are charge conjugates of the modes below.

<b><math>D_{S1}(2536)^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$D^*(2010)^+ K^0$	$0.85 \pm 0.12$		149
$(D^*(2010)^+ K^0)_{S\text{-wave}}$	$0.61 \pm 0.09$		149
$K_S^0 D^*(2010)^+$	$0.48 \pm 0.07$		149
$D^+ \pi^- K^+$	$0.028 \pm 0.005$		176
$D^*(2007)^0 K^+$	<b>DEFINED AS 1</b>		167
$D^+ K^0$	<0.34	90%	381
$D^0 K^+$	<0.12	90%	391

See Particle Listings for 2 decay modes that have been seen / not seen.

 **$D_{S2}^*(2573)$** 

$$I(J^P) = 0(2^+)$$

Mass  $m = 2569.1 \pm 0.8$  MeV (S = 2.4)

$$m_{D_{S2}^*(2573)} - m_{D^0} = 704 \pm 3.2 \text{ MeV}$$

Full width  $\Gamma = 16.9 \pm 0.7$  MeV

 **$D_{S1}^*(2700)^\pm$** 

$$I(J^P) = 0(1^-)$$

Mass  $m = 2714 \pm 5$  MeV (S = 1.5)

Full width  $\Gamma = 122 \pm 10$  MeV

 **$D_{S3}^*(2860)^\pm$** 

$$I(J^P) = 0(3^-)$$

Mass  $m = 2860 \pm 7$  MeV

Full width  $\Gamma = 53 \pm 10$  MeV

## BOTTOM MESONS ( $B = \pm 1$ )

$$B^+ = u\bar{b}, B^0 = d\bar{b}, \bar{B}^0 = \bar{d}b, B^- = \bar{u}b, \text{ similarly for } B^{*'}\text{'s}$$

### **B-particle organization**

Many measurements of  $B$  decays involve admixtures of  $B$  hadrons. Previously we arbitrarily included such admixtures in the  $B^\pm$  section, but because of their importance we have created two new sections: “ $B^\pm/B^0$  Admixture” for  $\Upsilon(4S)$  results and “ $B^\pm/B^0/B_s^0/b$ -baryon Admixture” for results at higher energies. Most inclusive decay branching fractions and  $\chi_b$  at high energy are found in the Admixture sections.  $B^0$ - $\bar{B}^0$  mixing data are found in the  $B^0$  section, while  $B_s^0$ - $\bar{B}_s^0$  mixing data and  $B$ - $\bar{B}$  mixing data for a  $B^0/B_s^0$  admixture are found in the  $B_s^0$  section.  $CP$ -violation data are found in the  $B^\pm$ ,  $B^0$ , and  $B^\pm B^0$  Admixture sections.  $b$ -baryons are found near the end of the Baryon section.

The organization of the  $B$  sections is now as follows, where bullets indicate particle sections and brackets indicate reviews.

- $B^\pm$   
mass, mean life,  $CP$  violation, branching fractions
- $B^0$   
mass, mean life,  $B^0$ - $\bar{B}^0$  mixing,  $CP$  violation, branching fractions
- $B^\pm/B^0$  Admixtures  
 $CP$  violation, branching fractions
- $B^\pm/B^0/B_s^0/b$ -baryon Admixtures  
mean life, production fractions, branching fractions
- $B^*$ ,  $B_1(5721)$ ,  $B_2^*(5747)$ ,  $B_J(5970)$   
mass, width
- $B_s^0$   
mass, mean life,  $B_s^0$ - $\bar{B}_s^0$  mixing,  $CP$  violation, branching fractions
- $B_s^*$ ,  $B_{s1}(5830)^0$ ,  $B_{s2}^*(5840)^0$   
mass, width
- $B_c^\pm$   
mass, mean life, branching fractions
- $B_c(2S)^\pm$   
mass

At the end of Baryon Listings:

- $\Lambda_b$   
mass, mean life, branching fractions



- $\Lambda_b(5912)^0, \Lambda_b(5920)^0, \Lambda_b(6070)^0, \Lambda_b(6146)^0, \Lambda_b(6152)^0$   
mass, width
- $\Sigma_b$   
mass
- $\Sigma_b^*, \Sigma_b(6097)^+, \Sigma_b(6097)^-$   
mass, width
- $\Xi_b^0, \Xi_b^-$   
mass, mean life, branching fractions
- $\Xi_b'(5935)^-, \Xi_b(5945)^0, \Xi_b(5955)^-, \Xi_b(6100)^-, \Xi_b(6227)^-,$   
 $\Xi_b(6227)^0, \Xi_b(6327)^0, \Xi_b(6333)^0$   
mass, width
- $\Omega_b^-$   
mass, mean life, branching fractions
- $\Omega_b(6316)^-, \Omega_b(6330)^-, \Omega_b(6340)^-, \Omega_b(6350)^-$   
mass
- $b$ -baryon Admixture  
mean life, branching fractions

 **$B^\pm$** 

$$I(J^P) = \frac{1}{2}(0^-)$$

$I, J, P$  need confirmation. Quantum numbers shown are quark-model predictions.

$$\text{Mass } m_{B^\pm} = 5279.41 \pm 0.07 \text{ MeV}$$

$$\text{Mean life } \tau_{B^\pm} = (1.638 \pm 0.004) \times 10^{-12} \text{ s}$$

$$c\tau = 491.1 \mu\text{m}$$

### CP violation

$$A_{CP}(B^+ \rightarrow J/\psi(1S)K^+) = (1.8 \pm 3.0) \times 10^{-3} \quad (S = 1.5)$$

$$A_{CP}(B^+ \rightarrow J/\psi(1S)\pi^+) = (1.8 \pm 1.2) \times 10^{-2} \quad (S = 1.3)$$

$$A_{CP}(B^+ \rightarrow J/\psi\rho^+) = -0.05 \pm 0.05$$

$$A_{CP}(B^+ \rightarrow J/\psi K^*(892)^+) = -0.048 \pm 0.033$$

$$A_{CP}(B^+ \rightarrow \eta_c K^+) = 0.01 \pm 0.07 \quad (S = 2.2)$$

$$A_{CP}(B^+ \rightarrow \psi(2S)\pi^+) = 0.03 \pm 0.06$$

$$A_{CP}(B^+ \rightarrow \psi(2S)K^+) = 0.012 \pm 0.020 \quad (S = 1.5)$$

$$A_{CP}(B^+ \rightarrow \psi(2S)K^*(892)^+) = 0.08 \pm 0.21$$

$$A_{CP}(B^+ \rightarrow \chi_{c1}(1P)\pi^+) = 0.07 \pm 0.18$$

$$A_{CP}(B^+ \rightarrow \chi_{c0}K^+) = -0.20 \pm 0.18 \quad (S = 1.5)$$

$$A_{CP}(B^+ \rightarrow \chi_{c1}K^+) = -0.009 \pm 0.033$$

$$A_{CP}(B^+ \rightarrow \chi_{c1}K^*(892)^+) = 0.5 \pm 0.5$$

$$A_{CP}(B^+ \rightarrow D^0\ell^+\nu_\ell) = (-0.14 \pm 0.20) \times 10^{-2}$$

$$A_{CP}(B^+ \rightarrow \overline{D}^0\pi^+) = (-3 \pm 5) \times 10^{-3}$$

$$A_{CP}(B^+ \rightarrow D_{CP(+1)}\pi^+) = -0.0080 \pm 0.0024$$

$$A_{CP}(B^+ \rightarrow D_{CP(-1)}\pi^+) = 0.017 \pm 0.026$$

$$A_{CP}([K^\mp\pi^\pm\pi^+\pi^-]_D\pi^+) = 0.070 \pm 0.020$$

$$A_{CP}(B^+ \rightarrow [\pi^+\pi^+\pi^-\pi^-]_D K^+) = 0.061 \pm 0.013$$

$$A_{CP}(B^+ \rightarrow [\pi^+\pi^-\pi^+\pi^-]_D K^*(892)^+) = 0.02 \pm 0.11$$

$$\begin{aligned}
A_{CP}(B^+ \rightarrow [K^+ K^- \pi^+ \pi^-]_D K^+) &= 0.095 \pm 0.023 \\
A_{CP}(B^+ \rightarrow [K^+ K^- \pi^+ \pi^-]_D \pi^+) &= -0.009 \pm 0.006 \\
A_{CP}(B^+ \rightarrow \overline{D}^0 K^+) &= -0.017 \pm 0.005 \\
A_{CP}([K^\mp \pi^\pm \pi^+ \pi^-]_D K^+) &= -0.32 \pm 0.04 \\
A_{CP}(B^+ \rightarrow [\pi^+ \pi^+ \pi^- \pi^-]_D \pi^+) &= (-8.2 \pm 3.2) \times 10^{-3} \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_D K^+) &= -0.58 \pm 0.21 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+ \pi^0]_D K^+) &= -0.27 \pm 0.27 \quad (S = 2.4) \\
A_{CP}(B^+ \rightarrow [K^+ \pi^- \pi^0]_D K^+) &= -0.024 \pm 0.013 \\
A_{CP}(B^+ \rightarrow [K^+ K^- \pi^0]_D K^+) &= 0.07 \pm 0.07 \\
A_{CP}(B^+ \rightarrow [\pi^+ \pi^- \pi^0]_D K^+) &= 0.11 \pm 0.04 \\
A_{CP}(B^+ \rightarrow \overline{D}^0 K^*(892)^+) &= -0.007 \pm 0.019 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_{\overline{D}} K^*(892)^+) &= -0.75 \pm 0.16 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+ \pi^- \pi^+]_{\overline{D}} K^*(892)^+) &= -0.45 \pm 0.25 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_D \pi^+) &= 0.00 \pm 0.09 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+ \pi^0]_D \pi^+) &= 0.08 \pm 0.09 \\
A_{CP}(B^+ \rightarrow [K^+ K^- \pi^0]_D \pi^+) &= -0.001 \pm 0.019 \\
A_{CP}(B^+ \rightarrow [\pi^+ \pi^- \pi^0]_D \pi^+) &= 0.001 \pm 0.010 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_{(D\pi)} \pi^+) &= -0.09 \pm 0.27 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_{(D\gamma)} \pi^+) &= -0.7 \pm 0.6 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_{(D\pi)} K^+) &= 0.8 \pm 0.4 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_{(D\gamma)} K^+) &= 0.4 \pm 1.0 \\
A_{CP}(B^+ \rightarrow [\pi^+ \pi^- \pi^0]_D K^+) &= -0.02 \pm 0.15 \\
A_{CP}(B^+ \rightarrow [K_S^0 K^+ \pi^-]_D K^+) &= 0.00 \pm 0.09 \quad (S = 1.4) \\
A_{CP}(B^+ \rightarrow [K_S^0 K^- \pi^+]_D K^+) &= 0.00 \pm 0.07 \\
A_{CP}(B^+ \rightarrow [K_S^0 K^- \pi^+]_D \pi^+) &= -0.003 \pm 0.014 \\
A_{CP}(B^+ \rightarrow [K_S^0 K^+ \pi^-]_D \pi^+) &= -0.016 \pm 0.025 \quad (S = 1.5) \\
A_{CP}(B^+ \rightarrow [K^*(892)^- K^+]_D K^+) &= 0.08 \pm 0.05 \\
A_{CP}(B^+ \rightarrow [K^*(892)^+ K^-]_D K^+) &= 0.07 \pm 0.09 \\
A_{CP}(B^+ \rightarrow [K^*(892)^+ K^-]_D \pi^+) &= 0.007 \pm 0.016 \\
A_{CP}(B^+ \rightarrow [K^*(892)^- K^+]_D \pi^+) &= -0.013 \pm 0.020 \quad (S = 1.9) \\
\mathbf{A_{CP}(B^+ \rightarrow D_{CP(+1)} K^+)} &= 0.132 \pm 0.015 \quad (S = 1.8) \\
A_{ADS}(B^+ \rightarrow D K^+) &= -0.451 \pm 0.026 \\
A_{ADS}(B^+ \rightarrow D \pi^+) &= 0.129 \pm 0.014 \\
A_{ADS}(B^+ \rightarrow D^*(D\gamma) K^+) &= -0.6 \pm 1.3 \\
A_{ADS}(B^+ \rightarrow D^*(D\pi^0) K^+) &= 0.72 \pm 0.29 \\
A_{ADS}(B^+ \rightarrow D^*(D\gamma) \pi^+) &= 0.08 \pm 0.13 \\
A_{ADS}(B^+ \rightarrow D^*(D\pi^0) \pi^+) &= -0.14 \pm 0.06 \\
A_{ADS}(B^+ \rightarrow [K^- \pi^+]_D K^+ \pi^- \pi^+) &= -0.33 \pm 0.35 \\
A_{ADS}(B^+ \rightarrow [K^- \pi^+]_D \pi^+ \pi^- \pi^+) &= -0.01 \pm 0.09 \\
A_{CP}(B^+ \rightarrow D_{CP(-1)} K^+) &= -0.10 \pm 0.07 \\
A_{CP}(B^+ \rightarrow [K^+ K^-]_D K^+ \pi^- \pi^+) &= -0.04 \pm 0.06 \\
A_{CP}(B^+ \rightarrow [\pi^+ \pi^-]_D K^+ \pi^- \pi^+) &= -0.05 \pm 0.10 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_D K^+ \pi^- \pi^+) &= 0.013 \pm 0.023 \\
A_{CP}(B^+ \rightarrow [K^+ K^-]_D \pi^+ \pi^- \pi^+) &= -0.019 \pm 0.015 \\
A_{CP}(B^+ \rightarrow [\pi^+ \pi^-]_D \pi^+ \pi^- \pi^+) &= -0.013 \pm 0.019 \\
A_{CP}(B^+ \rightarrow [K^- \pi^+]_D \pi^+ \pi^- \pi^+) &= -0.002 \pm 0.011 \\
A_{CP}(B^+ \rightarrow \overline{D}^{*0} \pi^+) &= -0.0004 \pm 0.0021 \quad (S = 1.1) \\
A_{CP}(B^+ \rightarrow D_{CP(+1)}^{*0} \pi^+) &= 0.010 \pm 0.007 \\
A_{CP}(B^+ \rightarrow D_{CP(-1)}^{*0} \pi^+) &= -0.09 \pm 0.05 \\
A_{CP}(B^+ \rightarrow D^{*0} K^+) &= 0.012 \pm 0.010 \quad (S = 1.5)
\end{aligned}$$

$$\begin{aligned}
A_{CP}(B^+ \rightarrow D_{CP(+1)}^{*0} K^+) &= -0.09 \pm 0.05 \quad (S = 2.6) \\
A_{CP}(B^+ \rightarrow D_{CP(-1)}^* K^+) &= 0.07 \pm 0.10 \\
A_{CP}(B^+ \rightarrow D_{CP(+1)} K^*(892)^+) &= 0.08 \pm 0.06 \\
A_{CP}(B^+ \rightarrow D_{CP(-1)} K^*(892)^+) &= -0.23 \pm 0.22 \\
A_{CP}(B^+ \rightarrow D_S^+ \phi) &= 0.0 \pm 0.4 \\
A_{CP}(B^+ \rightarrow D_S^+ \bar{D}^0) &= (0.5 \pm 0.6)\% \\
A_{CP}(B^+ \rightarrow D_S^{*+} \bar{D}^0) &= (-0.5 \pm 1.5) \times 10^{-2} \\
A_{CP}(B^+ \rightarrow D_S^+ \bar{D}^{*0}) &= (1.1 \pm 1.1) \times 10^{-2} \\
A_{CP}(B^+ \rightarrow D^{*+} \bar{D}^{*0}) &= (1.3 \pm 2.6) \times 10^{-2} \\
A_{CP}(B^+ \rightarrow D^{*+} \bar{D}^0) &= (3.1 \pm 1.7) \times 10^{-2} \\
A_{CP}(B^+ \rightarrow D^+ \bar{D}^{*0}) &= (0.0 \pm 2.4) \times 10^{-2} \\
A_{CP}(B^+ \rightarrow D^+ \bar{D}^0) &= (2.4 \pm 1.1) \times 10^{-2} \\
A_{CP}(B^+ \rightarrow K_S^0 \pi^+) &= -0.003 \pm 0.015 \quad (S = 1.1) \\
A_{CP}(B^+ \rightarrow K^+ \pi^0) &= 0.027 \pm 0.012 \\
A_{CP}(B^+ \rightarrow \eta' K^+) &= 0.004 \pm 0.011 \\
A_{CP}(B^+ \rightarrow \eta' K^*(892)^+) &= -0.26 \pm 0.27 \\
A_{CP}(B^+ \rightarrow \eta' K_0^*(1430)^+) &= 0.06 \pm 0.20 \\
A_{CP}(B^+ \rightarrow \eta' K_2^*(1430)^+) &= 0.15 \pm 0.13 \\
\mathbf{A_{CP}(B^+ \rightarrow \eta K^+)} &= -0.37 \pm 0.08 \\
A_{CP}(B^+ \rightarrow \eta K^*(892)^+) &= 0.02 \pm 0.06 \\
A_{CP}(B^+ \rightarrow \eta K_0^*(1430)^+) &= 0.05 \pm 0.13 \\
A_{CP}(B^+ \rightarrow \eta K_2^*(1430)^+) &= -0.45 \pm 0.30 \\
A_{CP}(B^+ \rightarrow \omega K^+) &= -0.02 \pm 0.04 \\
A_{CP}(B^+ \rightarrow \omega K^{*+}) &= 0.29 \pm 0.35 \\
A_{CP}(B^+ \rightarrow \omega (K\pi)_0^{*+}) &= -0.10 \pm 0.09 \\
A_{CP}(B^+ \rightarrow \omega K_2^*(1430)^+) &= 0.14 \pm 0.15 \\
A_{CP}(B^+ \rightarrow K^{*0} \pi^+) &= -0.021 \pm 0.032 \quad (S = 1.5) \\
A_{CP}(B^+ \rightarrow K^*(892)^+ \pi^0) &= -0.39 \pm 0.21 \quad (S = 1.6) \\
\mathbf{A_{CP}(B^+ \rightarrow K^+ \pi^- \pi^+)} &= 0.015 \pm 0.006 \quad (S = 1.4) \\
A_{CP}(B^+ \rightarrow K^+ K^- K^+ \text{nonresonant}) &= 0.06 \pm 0.05 \\
A_{CP}(B^+ \rightarrow f(980)^0 K^+) &= -0.08 \pm 0.09 \\
\mathbf{A_{CP}(B^+ \rightarrow f_2(1270) K^+)} &= -0.68_{-0.17}^{+0.19} \\
A_{CP}(B^+ \rightarrow f_0(1500) K^+) &= 0.28 \pm 0.30 \\
A_{CP}(B^+ \rightarrow f_2'(1525)^0 K^+) &= -0.08_{-0.04}^{+0.05} \\
\mathbf{A_{CP}(B^+ \rightarrow \rho^0 K^+)} &= 0.160 \pm 0.021 \\
A_{CP}(B^+ \rightarrow K^0 \pi^+ \pi^0) &= 0.07 \pm 0.06 \\
A_{CP}(B^+ \rightarrow K_0^*(1430)^0 \pi^+) &= 0.061 \pm 0.032 \\
A_{CP}(B^+ \rightarrow K_0^*(1430)^+ \pi^0) &= 0.26_{-0.14}^{+0.18} \\
A_{CP}(B^+ \rightarrow K_2^*(1430)^0 \pi^+) &= 0.05_{-0.24}^{+0.29} \\
A_{CP}(B^+ \rightarrow K^+ \pi^0 \pi^0) &= -0.06 \pm 0.07 \\
A_{CP}(B^+ \rightarrow K^0 \rho^+) &= -0.03 \pm 0.15 \\
A_{CP}(B^+ \rightarrow K^{*+} \pi^+ \pi^-) &= 0.07 \pm 0.08 \\
A_{CP}(B^+ \rightarrow \rho^0 K^*(892)^+) &= 0.31 \pm 0.13 \\
A_{CP}(B^+ \rightarrow K^*(892)^+ f_0(980)) &= -0.15 \pm 0.12 \\
A_{CP}(B^+ \rightarrow a_1^+ K^0) &= 0.12 \pm 0.11 \\
A_{CP}(B^+ \rightarrow b_1^+ K^0) &= -0.03 \pm 0.15 \\
A_{CP}(B^+ \rightarrow K^*(892)^0 \rho^+) &= -0.01 \pm 0.16 \\
A_{CP}(B^+ \rightarrow b_1^0 K^+) &= -0.46 \pm 0.20 \\
A_{CP}(B^+ \rightarrow K^0 K^+) &= 0.04 \pm 0.14
\end{aligned}$$

$$A_{CP}(B^+ \rightarrow K_S^0 K^+) = -0.21 \pm 0.14$$

$$A_{CP}(B^+ \rightarrow K^+ K_S^0 K_S^0) = 0.025 \pm 0.031$$

$$\mathbf{A_{CP}(B^+ \rightarrow K^+ K^- \pi^+) = -0.115 \pm 0.008}$$

$$A_{CP}(B^+ \rightarrow K^+ K^- \pi^+ \text{ nonresonant}) = -0.11 \pm 0.06$$

$$A_{CP}(B^+ \rightarrow \pi^+ K^+ K^-, m_{K^+ K^-} < 1.1 \text{ GeV}) = -0.17 \pm 0.07$$

$$A_{CP}(B^+ \rightarrow K^+ \bar{K}^*(892)^0) = 0.04 \pm 0.05$$

$$A_{CP}(B^+ \rightarrow K^+ \bar{K}_0^*(1430)^0) = 0.10 \pm 0.17$$

$$A_{CP}(B^+ \rightarrow \phi \pi^+) = 0.1 \pm 0.5$$

$$A_{CP}(B^+ \rightarrow \pi^+ (K^+ K^-)_{S\text{-wave}}) = -0.66 \pm 0.04$$

$$\mathbf{A_{CP}(B^+ \rightarrow K^+ K^- K^+) = -0.036 \pm 0.004}$$

$$A_{CP}(B^+ \rightarrow \phi K^+) = 0.017 \pm 0.017 \quad (S = 1.8)$$

$$A_{CP}(B^+ \rightarrow X_0(1550) K^+) = -0.04 \pm 0.07$$

$$A_{CP}(B^+ \rightarrow K^{*+} K^+ K^-) = 0.11 \pm 0.09$$

$$A_{CP}(B^+ \rightarrow \phi K^*(892)^+) = -0.01 \pm 0.08$$

$$A_{CP}(B^+ \rightarrow \phi (K\pi)_0^{*+}) = 0.04 \pm 0.16$$

$$A_{CP}(B^+ \rightarrow \phi K_1(1270)^+) = 0.15 \pm 0.20$$

$$A_{CP}(B^+ \rightarrow \phi K_2^*(1430)^+) = -0.23 \pm 0.20$$

$$A_{CP}(B^+ \rightarrow K^+ \phi \phi) = -0.08 \pm 0.07$$

$$A_{CP}(B^+ \rightarrow K^+ [\phi \phi]_{\eta_c}) = 0.10 \pm 0.08$$

$$A_{CP}(B^+ \rightarrow K^*(892)^+ \gamma) = 0.014 \pm 0.018$$

$$A_{CP}(B^+ \rightarrow X_S \gamma) = 0.028 \pm 0.019$$

$$A_{CP}(B^+ \rightarrow \eta K^+ \gamma) = -0.12 \pm 0.07$$

$$A_{CP}(B^+ \rightarrow \phi K^+ \gamma) = -0.13 \pm 0.11 \quad (S = 1.1)$$

$$A_{CP}(B^+ \rightarrow \rho^+ \gamma) = -0.11 \pm 0.33$$

$$A_{CP}(B^+ \rightarrow \pi^+ \pi^0) = -0.01 \pm 0.04 \quad (S = 1.1)$$

$$\mathbf{A_{CP}(B^+ \rightarrow \pi^+ \pi^- \pi^+) = 0.076 \pm 0.008 \quad (S = 1.5)}$$

$$A_{CP}(B^+ \rightarrow \pi^+ \pi^0 \pi^0) = (9 \pm 7) \times 10^{-2}$$

$$A_{CP}(B^+ \rightarrow \rho^0 \pi^+) = 0.003 \pm 0.014$$

$$A_{CP}(B^+ \rightarrow f_2(1270) \pi^+) = 0.40 \pm 0.06$$

$$A_{CP}(B^+ \rightarrow \rho^0(1450) \pi^+) = -0.11 \pm 0.05$$

$$A_{CP}(B^+ \rightarrow \rho_3(1690) \pi^+) = -0.80 \pm 0.28$$

$$\mathbf{A_{CP}(B^+ \rightarrow f_0(1370) \pi^+) = 0.72 \pm 0.22}$$

$$A_{CP}(B^+ \rightarrow \pi^+ \pi^- \pi^+ \text{ nonresonant}) = -0.14_{-0.16}^{+0.23}$$

$$A_{CP}(B^+ \rightarrow \rho^+ \pi^0) = 0.03 \pm 0.10$$

$$A_{CP}(B^+ \rightarrow X \pi^+, X \rightarrow \pi^0 \pi^0) = 0.18 \pm 0.12$$

$$A_{CP}(B^+ \rightarrow \rho^+ \rho^0) = -0.05 \pm 0.05$$

$$A_{CP}(B^+ \rightarrow \omega \pi^+) = -0.04 \pm 0.05$$

$$A_{CP}(B^+ \rightarrow \omega \rho^+) = -0.20 \pm 0.09$$

$$A_{CP}(B^+ \rightarrow \eta \pi^+) = -0.14 \pm 0.07 \quad (S = 1.4)$$

$$A_{CP}(B^+ \rightarrow \eta \rho^+) = 0.11 \pm 0.11$$

$$A_{CP}(B^+ \rightarrow \eta' \pi^+) = 0.06 \pm 0.16$$

$$A_{CP}(B^+ \rightarrow \eta' \rho^+) = 0.26 \pm 0.17$$

$$A_{CP}(B^+ \rightarrow b_1^0 \pi^+) = 0.05 \pm 0.16$$

$$A_{CP}(B^+ \rightarrow p \bar{p} \pi^+) = 0.00 \pm 0.04$$

$$A_{CP}(B^+ \rightarrow p \bar{p} K^+) = 0.00 \pm 0.04 \quad (S = 2.2)$$

$$A_{CP}(B^+ \rightarrow p \bar{p} K^*(892)^+) = 0.21 \pm 0.16 \quad (S = 1.4)$$

$$A_{CP}(B^+ \rightarrow p \bar{\Lambda} \gamma) = 0.17 \pm 0.17$$

$$A_{CP}(B^+ \rightarrow p \bar{\Lambda} \pi^0) = 0.01 \pm 0.17$$

$$A_{CP}(B^+ \rightarrow K^+ \ell^+ \ell^-) = -0.02 \pm 0.08$$

$$A_{CP}(B^+ \rightarrow K^+ e^+ e^-) = 0.14 \pm 0.14$$

$$A_{CP}(B^+ \rightarrow K^+ \mu^+ \mu^-) = 0.011 \pm 0.017$$

$$\begin{aligned}
A_{CP}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) &= -0.11 \pm 0.12 \\
A_{CP}(B^+ \rightarrow K^{*+} \ell^+ \ell^-) &= -0.09 \pm 0.14 \\
A_{CP}(B^+ \rightarrow K^* e^+ e^-) &= -0.14 \pm 0.23 \\
A_{CP}(B^+ \rightarrow K^* \mu^+ \mu^-) &= -0.12 \pm 0.24 \\
\gamma &= (65.9_{-3.1}^{+2.9})^\circ \\
r_B(B^+ \rightarrow D^0 K^+) &= (9.94 \pm 0.26) \times 10^{-2} \\
\delta_B(B^+ \rightarrow D^0 K^+) &= (127.7_{-3.9}^{+3.6})^\circ \\
r_B(B^+ \rightarrow D^0 K^{*+}) &= 0.101_{-0.034}^{+0.016} \\
\delta_B(B^+ \rightarrow D^0 K^{*+}) &= (48_{-16}^{+59})^\circ \\
r_B(B^+ \rightarrow D^{*0} K^+) &= 0.104_{-0.014}^{+0.013} \\
\delta_B(B^+ \rightarrow D^{*0} K^+) &= (314.8_{-9.9}^{+7.9})^\circ
\end{aligned}$$

$B^-$  modes are charge conjugates of the modes below. Modes which do not identify the charge state of the  $B$  are listed in the  $B^\pm/B^0$  ADMIXTURE section.

The branching fractions listed below assume 50%  $B^0 \bar{B}^0$  and 50%  $B^+ B^-$  production at the  $\Upsilon(4S)$ . We have attempted to bring older measurements up to date by rescaling their assumed  $\Upsilon(4S)$  production ratio to 50:50 and their assumed  $D$ ,  $D_S$ ,  $D^*$ , and  $\psi$  branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

For inclusive branching fractions, e.g.,  $B \rightarrow D^\pm X$ , the values usually are multiplicities, not branching fractions. They can be greater than one.

<b><math>B^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level (MeV/c)	$p$
<b>Semileptonic and leptonic modes</b>			
$\ell^+ \nu_\ell X$	[hhh] ( 10.99 $\pm$ 0.28 ) %		—
$e^+ \nu_e X_C$	( 10.8 $\pm$ 0.4 ) %		—
$\ell^+ \nu_\ell X_u$	[hhh] ( 1.65 $\pm$ 0.21 ) $\times 10^{-3}$		—
$D \ell^+ \nu_\ell X$	[hhh] ( 9.5 $\pm$ 0.7 ) %		—
$\bar{D}^0 \ell^+ \nu_\ell$	[hhh] ( 2.21 $\pm$ 0.06 ) %		2310
$\bar{D}^0 \tau^+ \nu_\tau$	( 7.7 $\pm$ 2.5 ) $\times 10^{-3}$		1911
$\bar{D}^*(2007)^0 \ell^+ \nu_\ell$	[hhh] ( 5.53 $\pm$ 0.22 ) %		2258
$\bar{D}^*(2007)^0 \tau^+ \nu_\tau$	( 1.88 $\pm$ 0.20 ) %		1839
$D^{(*)} n \pi \ell^+ \nu_\ell$ ( $n \geq 1$ )	[hhh] ( 1.83 $\pm$ 0.25 ) %		—
$D^- \pi^+ \ell^+ \nu_\ell$	[hhh] ( 3.82 $\pm$ 0.20 ) $\times 10^{-3}$		2306
$\bar{D}_2^*(2460)^0 \ell^+ \nu_\ell, \bar{D}_2^{*0} \rightarrow$	[hhh] ( 1.59 $\pm$ 0.10 ) $\times 10^{-3}$		2065
$\bar{D}_0^*(2420)^0 \ell^+ \nu_\ell, \bar{D}_0^{*0} \rightarrow$	( 9 $\pm$ 5 ) $\times 10^{-4}$	S=2.6	—
$D^{*-} \pi^+ \ell^+ \nu_\ell$	[hhh] ( 5.42 $\pm$ 0.28 ) $\times 10^{-3}$		2254
$\bar{D}_1(2420)^0 \ell^+ \nu_\ell, \bar{D}_1^0 \rightarrow$	[hhh] ( 2.84 $\pm$ 0.17 ) $\times 10^{-3}$	S=1.1	2084
$\bar{D}'_1(2430)^0 \ell^+ \nu_\ell, \bar{D}'_1{}^0 \rightarrow$	[hhh] ( 1.7 $\pm$ 0.6 ) $\times 10^{-3}$	S=1.8	—
$\bar{D}_2^*(2460)^0 \ell^+ \nu_\ell, \bar{D}_2^{*0} \rightarrow$	[hhh] ( 1.06 $\pm$ 0.18 ) $\times 10^{-3}$	S=1.7	2065
$\bar{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$	[hhh] ( 1.73 $\pm$ 0.19 ) $\times 10^{-3}$		2301
$\bar{D}_1(2420)^0 \ell^+ \nu_\ell, \bar{D}_1^0 \rightarrow$	[hhh] ( 1.05 $\pm$ 0.14 ) $\times 10^{-3}$		—
$\bar{D}^0 \pi^+ \pi^-$			

$\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$	[hhh]	( 7.0 ± 1.7 ) × 10 <sup>-4</sup>		2248
$D_S^{(*)-} K^+ \ell^+ \nu_\ell$	[hhh]	( 6.1 ± 1.0 ) × 10 <sup>-4</sup>		—
$D_S^- K^+ \ell^+ \nu_\ell$	[hhh]	( 3.0 $\begin{smallmatrix} + 1.4 \\ - 1.2 \end{smallmatrix}$ ) × 10 <sup>-4</sup>		2242
$D_S^{*-} K^+ \ell^+ \nu_\ell$	[hhh]	( 2.9 ± 1.9 ) × 10 <sup>-4</sup>		2185
$\pi^0 \ell^+ \nu_\ell$	[hhh]	( 7.80 ± 0.27 ) × 10 <sup>-5</sup>		2638
$\eta \ell^+ \nu_\ell$	[hhh]	( 3.5 ± 0.4 ) × 10 <sup>-5</sup>		2611
$\eta' \ell^+ \nu_\ell$	[hhh]	( 2.4 ± 0.7 ) × 10 <sup>-5</sup>		2553
$\omega \ell^+ \nu_\ell$	[hhh]	( 1.19 ± 0.09 ) × 10 <sup>-4</sup>		2582
$\rho^0 \ell^+ \nu_\ell$	[hhh]	( 1.58 ± 0.11 ) × 10 <sup>-4</sup>		2583
$\pi^+ \pi^- \ell^+ \nu_\ell$	[hhh]	( 2.3 ± 0.4 ) × 10 <sup>-4</sup>		2636
$p \overline{p} \ell^+ \nu_\ell$	[hhh]	( 5.8 $\begin{smallmatrix} + 2.6 \\ - 2.3 \end{smallmatrix}$ ) × 10 <sup>-6</sup>		2467
$p \overline{p} \mu^+ \nu_\mu$		( 5.32 ± 0.34 ) × 10 <sup>-6</sup>		2446
$p \overline{p} e^+ \nu_e$		( 8.2 $\begin{smallmatrix} + 4.0 \\ - 3.3 \end{smallmatrix}$ ) × 10 <sup>-6</sup>		2467
$e^+ \nu_e$	<	9.8 × 10 <sup>-7</sup>	CL=90%	2640
$\mu^+ \nu_\mu$	<	8.6 × 10 <sup>-7</sup>	CL=90%	2639
$\tau^+ \nu_\tau$		( 1.09 ± 0.24 ) × 10 <sup>-4</sup>	S=1.2	2341
$\ell^+ \nu_\ell \gamma$	[hhh]	< 3.0 × 10 <sup>-6</sup>	CL=90%	2640
$e^+ \nu_e \gamma$	<	4.3 × 10 <sup>-6</sup>	CL=90%	2640
$\mu^+ \nu_\mu \gamma$	<	3.4 × 10 <sup>-6</sup>	CL=90%	2639
$\mu^+ \mu^- \mu^+ \nu_\mu$	<	1.6 × 10 <sup>-8</sup>	CL=95%	2634

## Inclusive modes

$D^0 X$		( 8.6 ± 0.7 ) %		—
$\overline{D}^0 X$		( 79 ± 4 ) %		—
$D^+ X$		( 2.5 ± 0.5 ) %		—
$D^- X$		( 9.9 ± 1.2 ) %		—
$D_S^+ X$		( 7.9 $\begin{smallmatrix} + 1.4 \\ - 1.3 \end{smallmatrix}$ ) %		—
$D_S^- X$		( 1.10 $\begin{smallmatrix} + 0.40 \\ - 0.32 \end{smallmatrix}$ ) %		—
$\Lambda_c^+ X$		( 2.1 $\begin{smallmatrix} + 0.9 \\ - 0.6 \end{smallmatrix}$ ) %		—
$\overline{\Lambda}_c^- X$		( 2.8 $\begin{smallmatrix} + 1.1 \\ - 0.9 \end{smallmatrix}$ ) %		—
$\overline{c} X$		( 97 ± 4 ) %		—
$c X$		( 23.4 $\begin{smallmatrix} + 2.2 \\ - 1.8 \end{smallmatrix}$ ) %		—
$c / \overline{c} X$		( 120 ± 6 ) %		—

D, D\*, or D<sub>S</sub> modes

$\overline{D}^0 \pi^+$		( 4.61 ± 0.10 ) × 10 <sup>-3</sup>		2308
$D_{CP(+1)} \pi^+$	[iii]	( 2.03 ± 0.19 ) × 10 <sup>-3</sup>		—
$D_{CP(-1)} \pi^+$	[iii]	( 2.0 ± 0.4 ) × 10 <sup>-3</sup>		—
$\overline{D}^0 \rho^+$		( 1.34 ± 0.18 ) %		2237
$\overline{D}^0 K^+$		( 3.64 ± 0.15 ) × 10 <sup>-4</sup>		2281
$D_{CP(+1)} K^+$	[iii]	( 1.80 ± 0.08 ) × 10 <sup>-4</sup>		—
$D_{CP(-1)} K^+$	[iii]	( 1.96 ± 0.18 ) × 10 <sup>-4</sup>		—
$D^0 K^+$		( 3.60 ± 0.24 ) × 10 <sup>-6</sup>		2281
$[K^- \pi^+]_D K^+$	[jj]	< 2.8 × 10 <sup>-7</sup>	CL=90%	—
$[K^+ \pi^-]_D K^+$	[jj]	< 2.0 × 10 <sup>-5</sup>	CL=90%	—
$[K^- \pi^+]_D \pi^+$	[jj]	( 6.3 ± 1.1 ) × 10 <sup>-7</sup>		—
$[K^+ \pi^-]_D \pi^+$		( 1.7 ± 0.4 ) × 10 <sup>-4</sup>		—
$[\pi^+ \pi^- \pi^0]_D K^-$		( 4.6 ± 0.9 ) × 10 <sup>-6</sup>		—
$\overline{D}^0 K^*(892)^+$		( 5.3 ± 0.4 ) × 10 <sup>-4</sup>		2213
$D_{CP(-1)} K^*(892)^+$	[iii]	( 2.7 ± 0.8 ) × 10 <sup>-4</sup>		—

$D_{CP(+1)} K^*(892)^+$	[iii]	$( 6.2 \pm 0.7 ) \times 10^{-4}$		-
$D^0 K^*(892)^+$		$( 5.4 \pm 1.8 ) \times 10^{-6}$		2213
$\overline{D}^0 K^+ \pi^+ \pi^-$		$( 5.2 \pm 2.1 ) \times 10^{-4}$		2237
$\overline{D}^0 K^+ \overline{K}^0$		$( 5.5 \pm 1.6 ) \times 10^{-4}$		2189
$\overline{D}^0 K^+ \overline{K}^*(892)^0$		$( 7.5 \pm 1.7 ) \times 10^{-4}$		2072
$\overline{D}^0 \pi^+ \pi^+ \pi^-$		$( 5.5 \pm 2.0 ) \times 10^{-3}$	S=3.6	2289
$\overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant		$( 5 \pm 4 ) \times 10^{-3}$		2289
$\overline{D}^0 \pi^+ \rho^0$		$( 4.2 \pm 3.0 ) \times 10^{-3}$		2208
$\overline{D}^0 a_1(1260)^+$		$( 4 \pm 4 ) \times 10^{-3}$		2123
$\overline{D}^0 \omega \pi^+$		$( 4.1 \pm 0.9 ) \times 10^{-3}$		2206
$D^*(2010)^- \pi^+ \pi^+$		$( 1.35 \pm 0.22 ) \times 10^{-3}$		2247
$D^*(2010)^- K^+ \pi^+$		$( 8.2 \pm 1.4 ) \times 10^{-5}$		2206
$\overline{D}_1(2420)^0 \pi^+, \overline{D}_1^- \rightarrow$ $D^*(2010)^- \pi^+$		$( 8.4 \pm 1.5 ) \times 10^{-4}$		2081
$D^- \pi^+ \pi^+$		$( 1.07 \pm 0.05 ) \times 10^{-3}$		2299
$D^- K^+ \pi^+$		$( 7.7 \pm 0.5 ) \times 10^{-5}$		2260
$D_0^*(2300)^0 K^+, D_0^{*0} \rightarrow$ $D^- \pi^+$		$( 6.1 \pm 2.4 ) \times 10^{-6}$		-
$D_2^*(2460)^0 K^+, D_2^{*0} \rightarrow$ $D^- \pi^+$		$( 2.32 \pm 0.23 ) \times 10^{-5}$		-
$D_1^*(2760)^0 K^+, D_1^{*0} \rightarrow$ $D^- \pi^+$		$( 3.6 \pm 1.2 ) \times 10^{-6}$		-
$D^+ K^0$		$< 2 \times 10^{-6}$	CL=90%	2278
$D^+ K^+ \pi^-$		$( 5.6 \pm 1.1 ) \times 10^{-6}$		2260
$D^+ \eta$		$< 1.2 \times 10^{-5}$	CL=90%	2272
$D_2^*(2460)^0 K^+, D_2^{*0} \rightarrow$ $D^+ \pi^-$		$< 6.3 \times 10^{-7}$	CL=90%	-
$D^+ K^{*0}$		$< 4.9 \times 10^{-7}$	CL=90%	2211
$D^+ \overline{K}^{*0}$		$< 1.4 \times 10^{-6}$	CL=90%	2211
$\overline{D}^*(2007)^0 \pi^+$		$( 5.17 \pm 0.15 ) \times 10^{-3}$		2256
$\overline{D}_{CP(+1)}^* \pi^+$	[kkk]	$( 2.9 \pm 0.6 ) \times 10^{-3}$		-
$D_{CP(-1)}^{*0} \pi^+$	[kkk]	$( 2.6 \pm 1.0 ) \times 10^{-3}$		-
$\overline{D}^*(2007)^0 \omega \pi^+$		$( 4.5 \pm 1.2 ) \times 10^{-3}$		2149
$\overline{D}^*(2007)^0 \rho^+$		$( 9.8 \pm 1.7 ) \times 10^{-3}$		2182
$\overline{D}^*(2007)^0 K^+$		$( 4.19 \pm 0.31 ) \times 10^{-4}$		2227
$\overline{D}_{CP(+1)}^{*0} K^+$	[kkk]	$( 2.75 \pm 0.35 ) \times 10^{-4}$		-
$\overline{D}_{CP(-1)}^{*0} K^+$	[kkk]	$( 2.31 \pm 0.31 ) \times 10^{-4}$		-
$D^*(2007)^0 K^+$		$( 4.5 \pm 1.2 ) \times 10^{-6}$		2227
$\overline{D}^*(2007)^0 K^*(892)^+$		$( 8.1 \pm 1.4 ) \times 10^{-4}$		2156
$\overline{D}^*(2007)^0 K^+ \overline{K}^0$		$< 1.06 \times 10^{-3}$	CL=90%	2132
$\overline{D}^*(2007)^0 K^+ \overline{K}^*(892)^0$		$( 1.5 \pm 0.4 ) \times 10^{-3}$		2009
$\overline{D}^*(2007)^0 \pi^+ \pi^+ \pi^-$		$( 1.03 \pm 0.12 ) \%$		2236
$\overline{D}^*(2007)^0 a_1(1260)^+$		$( 1.9 \pm 0.5 ) \%$		2063
$\overline{D}^*(2007)^0 \pi^- \pi^+ \pi^+ \pi^0$		$( 1.8 \pm 0.4 ) \%$		2219
$\overline{D}^{*0} 3\pi^+ 2\pi^-$		$( 5.7 \pm 1.2 ) \times 10^{-3}$		2196
$D^*(2010)^+ \pi^0$		$< 3.6 \times 10^{-6}$		2255
$D^*(2010)^+ K^0$		$< 9.0 \times 10^{-6}$	CL=90%	2225
$D^*(2010)^- \pi^+ \pi^+ \pi^0$		$( 1.5 \pm 0.7 ) \%$		2235
$D^*(2010)^- \pi^+ \pi^+ \pi^+ \pi^-$		$( 2.6 \pm 0.4 ) \times 10^{-3}$		2217
$\overline{D}^{*0} \pi^+$	[iii]	$( 5.6 \pm 1.2 ) \times 10^{-3}$		-
$\overline{D}_1^*(2420)^0 \pi^+$		$( 1.5 \pm 0.6 ) \times 10^{-3}$	S=1.3	2081

$\bar{D}_1(2420)^0 \pi^+ \times B(\bar{D}_1^0 \rightarrow \bar{D}^0 \pi^+ \pi^-)$	$(2.5 \pm 1.6) \times 10^{-4}$	S=3.8	2081
$\bar{D}_1(2420)^0 \pi^+ \times B(\bar{D}_1^0 \rightarrow \bar{D}^0 \pi^+ \pi^- \text{ (nonresonant)})$	$(2.2 \pm 0.9) \times 10^{-4}$		2081
$\bar{D}_1(2430)^0 \pi^+, \bar{D}_1^0 \rightarrow D^*(2010)^- \pi^+$	$(3.5 \pm 0.6) \times 10^{-4}$		2079
$\bar{D}(2550)^0 \pi^+, \bar{D}^0 \rightarrow D^*(2010)^- \pi^+$	$(7.2 \pm 1.4) \times 10^{-5}$		-
$\bar{D}_J^*(2600)^0 \pi^+, \bar{D}_J^{*0} \rightarrow D^*(2010)^- \pi^+$	$(6.8 \pm 1.3) \times 10^{-5}$		-
$\bar{D}_2^*(2462)^0 \pi^+, \bar{D}_2^{*0} \rightarrow D^- \pi^+$	$(3.56 \pm 0.24) \times 10^{-4}$		-
$\bar{D}_2^*(2462)^0 \pi^+, \bar{D}_2^{*0} \rightarrow \bar{D}^0 \pi^- \pi^+$	$(2.2 \pm 1.0) \times 10^{-4}$		-
$\bar{D}_2^*(2462)^0 \pi^+, \bar{D}_2^{*0} \rightarrow \bar{D}^0 \pi^- \pi^+ \text{ (nonresonant)}$	$< 1.6 \times 10^{-4}$	CL=90%	-
$\bar{D}_2^*(2462)^0 \pi^+, \bar{D}_2^{*0} \rightarrow D^*(2010)^- \pi^+$	$(2.1 \pm 1.0) \times 10^{-4}$		-
$\bar{D}_0^*(2400)^0 \pi^+ \times B(\bar{D}_0^*(2400)^0 \rightarrow D^- \pi^+)$	$(6.4 \pm 1.4) \times 10^{-4}$		2136
$\bar{D}_1(2421)^0 \pi^+, \bar{D}_1^0 \rightarrow D^{*-} \pi^+$	$(7.4 \pm 1.0) \times 10^{-4}$		-
$\bar{D}_2^*(2462)^0 \pi^+, \bar{D}_2^{*0} \rightarrow D^{*-} \pi^+$	$(1.98 \pm 0.30) \times 10^{-4}$		-
$\bar{D}_1^J(2427)^0 \pi^+, \bar{D}_1^{J0} \rightarrow D^{*-} \pi^+$	$(3.5 \pm 0.9) \times 10^{-4}$	S=1.5	-
$\bar{D}_1(2420)^0 \pi^+ \times B(\bar{D}_1^0 \rightarrow \bar{D}^{*0} \pi^+ \pi^-)$	$< 6 \times 10^{-6}$	CL=90%	2081
$\bar{D}_1^*(2420)^0 \rho^+$	$< 1.4 \times 10^{-3}$	CL=90%	1996
$\bar{D}_2^*(2460)^0 \pi^+$	$< 1.3 \times 10^{-3}$	CL=90%	2063
$\bar{D}_2^*(2460)^0 \pi^+ \times B(\bar{D}_2^{*0} \rightarrow \bar{D}^{*0} \pi^+ \pi^-)$	$< 2.2 \times 10^{-5}$	CL=90%	2063
$\bar{D}_1^*(2680)^0 \pi^+, \bar{D}_1^*(2680)^0 \rightarrow D^- \pi^+$	$(8.4 \pm 2.1) \times 10^{-5}$		-
$\bar{D}(2740)^0 \pi^+, \bar{D}^0 \rightarrow D^*(2010)^- \pi^+$	$(3.3 \pm 1.5) \times 10^{-5}$		-
$\bar{D}_3^*(2750)^0 \pi^+, \bar{D}_3^{*0} \rightarrow D^*(2010)^- \pi^+$	$(1.10 \pm 0.32) \times 10^{-5}$		1913
$\bar{D}_3^*(2760)^0 \pi^+, \bar{D}_3^*(2760)^0 \pi^+ \rightarrow D^- \pi^+$	$(1.00 \pm 0.22) \times 10^{-5}$		-
$\bar{D}_2^*(3000)^0 \pi^+, \bar{D}_2^*(3000)^0 \pi^+ \rightarrow \bar{D}^0 D_s^+$	$(2.0 \pm 1.4) \times 10^{-6}$		-
$\bar{D}_2^*(2460)^0 \rho^+$	$< 4.7 \times 10^{-3}$	CL=90%	1977
$\bar{D}_5^0 D_s^+$	$(9.0 \pm 0.9) \times 10^{-3}$		1815
$D_{S0}^*(2317)^+ \bar{D}^0, D_{S0}^{*+} \rightarrow D_s^+ \pi^0$	$(8.0 \pm 1.6) \times 10^{-4}$		1605
$D_{S0}(2317)^+ \bar{D}^0 \times B(D_{S0}(2317)^+ \rightarrow D_s^{*+} \gamma)$	$< 7.6 \times 10^{-4}$	CL=90%	1605
$D_{S0}(2317)^+ \bar{D}^*(2007)^0 \times B(D_{S0}(2317)^+ \rightarrow D_s^+ \pi^0)$	$(9 \pm 7) \times 10^{-4}$		1511
$D_{sJ}(2457)^+ \bar{D}^0$	$(3.1 \pm 1.0) \times 10^{-3}$		-
$D_{sJ}(2457)^+ \bar{D}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^+ \gamma)$	$(4.6 \pm 1.3) \times 10^{-4}$		-
$D_{sJ}(2457)^+ \bar{D}^0 \times B(D_{sJ}(2457)^+ \rightarrow D_s^+ \pi^+ \pi^-)$	$< 2.2 \times 10^{-4}$	CL=90%	-



$D_{sJ}(2457)^+ \bar{D}^0 \times$ $B(D_{sJ}(2457)^+ \rightarrow D_s^+ \pi^0)$	< 2.7	$\times 10^{-4}$	CL=90%	-
$D_{sJ}(2457)^+ \bar{D}^0 \times$ $B(D_{sJ}(2457)^+ \rightarrow D_s^{*+} \gamma)$	< 9.8	$\times 10^{-4}$	CL=90%	-
$D_{sJ}(2457)^+ \bar{D}^*(2007)^0$	( 1.20 $\pm$ 0.30 )	%		-
$D_{sJ}(2457)^+ \bar{D}^*(2007)^0 \times$ $B(D_{sJ}(2457)^+ \rightarrow D_s^+ \gamma)$	( 1.4 $\pm$ 0.7 )	$\times 10^{-3}$		-
$\bar{D}^0 D_{s1}(2536)^+ \times$ $B(D_{s1}(2536)^+ \rightarrow$ $D^*(2007)^0 K^+ +$ $D^*(2010)^+ K^0)$	( 4.0 $\pm$ 1.0 )	$\times 10^{-4}$		1447
$\bar{D}^0 D_{s1}(2536)^+ \times$ $B(D_{s1}(2536)^+ \rightarrow$ $D^*(2007)^0 K^+)$	( 2.2 $\pm$ 0.7 )	$\times 10^{-4}$		1447
$\bar{D}^*(2007)^0 D_{s1}(2536)^+ \times$ $B(D_{s1}(2536)^+ \rightarrow$ $D^*(2007)^0 K^+)$	( 5.5 $\pm$ 1.6 )	$\times 10^{-4}$		1339
$\bar{D}^0 D_{s1}(2536)^+ \times$ $B(D_{s1}(2536)^+ \rightarrow D^{*+} K^0)$	( 2.3 $\pm$ 1.1 )	$\times 10^{-4}$		1447
$\bar{D}^0 D_{sJ}(2700)^+ \times$ $B(D_{sJ}(2700)^+ \rightarrow D^0 K^+)$	( 5.6 $\pm$ 1.8 )	$\times 10^{-4}$	S=1.7	-
$\bar{D}^{*0} D_{s1}(2536)^+, D_{s1}^+ \rightarrow$ $D^{*+} K^0$	( 3.9 $\pm$ 2.6 )	$\times 10^{-4}$		1339
$\bar{D}^0 D_{sJ}(2573)^+, D_{sJ}^+ \rightarrow D^0 K^+$	( 8 $\pm$ 15 )	$\times 10^{-6}$		-
$\bar{D}^{*0} D_{sJ}(2573), D_{sJ}^+ \rightarrow D^0 K^+$	< 2	$\times 10^{-4}$	CL=90%	1306
$\bar{D}^*(2007)^0 D_{sJ}(2573), D_{sJ}^+ \rightarrow$ $D^0 K^+$	< 5	$\times 10^{-4}$	CL=90%	1306
$\bar{D}^0 D_s^{*+}$	( 7.6 $\pm$ 1.6 )	$\times 10^{-3}$		1734
$\bar{D}^*(2007)^0 D_s^+$	( 8.2 $\pm$ 1.7 )	$\times 10^{-3}$		1737
$\bar{D}^*(2007)^0 D_s^{*+}$	( 1.71 $\pm$ 0.24 )	%		1651
$D_s^{(*)+} \bar{D}^{*0}$	( 2.7 $\pm$ 1.2 )	%		-
$\bar{D}^*(2007)^0 D^*(2010)^+$	( 8.1 $\pm$ 1.7 )	$\times 10^{-4}$		1713
$\bar{D}^0 D^*(2010)^+ + \bar{D}^*(2007)^0 D^+$	< 1.30	%	CL=90%	1792
$\bar{D}^0 D^*(2010)^+$	( 3.9 $\pm$ 0.5 )	$\times 10^{-4}$		1792
$\bar{D}^0 D^+$	( 3.8 $\pm$ 0.4 )	$\times 10^{-4}$		1866
$\bar{D}^0 D^+ K^0$	( 1.55 $\pm$ 0.21 )	$\times 10^{-3}$		1571
$D^+ \bar{D}^*(2007)^0$	( 6.3 $\pm$ 1.7 )	$\times 10^{-4}$		1791
$\bar{D}^*(2007)^0 D^+ K^0$	( 2.1 $\pm$ 0.5 )	$\times 10^{-3}$		1475
$\bar{D}^0 D^*(2010)^+ K^0$	( 3.8 $\pm$ 0.4 )	$\times 10^{-3}$		1476
$\bar{D}^*(2007)^0 D^*(2010)^+ K^0$	( 9.2 $\pm$ 1.2 )	$\times 10^{-3}$		1362
$\bar{D}^0 D^0 K^+$	( 1.45 $\pm$ 0.33 )	$\times 10^{-3}$	S=2.6	1577
$\bar{D}^*(2007)^0 D^0 K^+$	( 2.26 $\pm$ 0.23 )	$\times 10^{-3}$		1481
$\bar{D}^0 D^*(2007)^0 K^+$	( 6.3 $\pm$ 0.5 )	$\times 10^{-3}$		1481
$\bar{D}^*(2007)^0 D^*(2007)^0 K^+$	( 1.12 $\pm$ 0.13 )	%		1368
$D^- D^+ K^+$	( 2.2 $\pm$ 0.7 )	$\times 10^{-4}$		1571
$T_{cs0}^*(2870)^0 D^+, T_{cs0}^{*0} \rightarrow$ $D^- K^+$	( 1.2 $\pm$ 0.5 )	$\times 10^{-5}$		-
$T_{cs1}^*(2900)^0 D^+, T_{cs1}^{*0} \rightarrow$ $D^- K^+$	( 6.7 $\pm$ 2.3 )	$\times 10^{-5}$		-
$D^- D^+ K^+$ nonresonant	( 5.3 $\pm$ 1.8 )	$\times 10^{-5}$		1571
$D^- D^*(2010)^+ K^+$	( 6.3 $\pm$ 1.1 )	$\times 10^{-4}$		1475
$D^*(2010)^- D^+ K^+$	( 6.0 $\pm$ 1.3 )	$\times 10^{-4}$		1475
$D^*(2010)^- D^*(2010)^+ K^+$	( 1.32 $\pm$ 0.18 )	$\times 10^{-3}$		1363

$(\bar{D} + \bar{D}^*)(D + D^*)K$	$(4.05 \pm 0.30) \%$		—
$D_S^- D_S^+ K^+$	$(1.2 \pm 0.4) \times 10^{-4}$		1429
$D_S^+ \pi^0$	$(1.6 \pm 0.5) \times 10^{-5}$		2270
$D_S^{*+} \pi^0$	$< 2.6 \times 10^{-4}$	CL=90%	2215
$D_S^+ \eta$	$< 1.4 \times 10^{-5}$	CL=90%	2235
$D_S^{*+} \eta$	$< 1.7 \times 10^{-5}$	CL=90%	2178
$D_S^+ \rho^0$	$< 3.0 \times 10^{-4}$	CL=90%	2197
$D_S^{*+} \rho^0$	$< 4 \times 10^{-4}$	CL=90%	2138
$D_S^+ \omega$	$< 4 \times 10^{-4}$	CL=90%	2195
$D_S^{*+} \omega$	$< 6 \times 10^{-4}$	CL=90%	2136
$D_S^+ a_1(1260)^0$	$< 1.8 \times 10^{-3}$	CL=90%	2080
$D_S^{*+} a_1(1260)^0$	$< 1.3 \times 10^{-3}$	CL=90%	2015
$D_S^+ K^+ K^-$	$(7.2 \pm 1.1) \times 10^{-6}$		2149
$D_S^+ \phi$	$< 4.2 \times 10^{-7}$	CL=90%	2141
$D_S^{*+} \phi$	$< 1.2 \times 10^{-5}$	CL=90%	2079
$D_S^+ \bar{K}^0$	$< 3 \times 10^{-6}$	CL=90%	2242
$D_S^{*+} \bar{K}^0$	$< 6 \times 10^{-6}$	CL=90%	2185
$D_S^+ \bar{K}^*(892)^0$	$< 4.4 \times 10^{-6}$	CL=90%	2172
$D_S^+ K^{*0}$	$< 3.5 \times 10^{-6}$	CL=90%	2172
$D_S^{*+} \bar{K}^*(892)^0$	$< 3.5 \times 10^{-4}$	CL=90%	2112
$D_S^- \pi^+ K^+$	$(1.80 \pm 0.22) \times 10^{-4}$		2222
$D_S^{*-} \pi^+ K^+$	$(1.45 \pm 0.24) \times 10^{-4}$		2164
$D_S^- \pi^+ K^*(892)^+$	$< 5 \times 10^{-3}$	CL=90%	2138
$D_S^{*-} \pi^+ K^*(892)^+$	$< 7 \times 10^{-3}$	CL=90%	2076
$D_S^- K^+ K^+$	$(9.7 \pm 2.1) \times 10^{-6}$		2149
$D_S^{*-} K^+ K^+$	$< 1.5 \times 10^{-5}$	CL=90%	2088
<b>Charmonium modes</b>			
$\eta_c K^+$	$(1.10 \pm 0.07) \times 10^{-3}$	S=1.1	1751
$\eta_c K^*(892)^+$	$(1.2 \pm_{-0.4}^{0.5}) \times 10^{-3}$		1646
$\eta_c K^+ \pi^+ \pi^-$	$< 3.9 \times 10^{-4}$	CL=90%	1684
$\eta_c K^+ \omega(782)$	$< 5.3 \times 10^{-4}$	CL=90%	1475
$\eta_c K^+ \eta$	$< 2.2 \times 10^{-4}$	CL=90%	1588
$\eta_c K^+ \pi^0$	$< 6.2 \times 10^{-5}$	CL=90%	1723
$\eta_c(2S) K^+$	$(4.4 \pm 1.0) \times 10^{-4}$		1320
$\eta_c(2S) K^+, \eta_c \rightarrow p \bar{p}$	$(3.5 \pm 0.8) \times 10^{-8}$		—
$\eta_c(2S) K^+, \eta_c \rightarrow K_S^0 K^\mp \pi^\pm$	$(3.4 \pm_{-1.6}^{2.3}) \times 10^{-6}$		—
$\eta_c(2S) K^+, \eta_c \rightarrow p \bar{p} \pi^+ \pi^-$	$(1.12 \pm 0.18) \times 10^{-6}$		—
$h_c(1P) K^+, h_c \rightarrow J/\psi \pi^+ \pi^-$	$< 3.4 \times 10^{-6}$	CL=90%	1401
$X(3730)^0 K^+, X^0 \rightarrow \eta_c \eta$	$< 4.6 \times 10^{-5}$	CL=90%	—
$X(3730)^0 K^+, X^0 \rightarrow \eta_c \pi^0$	$< 5.7 \times 10^{-6}$	CL=90%	—
$\eta_{c2}(1D) K^+, \eta_{c2} \rightarrow h_c \gamma$	$< 3.7 \times 10^{-5}$	CL=90%	—
$\eta_{c2}(1D) \pi^+ K_S^0, \eta_{c2} \rightarrow h_c \gamma$	$< 1.1 \times 10^{-4}$	CL=90%	—
$\psi_2(3823) K^+, \psi_2 \rightarrow J/\psi \pi^+ \pi^-$	$(2.8 \pm 0.6) \times 10^{-7}$		—
$\psi_2(3823) K^+, \psi_2 \rightarrow J/\psi \eta$	$(1.2 \pm_{-0.5}^{0.7}) \times 10^{-6}$		—
$\psi_3(3842) K^+, \psi_3 \rightarrow J/\psi \eta$	$< 6.1 \times 10^{-7}$	CL=90%	—
$\chi_{c1}(3872) K^+$	$(2.3 \pm 0.6) \times 10^{-4}$		1141
$\chi_{c0}(3915) K^+$	$< 2.8 \times 10^{-4}$	CL=90%	1100
$\chi_{c0}(3915) K^+, \chi_{c0} \rightarrow D^+ D^-$	$(8.1 \pm 3.3) \times 10^{-6}$		—
$\chi_{c0}(3915) K^+, \chi_{c0} \rightarrow \eta_c \eta$	$< 4.7 \times 10^{-5}$	CL=90%	—
$\chi_{c0}(3915) K^+, \chi_{c0} \rightarrow \eta_c \pi^0$	$< 1.7 \times 10^{-5}$	CL=90%	—

$X(4014)^0 K^+, X^0 \rightarrow \eta_c \eta$	< 3.9	$\times 10^{-5}$	CL=90%	-
$X(4014)^0 K^+, X^0 \rightarrow \eta_c \pi^0$	< 1.2	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(3900)^0 K^+, T_{c\bar{c}1}^0 \rightarrow$ $\eta_c \pi^+ \pi^-$	< 4.7	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(3900)^0 K^+, T_{c\bar{c}1}^0 \rightarrow$ $J/\psi \eta$	< 4.3	$\times 10^{-7}$	CL=90%	-
$T_{c\bar{c}}(4020)^0 K^+, T_{c\bar{c}}^0 \rightarrow$ $\eta_c \pi^+ \pi^-$	< 1.6	$\times 10^{-5}$	CL=90%	-
$\chi_{c1}(3872) K^*(892)^+$	< 6	$\times 10^{-4}$	CL=90%	940
$\chi_{c1}(3872)^+ K^0, \chi_{c1}^+ \rightarrow$ $J/\psi(1S) \pi^+ \pi^0$	[ <i>nnn</i> ] < 6.1	$\times 10^{-6}$	CL=90%	-
$\chi_{c1}(3872) K^0 \pi^+$	( 3.0 $\pm$ 1.2 )	$\times 10^{-4}$		1085
$T_{c\bar{c}1}(4430)^+ K^0, T_{c\bar{c}1}^+ \rightarrow$ $J/\psi \pi^+$	< 1.5	$\times 10^{-5}$	CL=95%	-
$T_{c\bar{c}1}(4430)^+ K^0, T_{c\bar{c}1}^+ \rightarrow$ $\psi(2S) \pi^+$	< 4.7	$\times 10^{-5}$	CL=95%	-
$T_{c\bar{c}1}(4430)^0 K^+, T_{c\bar{c}1}^0 \rightarrow$ $J/\psi \eta$	< 1.27	$\times 10^{-6}$	CL=90%	-
$\psi(4230)^0 K^+, \psi^0 \rightarrow J/\psi \pi^+ \pi^-$	< 1.56	$\times 10^{-5}$	CL=95%	-
$\psi(4230) K^+, \psi \rightarrow J/\psi \eta$	< 3.9	$\times 10^{-7}$	CL=90%	-
$\psi(4360) K^+, \psi \rightarrow J/\psi \eta$	< 1.24	$\times 10^{-6}$	CL=90%	-
$\psi(4390) K^+, \psi \rightarrow J/\psi \eta$	< 2.41	$\times 10^{-6}$	CL=90%	-
$\chi_{c0}(3915) K^+, \chi_{c0} \rightarrow J/\psi \gamma$	< 1.4	$\times 10^{-5}$	CL=90%	-
$\chi_{c0}(3915) K^+, \chi_{c0} \rightarrow$ $\chi_{c1}(1P) \pi^0$	< 3.8	$\times 10^{-5}$	CL=90%	-
$X(3930)^0 K^+, X^0 \rightarrow J/\psi \gamma$	< 2.5	$\times 10^{-6}$	CL=90%	-
$J/\psi(1S) K^+$	( 1.020 $\pm$ 0.019 )	$\times 10^{-3}$		1684
$J/\psi(1S) K^0 \pi^+$	( 1.14 $\pm$ 0.11 )	$\times 10^{-3}$		1651
$J/\psi(1S) K^+ \pi^+ \pi^-$	( 8.1 $\pm$ 1.3 )	$\times 10^{-4}$	S=2.5	1612
$J/\psi(1S) K^+ K^- K^+$	( 3.37 $\pm$ 0.29 )	$\times 10^{-5}$		1252
$\chi_{c0}(3915) K^+, \chi_{c0} \rightarrow p \bar{p}$	< 7.1	$\times 10^{-8}$	CL=95%	-
$J/\psi(1S) K^*(892)^+$	( 1.43 $\pm$ 0.08 )	$\times 10^{-3}$		1571
$J/\psi(1S) K(1270)^+$	( 1.8 $\pm$ 0.5 )	$\times 10^{-3}$		1402
$J/\psi(1S) K(1400)^+$	< 5	$\times 10^{-4}$	CL=90%	1308
$J/\psi(1S) \eta K^+$	( 1.24 $\pm$ 0.14 )	$\times 10^{-4}$		1510
$\chi_{c1-odd}(3872) K^+,$ $\chi_{c1-odd} \rightarrow J/\psi \eta$	< 3.8	$\times 10^{-6}$	CL=90%	-
$\psi(4160) K^+, \psi \rightarrow J/\psi \eta$	< 8.7	$\times 10^{-7}$	CL=90%	-
$J/\psi(1S) \eta' K^+$	( 3.1 $\pm$ 0.4 )	$\times 10^{-5}$		1273
$J/\psi(1S) \phi K^+$	( 5.0 $\pm$ 0.4 )	$\times 10^{-5}$		1227
$J/\psi(1S) K_1(1650), K_1 \rightarrow \phi K^+$	( 6 $\frac{+10}{-6}$ )	$\times 10^{-6}$		-
$J/\psi(1S) K^*(1680)^+, K^* \rightarrow$ $\phi K^+$	( 3.4 $\frac{+1.9}{-2.2}$ )	$\times 10^{-6}$		-
$J/\psi(1S) K_2^*(1980), K_2^* \rightarrow \phi K^+$	( 1.5 $\frac{+0.9}{-0.5}$ )	$\times 10^{-6}$		-
$J/\psi(1S) K(1830)^+,$ $K(1830)^+ \rightarrow \phi K^+$	( 1.3 $\frac{+1.3}{-1.1}$ )	$\times 10^{-6}$		-
$\chi_{c1}(4140) K^+, \chi_{c1} \rightarrow$ $J/\psi(1S) \phi$	( 10 $\pm$ 4 )	$\times 10^{-6}$		-
$\chi_{c1}(4274) K^+, \chi_{c1} \rightarrow$ $J/\psi(1S) \phi$	( 3.6 $\frac{+2.2}{-1.8}$ )	$\times 10^{-6}$		-
$\chi_{c0}(4500) K^+, \chi_{c0} \rightarrow$ $J/\psi(1S) \phi$	( 3.3 $\frac{+2.1}{-1.7}$ )	$\times 10^{-6}$		-

$\chi_{c0}(4700)K^+, \chi_{c0} \rightarrow J/\psi(1S)\phi$	$(6 \pm \frac{5}{4}) \times 10^{-6}$		-
$J/\psi(1S)\omega K^+$	$(3.20 \pm \frac{0.60}{0.32}) \times 10^{-4}$		1388
$\chi_{c0}(3915)K^+, \chi_{c0} \rightarrow J/\psi\omega$	$(3.0 \pm \frac{0.9}{0.7}) \times 10^{-5}$		1103
$J/\psi(1S)\pi^+$	$(3.92 \pm 0.09) \times 10^{-5}$		1728
$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	$(1.17 \pm 0.13) \times 10^{-5}$		1635
$\psi(2S)\pi^+\pi^+\pi^-$	$(1.9 \pm 0.4) \times 10^{-5}$		1304
$J/\psi(1S)\rho^+$	$(4.1 \pm 0.5) \times 10^{-5}$	S=1.4	1612
$J/\psi(1S)\pi^+\pi^0$ nonresonant	$< 7.3 \times 10^{-6}$	CL=90%	1717
$J/\psi(1S)a_1(1260)^+$	$< 1.2 \times 10^{-3}$	CL=90%	1415
$J/\psi(1S)\rho\bar{p}\pi^+$	$< 5.0 \times 10^{-7}$	CL=90%	644
$J/\psi(1S)\rho\bar{\Lambda}$	$(1.46 \pm 0.12) \times 10^{-5}$		568
$J/\psi(1S)\bar{\Sigma}^0\rho$	$< 1.1 \times 10^{-5}$	CL=90%	-
$J/\psi(1S)D^+$	$< 1.2 \times 10^{-4}$	CL=90%	871
$J/\psi(1S)\bar{D}^0\pi^+$	$< 2.5 \times 10^{-5}$	CL=90%	665
$\psi(2S)\pi^+$	$(2.44 \pm 0.30) \times 10^{-5}$		1348
$\psi(2S)K^+$	$(6.24 \pm 0.21) \times 10^{-4}$		1284
$\psi(2S)K^*(892)^+$	$(6.7 \pm 1.4) \times 10^{-4}$	S=1.3	1116
$\psi(2S)K^+\pi^+\pi^-$	$(4.3 \pm 0.5) \times 10^{-4}$		1179
$\psi(2S)\phi(1020)K^+$	$(4.0 \pm 0.7) \times 10^{-6}$		418
$\psi(3770)K^+$	$(4.3 \pm 1.1) \times 10^{-4}$		1218
$\psi(3770)K^+, \psi \rightarrow D^0\bar{D}^0$	$(1.5 \pm 0.5) \times 10^{-4}$	S=1.4	1218
$\psi(3770)K^+, \psi \rightarrow D^+D^-$	$(9.4 \pm 3.5) \times 10^{-5}$		1218
$\psi(3770)K^+, \psi \rightarrow \rho\bar{p}$	$< 2 \times 10^{-7}$	CL=95%	-
$\psi(3770)K^+, \psi \rightarrow J/\psi\eta$	$< 4.6 \times 10^{-7}$	CL=90%	-
$\psi(4040)K^+$	$(1.6 \pm 0.5) \times 10^{-3}$		1002
$\psi(4040)K^+, \psi \rightarrow D^+D^-$	$(1.1 \pm 0.5) \times 10^{-5}$		-
$\psi(4160)K^+$	$(5.1 \pm 2.7) \times 10^{-4}$		869
$\psi(4160)K^+, \psi \rightarrow \bar{D}^0D^0$	$(8 \pm 5) \times 10^{-5}$		-
$\psi(4160)K^+, \psi \rightarrow D^+D^-$	$(1.5 \pm 0.6) \times 10^{-5}$		-
$\psi(4415)K^+, \psi \rightarrow D^+D^-$	$(2.0 \pm 0.8) \times 10^{-5}$		-
$\psi(4415)K^+, \psi \rightarrow J/\psi\eta$	$< 9.6 \times 10^{-7}$	CL=90%	-
$\chi_{c0}\pi^+, \chi_{c0} \rightarrow \pi^+\pi^-$	$< 1 \times 10^{-7}$	CL=90%	1531
$\chi_{c0}\pi^+, \chi_{c0} \rightarrow \pi^0\pi^0$	$< 5 \times 10^{-7}$	CL=90%	-
$\chi_{c0}K^+$	$(1.51 \pm \frac{0.15}{0.13}) \times 10^{-4}$		1478
$\chi_{c0}K^0\pi^+$	$(1.45 \pm 0.21) \times 10^{-3}$		1439
$\chi_{c0}K^*(892)^+$	$< 2.1 \times 10^{-4}$	CL=90%	1341
$\chi_{c1}(1P)\pi^+$	$(2.2 \pm 0.5) \times 10^{-5}$		1468
$\chi_{c1}(1P)K^+$	$(4.74 \pm 0.22) \times 10^{-4}$		1412
$\chi_{c1}(1P)K^*(892)^+$	$(3.0 \pm 0.6) \times 10^{-4}$	S=1.1	1265
$\chi_{c1}(1P)K^0\pi^+$	$(5.8 \pm 0.4) \times 10^{-4}$		1370
$\chi_{c1}(1P)K^+\pi^0$	$(3.29 \pm 0.35) \times 10^{-4}$		1373
$\chi_{c1}(1P)K^+\pi^+\pi^-$	$(3.74 \pm 0.30) \times 10^{-4}$		1319
$\chi_{c1}(2P)K^+, \chi_{c1}(2P) \rightarrow \pi^+\pi^-\chi_{c1}(1P)$	$< 1.1 \times 10^{-5}$	CL=90%	-
$\chi_{c2}\pi^+, \chi_{c2} \rightarrow \pi^0\pi^0$	$< 7 \times 10^{-7}$	CL=90%	-
$\chi_{c2}K^+$	$(1.1 \pm 0.4) \times 10^{-5}$		1379
$\chi_{c2}K^+, \chi_{c2} \rightarrow \rho\bar{p}\pi^+\pi^-$	$< 1.9 \times 10^{-7}$		-
$\chi_{c2}K^*(892)^+$	$< 1.2 \times 10^{-4}$	CL=90%	1228
$\chi_{c2}K^0\pi^+$	$(1.24 \pm 0.25) \times 10^{-4}$		1336
$\chi_{c2}K^+\pi^0$	$< 6.2 \times 10^{-5}$	CL=90%	1339
$\chi_{c2}K^+\pi^+\pi^-$	$(1.34 \pm 0.19) \times 10^{-4}$		1284
$\chi_{c2}(3930)K^+, \chi_{c2} \rightarrow D^+D^-$	$(1.6 \pm 0.6) \times 10^{-5}$		-

$\chi_{c2}(3930)\pi^+$ , $\chi_{c2} \rightarrow \pi^+\pi^-$	< 1	$\times 10^{-7}$	CL=90%	1437
$h_c(1P)K^+$	( 3.7 $\pm$ 1.2 )	$\times 10^{-5}$		1401
$h_c(1P)K^+$ , $h_c \rightarrow p\bar{p}$	< 6.4	$\times 10^{-8}$	CL=95%	-
<b>K or K* modes</b>				
$K^0\pi^+$	( 2.39 $\pm$ 0.06 )	$\times 10^{-5}$		2614
$K^+\pi^0$	( 1.32 $\pm$ 0.04 )	$\times 10^{-5}$		2615
$\eta'K^+$	( 7.04 $\pm$ 0.25 )	$\times 10^{-5}$		2528
$\eta'K^*(892)^+$	( 4.8 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 1.8 / 1.6 )	$\times 10^{-6}$		2472
$\eta'K_0^*(1430)^+$	( 5.2 $\pm$ 2.1 )	$\times 10^{-6}$		-
$\eta'K_2^*(1430)^+$	( 2.8 $\pm$ 0.5 )	$\times 10^{-5}$		2346
$\eta K^+$	( 2.4 $\pm$ 0.4 )	$\times 10^{-6}$	S=1.7	2588
$\eta K^*(892)^+$	( 1.93 $\pm$ 0.16 )	$\times 10^{-5}$		2534
$\eta K_0^*(1430)^+$	( 1.8 $\pm$ 0.4 )	$\times 10^{-5}$		-
$\eta K_2^*(1430)^+$	( 9.1 $\pm$ 3.0 )	$\times 10^{-6}$		2414
$\eta(1295)K^+ \times B(\eta(1295) \rightarrow \eta\pi\pi)$	( 2.9 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.8 / 0.7 )	$\times 10^{-6}$		2455
$\eta(1405)K^+ \times B(\eta(1405) \rightarrow \eta\pi\pi)$	< 1.3	$\times 10^{-6}$	CL=90%	2425
$\eta(1405)K^+ \times B(\eta(1405) \rightarrow K^*K)$	< 1.2	$\times 10^{-6}$	CL=90%	2425
$\eta(1475)K^+ \times B(\eta(1475) \rightarrow K^*K)$	( 1.38 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.21 / 0.18 )	$\times 10^{-5}$		2406
$f_1(1285)K^+$	< 2.0	$\times 10^{-6}$	CL=90%	2458
$f_1(1420)K^+ \times B(f_1(1420) \rightarrow \eta\pi\pi)$	< 2.9	$\times 10^{-6}$	CL=90%	2420
$f_1(1420)K^+ \times B(f_1(1420) \rightarrow K^*K)$	< 4.1	$\times 10^{-6}$	CL=90%	2420
$\phi(1680)K^+ \times B(\phi(1680) \rightarrow K^*K)$	< 3.4	$\times 10^{-6}$	CL=90%	2344
$f_0(1500)K^+$	( 3.7 $\pm$ 2.2 )	$\times 10^{-6}$		2393
$\omega K^+$	( 6.5 $\pm$ 0.4 )	$\times 10^{-6}$		2558
$\omega K^*(892)^+$	< 7.4	$\times 10^{-6}$	CL=90%	2503
$\omega(K\pi)_0^{*+}$	( 2.8 $\pm$ 0.4 )	$\times 10^{-5}$		-
$\omega K_0^*(1430)^+$	( 2.4 $\pm$ 0.5 )	$\times 10^{-5}$		-
$\omega K_2^*(1430)^+$	( 2.1 $\pm$ 0.4 )	$\times 10^{-5}$		2379
$a_0(980)^+ K^0 \times B(a_0(980)^+ \rightarrow \eta\pi^+)$	< 3.9	$\times 10^{-6}$	CL=90%	-
$a_0(980)^0 K^+ \times B(a_0(980)^0 \rightarrow \eta\pi^0)$	< 2.5	$\times 10^{-6}$	CL=90%	-
$K^*(892)^0\pi^+$	( 1.01 $\pm$ 0.08 )	$\times 10^{-5}$		2562
$K^*(892)^+\pi^0$	( 6.8 $\pm$ 0.9 )	$\times 10^{-6}$		2563
$K^+\pi^-\pi^+$	( 5.10 $\pm$ 0.29 )	$\times 10^{-5}$		2609
$K^+\pi^-\pi^+$ nonresonant	( 1.63 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.21 / 0.15 )	$\times 10^{-5}$		2609
$\omega(782)K^+$	( 6 $\pm$ 9 )	$\times 10^{-6}$		2558
$K^+ f_0(980) \times B(f_0(980) \rightarrow \pi^+\pi^-)$	( 9.4 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 1.0 / 1.2 )	$\times 10^{-6}$		2522
$f_2(1270)^0 K^+$	( 1.07 $\pm$ 0.27 )	$\times 10^{-6}$		-
$f_0(1370)^0 K^+ \times B(f_0(1370)^0 \rightarrow \pi^+\pi^-)$	< 1.07	$\times 10^{-5}$	CL=90%	-
$\rho(14500)K^+ \times B(\rho(1450)^0 \rightarrow \pi^+\pi^-)$	< 1.17	$\times 10^{-5}$	CL=90%	-

$f'_2(1525)K^+ \times B(f'_2(1525) \rightarrow \pi^+ \pi^-)$	< 3.4	$\times 10^{-6}$	CL=90%	2394
$K^+ \rho^0$	( 3.7 $\pm$ 0.5 )	$\times 10^{-6}$		2559
$K_0^*(1430)^0 \pi^+$	( 3.9 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.6 / 0.5 )	$\times 10^{-5}$	S=1.4	2445
$K_2^*(1430)^0 \pi^+$	( 5.6 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 2.2 / 1.5 )	$\times 10^{-6}$		2445
$K^*(1410)^0 \pi^+$	< 4.5	$\times 10^{-5}$	CL=90%	2448
$K^*(1680)^0 \pi^+$	< 1.2	$\times 10^{-5}$	CL=90%	2358
$K^+ \pi^0 \pi^0$	( 1.62 $\pm$ 0.19 )	$\times 10^{-5}$		2610
$f_0(980)K^+ \times B(f_0 \rightarrow \pi^0 \pi^0)$	( 2.8 $\pm$ 0.8 )	$\times 10^{-6}$		2522
$K^- \pi^+ \pi^+$	< 4.6	$\times 10^{-8}$	CL=90%	2609
$K^- \pi^+ \pi^+$ nonresonant	< 5.6	$\times 10^{-5}$	CL=90%	2609
$K_1(1270)^0 \pi^+$	< 4.0	$\times 10^{-5}$	CL=90%	2489
$K_1(1400)^0 \pi^+$	< 3.9	$\times 10^{-5}$	CL=90%	2451
$K^0 \pi^+ \pi^0$	< 6.6	$\times 10^{-5}$	CL=90%	2609
$K_0^*(1430)^+ \pi^0$	( 1.19 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.20 / 0.23 )	$\times 10^{-5}$		-
$K^0 \rho^+$	( 7.3 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 1.0 / 1.2 )	$\times 10^{-6}$		2558
$K^*(892)^+ \pi^+ \pi^-$	( 7.5 $\pm$ 1.0 )	$\times 10^{-5}$		2557
$K^*(892)^+ \rho^0$	( 4.6 $\pm$ 1.1 )	$\times 10^{-6}$		2504
$K^*(892)^+ f_0(980)$	( 4.2 $\pm$ 0.7 )	$\times 10^{-6}$		2466
$a_1^+ K^0$	( 3.5 $\pm$ 0.7 )	$\times 10^{-5}$		-
$b_1^+ K^0 \times B(b_1^+ \rightarrow \omega \pi^+)$	( 9.6 $\pm$ 1.9 )	$\times 10^{-6}$		-
$K^*(892)^0 \rho^+$	( 9.2 $\pm$ 1.5 )	$\times 10^{-6}$		2504
$K_1(1400)^+ \rho^0$	< 7.8	$\times 10^{-4}$	CL=90%	2388
$K_2^*(1430)^+ \rho^0$	< 1.5	$\times 10^{-3}$	CL=90%	2381
$b_1^0 K^+ \times B(b_1^0 \rightarrow \omega \pi^0)$	( 9.1 $\pm$ 2.0 )	$\times 10^{-6}$		-
$b_1^+ K^{*0} \times B(b_1^+ \rightarrow \omega \pi^+)$	< 5.9	$\times 10^{-6}$	CL=90%	-
$b_1^0 K^{*+} \times B(b_1^0 \rightarrow \omega \pi^0)$	< 6.7	$\times 10^{-6}$	CL=90%	-
$K^+ \bar{K}^0$	( 1.32 $\pm$ 0.17 )	$\times 10^{-6}$	S=1.2	2593
$\bar{K}^0 K^+ \pi^0$	< 2.4	$\times 10^{-5}$	CL=90%	2578
$K^+ K_S^0 K_S^0$	( 1.05 $\pm$ 0.04 )	$\times 10^{-5}$		2521
$f_0(980)K^+, f_0 \rightarrow K_S^0 K_S^0$	( 1.47 $\pm$ 0.33 )	$\times 10^{-5}$		-
$f_0(1710)K^+, f_0 \rightarrow K_S^0 K_S^0$	( 4.8 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 4.0 / 2.6 )	$\times 10^{-7}$		-
$K^+ K_S^0 K_S^0$ nonresonant	( 2.0 $\pm$ 0.4 )	$\times 10^{-5}$		2521
$K_S^0 K_S^0 \pi^+$	< 5.1	$\times 10^{-7}$	CL=90%	2577
$K^+ K^- \pi^+$	( 5.2 $\pm$ 0.4 )	$\times 10^{-6}$		2578
$K^+ K^- \pi^+$ nonresonant	( 1.68 $\pm$ 0.26 )	$\times 10^{-6}$		2578
$K^+ \bar{K}^*(892)^0$	( 5.9 $\pm$ 0.8 )	$\times 10^{-7}$		2540
$K^+ \bar{K}_0^*(1430)^0$	( 3.8 $\pm$ 1.3 )	$\times 10^{-7}$		2421
$\pi^+ (K^+ K^-)_{S\text{-wave}}$	( 8.5 $\pm$ 0.9 )	$\times 10^{-7}$		2578
$\pi^+ K^+ K^-, m_{K^+ K^-} < 1.1$ GeV	( 5.4 $\pm$ 0.5 )	$\times 10^{-6}$		-
$K^+ K^+ \pi^-$	< 1.1	$\times 10^{-8}$	CL=90%	2578
$K^+ K^+ \pi^-$ nonresonant	< 8.79	$\times 10^{-5}$	CL=90%	2578
$f'_2(1525)K^+$	( 1.8 $\pm$ 0.5 )	$\times 10^{-6}$	S=1.1	2394
$K^{*+} \pi^+ K^-$	< 1.18	$\times 10^{-5}$	CL=90%	2524
$K^*(892)^+ K^*(892)^0$	( 9.1 $\pm$ 2.9 )	$\times 10^{-7}$		2485
$K^{*+} K^+ \pi^-$	< 6.1	$\times 10^{-6}$	CL=90%	2524
$K^+ K^- K^+$	( 3.40 $\pm$ 0.14 )	$\times 10^{-5}$	S=1.4	2523
$K^+ \phi$	( 8.8 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.7 / 0.6 )	$\times 10^{-6}$	S=1.1	2516

$f_0(980)K^+ \times B(f_0(980) \rightarrow K^+K^-)$	$(9.4 \pm 3.2) \times 10^{-6}$		2522
$a_2(1320)K^+ \times B(a_2(1320) \rightarrow K^+K^-)$	$< 1.1 \times 10^{-6}$	CL=90%	2449
$X_0(1550)K^+ \times B(X_0(1550) \rightarrow K^+K^-)$	$(4.3 \pm 0.7) \times 10^{-6}$		—
$\phi(1680)K^+ \times B(\phi(1680) \rightarrow K^+K^-)$	$< 8 \times 10^{-7}$	CL=90%	2344
$f_0(1710)K^+ \times B(f_0(1710) \rightarrow K^+K^-)$	$(1.1 \pm 0.6) \times 10^{-6}$		2327
$K^+K^-K^+$ nonresonant	$(2.38 \pm_{-0.50}^{+0.28}) \times 10^{-5}$		2523
$K^*(892)^+K^+K^-$	$(3.6 \pm 0.5) \times 10^{-5}$		2466
$K^*(892)^+\phi$	$(10.0 \pm 2.0) \times 10^{-6}$	S=1.7	2460
$K^0K^+K^-\pi^+$	$(3.40 \pm 0.33) \times 10^{-4}$		2494
$J/\psi K^+, J/\psi \rightarrow K^0K^-\pi^+$	$(5.4 \pm 1.2) \times 10^{-6}$		—
$\chi_{c1}K^+, \chi_{c1} \rightarrow K^0K^-\pi^+$	$(2.25 \pm 0.25) \times 10^{-6}$		—
$\eta_c K^+, \eta_c \rightarrow K^0K^-\pi^+$	$(2.83 \pm 0.30) \times 10^{-5}$		—
$\eta_c(2S)K^+, \eta_c(2S) \rightarrow K^0K^-\pi^+$	$(3.3 \pm 0.4) \times 10^{-6}$		—
$K^0K^+K^+\pi^-$	$(2.80 \pm 0.30) \times 10^{-4}$		2494
$J/\psi K^+, J/\psi \rightarrow K^0K^+\pi^-$	$(5.4 \pm 1.3) \times 10^{-6}$		—
$\chi_{c1}K^+, \chi_{c1} \rightarrow K^0K^+\pi^-$	$(2.06 \pm 0.32) \times 10^{-6}$		—
$\eta_c K^+, \eta_c \rightarrow K^0K^+\pi^-$	$(3.00 \pm 0.34) \times 10^{-5}$		—
$\eta_c(2S)K^+, \eta_c(2S) \rightarrow K^0K^+\pi^-$	$(3.1 \pm 0.6) \times 10^{-6}$		—
$\phi(K\pi)_0^{*+}$	$(8.3 \pm 1.6) \times 10^{-6}$		—
$\phi K_1(1270)^+$	$(6.1 \pm 1.9) \times 10^{-6}$		2380
$\phi K_1(1400)^+$	$< 3.2 \times 10^{-6}$	CL=90%	2339
$\phi K^*(1410)^+$	$< 4.3 \times 10^{-6}$	CL=90%	—
$\phi K_0^*(1430)^+$	$(7.0 \pm 1.6) \times 10^{-6}$		—
$\phi K_2^*(1430)^+$	$(8.4 \pm 2.1) \times 10^{-6}$		2332
$\phi K_2^*(1770)^+$	$< 1.50 \times 10^{-5}$	CL=90%	—
$\phi K_2^*(1820)^+$	$< 1.63 \times 10^{-5}$	CL=90%	—
$a_1^+K^{*0}$	$< 3.6 \times 10^{-6}$	CL=90%	—
$K^+\phi\phi$	$(4.2 \pm 0.8) \times 10^{-6}$	S=2.2	2306
$\eta'\eta'K^+$	$< 2.5 \times 10^{-5}$	CL=90%	2339
$\omega\phi K^+$	$< 1.9 \times 10^{-6}$	CL=90%	2374
$X(1812)K^+ \times B(X \rightarrow \omega\phi)$	$< 3.2 \times 10^{-7}$	CL=90%	—
$K^*(892)^+\gamma$	$(3.92 \pm 0.22) \times 10^{-5}$	S=1.7	2564
$K_1(1270)^+\gamma$	$(4.4 \pm_{-0.6}^{+0.7}) \times 10^{-5}$		2491
$\eta K^+\gamma$	$(7.9 \pm 0.9) \times 10^{-6}$		2588
$\eta'K^+\gamma$	$(2.9 \pm_{-0.9}^{+1.0}) \times 10^{-6}$		2528
$\phi K^+\gamma$	$(2.7 \pm 0.4) \times 10^{-6}$	S=1.2	2516
$K^+\pi^-\pi^+\gamma$	$(2.58 \pm 0.15) \times 10^{-5}$	S=1.3	2609
$K^*(892)^0\pi^+\gamma$	$(2.33 \pm 0.12) \times 10^{-5}$		2562
$K^+\rho^0\gamma$	$(8.2 \pm 0.9) \times 10^{-6}$		2559
$(K^+\pi^-)_{NR}\pi^+\gamma$	$(9.9 \pm_{-2.0}^{+1.7}) \times 10^{-6}$		2609
$K^0\pi^+\pi^0\gamma$	$(4.6 \pm 0.5) \times 10^{-5}$		2609
$K_1(1400)^+\gamma$	$(10 \pm_{-4}^{+5}) \times 10^{-6}$		2453
$K^*(1410)^+\gamma$	$(2.7 \pm_{-0.6}^{+0.8}) \times 10^{-5}$		—
$K_0^*(1430)^0\pi^+\gamma$	$(1.32 \pm_{-0.32}^{+0.26}) \times 10^{-6}$		2445

$K_2^*(1430)^+ \gamma$	$( 1.4 \pm 0.4 ) \times 10^{-5}$		2447
$K^*(1680)^+ \gamma$	$( 6.7 \begin{smallmatrix} + 1.7 \\ - 1.4 \end{smallmatrix} ) \times 10^{-5}$		2360
$K_3^*(1780)^+ \gamma$	$< 3.9 \times 10^{-5}$	CL=90%	2340
$K_4^*(2045)^+ \gamma$	$< 9.9 \times 10^{-3}$	CL=90%	2242

**Light unflavored meson modes**

$\rho^+ \gamma$	$( 9.8 \pm 2.5 ) \times 10^{-7}$		2583
$\pi^+ \pi^0$	$( 5.31 \pm 0.26 ) \times 10^{-6}$		2636
$\pi^+ \pi^+ \pi^-$	$( 1.52 \pm 0.14 ) \times 10^{-5}$		2630
$\rho^0 \pi^+$	$( 8.3 \pm 1.2 ) \times 10^{-6}$		2581
$\pi^+ f_0(980), f_0 \rightarrow \pi^+ \pi^-$	$< 1.5 \times 10^{-6}$	CL=90%	2545
$\pi^+ f_2(1270)$	$( 2.2 \begin{smallmatrix} + 0.7 \\ - 0.4 \end{smallmatrix} ) \times 10^{-6}$		2484
$\rho(1450)^0 \pi^+, \rho^0 \rightarrow \pi^+ \pi^-$	$( 1.4 \begin{smallmatrix} + 0.6 \\ - 0.9 \end{smallmatrix} ) \times 10^{-6}$		2434
$\rho(1450)^0 \pi^+, \rho^0 \rightarrow K^+ K^-$	$( 1.60 \pm 0.14 ) \times 10^{-6}$		-
$f_0(1370) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$< 4.0 \times 10^{-6}$	CL=90%	2460
$f_0(1370) \pi^+, f_0 \rightarrow \pi^0 \pi^0$	$< 1.1 \times 10^{-6}$	CL=90%	-
$f_0(500) \pi^+, f_0 \rightarrow \pi^+ \pi^-$	$< 4.1 \times 10^{-6}$	CL=90%	-
$\pi^+ \pi^- \pi^+$ nonresonant	$( 5.3 \begin{smallmatrix} + 1.5 \\ - 1.1 \end{smallmatrix} ) \times 10^{-6}$		2630
$\pi^+ \pi^0 \pi^0$	$( 1.90 \pm 0.21 ) \times 10^{-5}$		2631
$\rho^+ \pi^0$	$( 1.06 \begin{smallmatrix} + 0.12 \\ - 0.13 \end{smallmatrix} ) \times 10^{-5}$		2581
$\rho(1450)^+ \pi^0, \rho^+ \rightarrow \pi^+ \pi^0$	$( 1.2 \pm 0.6 ) \times 10^{-6}$		-
$\pi^+ \pi^0 \pi^0$ nonresonant	$< 6 \times 10^{-7}$	CL=90%	2631
$X p i^+, X \rightarrow \pi^0 \pi^0$	$( 6.9 \pm 1.1 ) \times 10^{-6}$		-
$\pi^+ \pi^- \pi^+ \pi^0$	$< 4.0 \times 10^{-3}$	CL=90%	2622
$\rho^+ \rho^0$	$( 2.40 \pm 0.19 ) \times 10^{-5}$		2523
$\rho^+ f_0(980), f_0 \rightarrow \pi^+ \pi^-$	$< 2.0 \times 10^{-6}$	CL=90%	2486
$a_1(1260)^+ \pi^0$	$( 2.6 \pm 0.7 ) \times 10^{-5}$		2494
$a_1(1260)^0 \pi^+$	$( 2.0 \pm 0.6 ) \times 10^{-5}$		2494
$\omega \pi^+$	$( 6.9 \pm 0.5 ) \times 10^{-6}$		2580
$\omega \rho^+$	$( 1.59 \pm 0.21 ) \times 10^{-5}$		2522
$\eta \pi^+$	$( 4.02 \pm 0.27 ) \times 10^{-6}$		2609
$\eta \rho^+$	$( 7.0 \pm 2.9 ) \times 10^{-6}$	S=2.8	2553
$\eta' \pi^+$	$( 2.7 \pm 0.9 ) \times 10^{-6}$	S=1.9	2551
$\eta' \rho^+$	$( 9.7 \pm 2.2 ) \times 10^{-6}$		2492
$\phi \pi^+$	$( 3.2 \pm 1.5 ) \times 10^{-8}$		2539
$\phi \rho^+$	$< 3.0 \times 10^{-6}$	CL=90%	2480
$a_0(980)^0 \pi^+, a_0^0 \rightarrow \eta \pi^0$	$< 5.8 \times 10^{-6}$	CL=90%	-
$a_0(980)^+ \pi^0, a_0^+ \rightarrow \eta \pi^+$	$< 1.4 \times 10^{-6}$	CL=90%	-
$\pi^+ \pi^+ \pi^+ \pi^- \pi^-$	$< 8.6 \times 10^{-4}$	CL=90%	2608
$\rho^0 a_1(1260)^+$	$< 6.2 \times 10^{-4}$	CL=90%	2433
$\rho^0 a_2(1320)^+$	$< 7.2 \times 10^{-4}$	CL=90%	2410
$b_1^0 \pi^+, b_1^0 \rightarrow \omega \pi^0$	$( 6.7 \pm 2.0 ) \times 10^{-6}$		-
$b_1^+ \pi^0, b_1^+ \rightarrow \omega \pi^+$	$< 3.3 \times 10^{-6}$	CL=90%	-
$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0$	$< 6.3 \times 10^{-3}$	CL=90%	2592
$b_1^+ \rho^0, b_1^+ \rightarrow \omega \pi^+$	$< 5.2 \times 10^{-6}$	CL=90%	-
$a_1(1260)^+ a_1(1260)^0$	$< 1.3 \%$	CL=90%	2336
$b_1^0 \rho^+, b_1^0 \rightarrow \omega \pi^0$	$< 3.3 \times 10^{-6}$	CL=90%	-

**Charged particle ( $h^\pm$ ) modes**

$$h^\pm = K^\pm \text{ or } \pi^\pm$$

$h^+ \pi^0$	$( 1.6 \begin{smallmatrix} + 0.7 \\ - 0.6 \end{smallmatrix} ) \times 10^{-5}$		2636
-------------	---	--	------



$\omega h^+$	( 1.38 $\pm$ 0.27 $-$ 0.24 ) $\times 10^{-5}$		2580
$h^+ X^0$ (Familon)	< 4.9	$\times 10^{-5}$	CL=90% -
$K^+ X^0, X^0 \rightarrow \mu^+ \mu^-$	< 1	$\times 10^{-7}$	CL=95% -
<b>Baryon modes</b>			
$p\bar{p}\pi^+$	( 1.62 $\pm$ 0.20 ) $\times 10^{-6}$		2439
$p\bar{p}\pi^+$ nonresonant	< 5.3	$\times 10^{-5}$	CL=90% 2439
$p\bar{p}\pi^+\pi^0$	( 4.6 $\pm$ 1.3 ) $\times 10^{-6}$		2407
$p\bar{p}K^+$	( 5.9 $\pm$ 0.5 ) $\times 10^{-6}$		S=1.5 2348
$\Theta(1710)^{++}\bar{p}, \Theta^{++} \rightarrow pK^+[000]$	< 9.1	$\times 10^{-8}$	CL=90% -
$f_J(2220)K^+, f_J \rightarrow p\bar{p}$ [000]	< 4.1	$\times 10^{-7}$	CL=90% 2135
$p\bar{n}\pi^0$	< 6.3	$\times 10^{-6}$	CL=90% 2440
$p\bar{\Lambda}(1520)$	( 3.1 $\pm$ 0.6 ) $\times 10^{-7}$		2322
$p\bar{p}K^+$ nonresonant	< 8.9	$\times 10^{-5}$	CL=90% 2348
$p\bar{p}K^*(892)^+$	( 3.6 $\pm$ 0.8 $-$ 0.7 ) $\times 10^{-6}$		2215
$f_J(2220)K^{*+}, f_J \rightarrow p\bar{p}$	< 7.7	$\times 10^{-7}$	CL=90% 2059
$p\bar{\Lambda}$	( 2.4 $\pm$ 1.0 $-$ 0.9 ) $\times 10^{-7}$		2430
$p\bar{\Lambda}\gamma$	( 2.4 $\pm$ 0.5 $-$ 0.4 ) $\times 10^{-6}$		2430
$p\bar{\Lambda}\pi^0$	( 3.0 $\pm$ 0.7 $-$ 0.6 ) $\times 10^{-6}$		2402
$p\bar{\Sigma}(1385)^0$	< 4.7	$\times 10^{-7}$	CL=90% 2362
$\Delta^+\bar{\Lambda}$	< 8.2	$\times 10^{-7}$	CL=90% -
$p\bar{\Sigma}\gamma$	< 4.6	$\times 10^{-6}$	CL=90% 2413
$p\bar{\Lambda}\pi^+\pi^-$	( 1.13 $\pm$ 0.13 ) $\times 10^{-5}$		2368
$p\bar{\Lambda}\pi^+\pi^-$ nonresonant	( 5.9 $\pm$ 1.1 ) $\times 10^{-6}$		2368
$p\bar{\Lambda}\rho^0, \rho^0 \rightarrow \pi^+\pi^-$	( 4.8 $\pm$ 0.9 ) $\times 10^{-6}$		2214
$p\bar{\Lambda}f_2(1270), f_2 \rightarrow \pi^+\pi^-$	( 2.0 $\pm$ 0.8 ) $\times 10^{-6}$		2026
$p\bar{\Lambda}K^+K^-$	( 4.1 $\pm$ 0.7 ) $\times 10^{-6}$		2132
$p\bar{\Lambda}\phi$	( 8.0 $\pm$ 2.2 ) $\times 10^{-7}$		2119
$\bar{p}\Lambda K^+K^-$	( 3.7 $\pm$ 0.6 ) $\times 10^{-6}$		2132
$\Lambda\bar{\Lambda}\pi^+$	< 9.4	$\times 10^{-7}$	CL=90% 2358
$\Lambda\bar{\Lambda}K^+$	( 3.4 $\pm$ 0.6 ) $\times 10^{-6}$		2251
$\Lambda\bar{\Lambda}K^{*+}$	( 2.2 $\pm$ 1.2 $-$ 0.9 ) $\times 10^{-6}$		2098
$\Lambda(1520)\bar{\Lambda}K^+$	( 2.2 $\pm$ 0.7 ) $\times 10^{-6}$		2126
$\Lambda\bar{\Lambda}(1520)K^+$	< 2.08	$\times 10^{-6}$	2126
$\bar{\Delta}^0\rho$	< 1.38	$\times 10^{-6}$	CL=90% 2403
$\Delta^{++}\bar{p}$	< 1.4	$\times 10^{-7}$	CL=90% 2403
$D^+p\bar{p}$	< 1.5	$\times 10^{-5}$	CL=90% 1860
$D^*(2010)^+p\bar{p}$	< 1.5	$\times 10^{-5}$	CL=90% 1786
$\bar{D}^0p\bar{p}\pi^+$	( 3.72 $\pm$ 0.27 ) $\times 10^{-4}$		1789
$\bar{D}^{*0}p\bar{p}\pi^+$	( 3.73 $\pm$ 0.32 ) $\times 10^{-4}$		1709
$D^-p\bar{p}\pi^+\pi^-$	( 1.66 $\pm$ 0.30 ) $\times 10^{-4}$		1705
$D^{*-}p\bar{p}\pi^+\pi^-$	( 1.86 $\pm$ 0.25 ) $\times 10^{-4}$		1621
$p\bar{\Lambda}^0\bar{D}^0$	( 1.43 $\pm$ 0.32 ) $\times 10^{-5}$		-
$p\bar{\Lambda}^0\bar{D}^*(2007)^0$	< 5	$\times 10^{-5}$	CL=90% -
$\bar{\Lambda}_c^-p\pi^+$	( 2.3 $\pm$ 0.4 ) $\times 10^{-4}$		S=2.4 1980
$\bar{\Lambda}_c^- \Delta(1232)^{++}$	< 1.9	$\times 10^{-5}$	CL=90% 1928
$\bar{\Lambda}_c^- \Delta_X(1600)^{++}$	( 4.7 $\pm$ 1.0 ) $\times 10^{-5}$		-
$\bar{\Lambda}_c^- \Delta_X(2420)^{++}$	( 3.8 $\pm$ 0.8 ) $\times 10^{-5}$		-
$(\bar{\Lambda}_c^- p)_s \pi^+$	[ppp] ( 3.1 $\pm$ 0.7 ) $\times 10^{-5}$		-
$\bar{\Sigma}_c(2520)^0\rho$	< 3	$\times 10^{-6}$	CL=90% 1904
$\bar{\Sigma}_c(2800)^0\rho$	( 2.7 $\pm$ 0.9 ) $\times 10^{-5}$		-

$\bar{\Lambda}_c^- p \pi^+ \pi^0$	( 1.8 ± 0.6 ) × 10 <sup>-3</sup>	1935
$\bar{\Lambda}_c^- p \pi^+ \pi^- \pi^0$	( 2.2 ± 0.7 ) × 10 <sup>-3</sup>	1880
$\bar{\Lambda}_c^- p \pi^+ \pi^- \pi^0$	< 1.34 %	CL=90% 1823
$\Lambda_c^+ \Lambda_c^- K^+$	( 4.9 ± 0.7 ) × 10 <sup>-4</sup>	739
$\Xi_c(2930) \Lambda_c^+, \Xi_c \rightarrow K^+ \Lambda_c^-$	( 1.7 ± 0.5 ) × 10 <sup>-4</sup>	-
$\bar{\Sigma}_c(2455)^0 p$	( 3.0 ± 0.7 ) × 10 <sup>-5</sup>	1938
$\bar{\Sigma}_c(2455)^0 p \pi^0$	( 3.5 ± 1.1 ) × 10 <sup>-4</sup>	1896
$\bar{\Sigma}_c(2455)^0 p \pi^- \pi^+$	( 3.5 ± 1.1 ) × 10 <sup>-4</sup>	1845
$\bar{\Sigma}_c(2455)^{-} p \pi^+ \pi^+$	( 2.38 ± 0.19 ) × 10 <sup>-4</sup>	1845
$\bar{\Lambda}_c(2593)^- / \bar{\Lambda}_c(2625)^- p \pi^+$	< 1.9 × 10 <sup>-4</sup>	CL=90% -
$\Xi_c^0 \Lambda_c^+$	( 9.5 ± 2.3 ) × 10 <sup>-4</sup>	1144
$\Xi_c^0 \Lambda_c^+, \Xi_c^0 \rightarrow \Xi^+ \pi^-$	( 1.76 ± 0.29 ) × 10 <sup>-5</sup>	1144
$\Xi_c^0 \Lambda_c^+, \Xi_c^0 \rightarrow \Lambda K^+ \pi^-$	( 1.14 ± 0.26 ) × 10 <sup>-5</sup>	1144
$\Xi_c^0 \Lambda_c^+, \Xi_c^0 \rightarrow p K^- K^- \pi^+$	( 5.5 ± 1.9 ) × 10 <sup>-6</sup>	-
$\Lambda_c^+ \Xi_c^0$	< 6.5 × 10 <sup>-4</sup>	CL=90% 1023
$\Lambda_c^+ \Xi_c(2645)^0$	< 7.9 × 10 <sup>-4</sup>	CL=90% -
$\Lambda_c^+ \Xi_c(2790)^0$	( 1.1 ± 0.4 ) × 10 <sup>-3</sup>	-

**Lepton Family number (LF) or Lepton number (L) or Baryon number (B)  
violating modes, or/and  $\Delta B = 1$  weak neutral current (BI) modes**

$\pi^+ \ell^+ \ell^-$	BI [hhh] < 4.9 × 10 <sup>-8</sup>	CL=90% 2638
$\pi^+ e^+ e^-$	BI < 8.0 × 10 <sup>-8</sup>	CL=90% 2638
$\pi^+ \mu^+ \mu^-$	BI ( 1.78 ± 0.23 ) × 10 <sup>-8</sup>	2634
$\pi^+ \nu \bar{\nu}$	BI < 1.4 × 10 <sup>-5</sup>	CL=90% 2638
$K^+ \ell^+ \ell^-$	BI [hhh] ( 4.7 ± 0.5 ) × 10 <sup>-7</sup>	S=2.3 2617
$K^+ e^+ e^-$	BI ( 5.6 ± 0.6 ) × 10 <sup>-7</sup>	2617
$K^+ \mu^+ \mu^-$	BI ( 4.53 ± 0.35 ) × 10 <sup>-7</sup>	S=1.8 2612
$K^+ \mu^+ \mu^-$ nonresonant	BI ( 4.37 ± 0.27 ) × 10 <sup>-7</sup>	2612
$K^+ \tau^+ \tau^-$	BI < 2.25 × 10 <sup>-3</sup>	CL=90% 1687
$K^+ \bar{\nu} \nu$	BI < 1.6 × 10 <sup>-5</sup>	CL=90% 2617
$\rho^+ \nu \bar{\nu}$	BI < 3.0 × 10 <sup>-5</sup>	CL=90% 2583
$K^*(892)^+ \ell^+ \ell^-$	BI [hhh] ( 1.01 ± 0.11 ) × 10 <sup>-6</sup>	S=1.1 2564
$K^*(892)^+ e^+ e^-$	BI ( 1.55 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ $\begin{smallmatrix} 0.40 \\ 0.31 \end{smallmatrix}$ ) × 10 <sup>-6</sup>	2564
$K^*(892)^+ \mu^+ \mu^-$	BI ( 9.6 ± 1.0 ) × 10 <sup>-7</sup>	2560
$K^*(892)^+ \nu \bar{\nu}$	BI < 4.0 × 10 <sup>-5</sup>	CL=90% 2564
$K^+ \pi^+ \pi^- \mu^+ \mu^-$	BI ( 4.3 ± 0.4 ) × 10 <sup>-7</sup>	2593
$\phi K^+ \mu^+ \mu^-$	BI ( 7.9 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ $\begin{smallmatrix} 2.1 \\ 1.7 \end{smallmatrix}$ ) × 10 <sup>-8</sup>	2490
$\bar{\Lambda} p \nu \bar{\nu}$	BI < 3.0 × 10 <sup>-5</sup>	CL=90% 2430
$\pi^+ e^+ \mu^-$	LF < 6.4 × 10 <sup>-3</sup>	CL=90% 2637
$\pi^+ e^- \mu^+$	LF < 6.4 × 10 <sup>-3</sup>	CL=90% 2637
$\pi^+ e^\pm \mu^\mp$	LF < 1.7 × 10 <sup>-7</sup>	CL=90% 2637
$\pi^+ e^+ \tau^-$	LF < 7.4 × 10 <sup>-5</sup>	CL=90% 2338
$\pi^+ e^- \tau^+$	LF < 2.0 × 10 <sup>-5</sup>	CL=90% 2338
$\pi^+ e^\pm \tau^\mp$	LF < 7.5 × 10 <sup>-5</sup>	CL=90% 2338
$\pi^+ \mu^+ \tau^-$	LF < 6.2 × 10 <sup>-5</sup>	CL=90% 2334
$\pi^+ \mu^- \tau^+$	LF < 4.5 × 10 <sup>-5</sup>	CL=90% 2334
$\pi^+ \mu^\pm \tau^\mp$	LF < 7.2 × 10 <sup>-5</sup>	CL=90% 2334
$K^+ e^+ \mu^-$	LF < 7.0 × 10 <sup>-9</sup>	CL=90% 2616
$K^+ e^- \mu^+$	LF < 6.4 × 10 <sup>-9</sup>	CL=90% 2616
$K^+ e^\pm \mu^\mp$	LF < 9.1 × 10 <sup>-8</sup>	CL=90% 2616
$K^+ e^+ \tau^-$	LF < 1.53 × 10 <sup>-5</sup>	CL=90% 2312
$K^+ e^- \tau^+$	LF < 1.5 × 10 <sup>-5</sup>	CL=90% 2312
$K^+ e^\pm \tau^\mp$	LF < 3.0 × 10 <sup>-5</sup>	CL=90% 2312

$K^+ \mu^+ \tau^-$	LF	< 2.45	$\times 10^{-5}$	CL=90%	2298
$K^+ \mu^- \tau^+$	LF	< 5.9	$\times 10^{-6}$	CL=90%	2298
$K^+ \mu^\pm \tau^\mp$	LF	< 4.8	$\times 10^{-5}$	CL=90%	2298
$K^*(892)^+ e^+ \mu^-$	LF	< 1.3	$\times 10^{-6}$	CL=90%	2563
$K^*(892)^+ e^- \mu^+$	LF	< 9.9	$\times 10^{-7}$	CL=90%	2563
$K^*(892)^+ e^\pm \mu^\mp$	LF	< 1.4	$\times 10^{-6}$	CL=90%	2563
$\pi^- e^+ e^+$	L	< 2.3	$\times 10^{-8}$	CL=90%	2638
$\pi^- \mu^+ \mu^+$	L	< 4.0	$\times 10^{-9}$	CL=95%	2634
$\pi^- e^+ \mu^+$	L	< 1.5	$\times 10^{-7}$	CL=90%	2637
$\rho^- e^+ e^+$	L	< 1.7	$\times 10^{-7}$	CL=90%	2583
$\rho^- \mu^+ \mu^+$	L	< 4.2	$\times 10^{-7}$	CL=90%	2578
$\rho^- e^+ \mu^+$	L	< 4.7	$\times 10^{-7}$	CL=90%	2582
$K^- e^+ e^+$	L	< 3.0	$\times 10^{-8}$	CL=90%	2617
$K^- \mu^+ \mu^+$	L	< 4.1	$\times 10^{-8}$	CL=90%	2612
$K^- e^+ \mu^+$	L	< 1.6	$\times 10^{-7}$	CL=90%	2616
$K^*(892)^- e^+ e^+$	L	< 4.0	$\times 10^{-7}$	CL=90%	2564
$K^*(892)^- \mu^+ \mu^+$	L	< 5.9	$\times 10^{-7}$	CL=90%	2560
$K^*(892)^- e^+ \mu^+$	L	< 3.0	$\times 10^{-7}$	CL=90%	2563
$D^- e^+ e^+$	L	< 2.6	$\times 10^{-6}$	CL=90%	2309
$D^- e^+ \mu^+$	L	< 1.8	$\times 10^{-6}$	CL=90%	2307
$D^- \mu^+ \mu^+$	L	< 6.9	$\times 10^{-7}$	CL=95%	2303
$D^{*-} \mu^+ \mu^+$	L	< 2.4	$\times 10^{-6}$	CL=95%	2251
$D_S^- \mu^+ \mu^+$	L	< 5.8	$\times 10^{-7}$	CL=95%	2267
$\overline{D}^0 \pi^- \mu^+ \mu^+$	L	< 1.5	$\times 10^{-6}$	CL=95%	2295
$\Lambda^0 \mu^+$	L,B	< 6	$\times 10^{-8}$	CL=90%	-
$\Lambda^0 e^+$	L,B	< 3.2	$\times 10^{-8}$	CL=90%	-
$\overline{\Lambda}^0 \mu^+$	L,B	< 6	$\times 10^{-8}$	CL=90%	-
$\overline{\Lambda}^0 e^+$	L,B	< 8	$\times 10^{-8}$	CL=90%	-

See Particle Listings for 15 decay modes that have been seen / not seen.

**$B^0$**

$$I(J^P) = \frac{1}{2}(0^-)$$

$I, J, P$  need confirmation. Quantum numbers shown are quark-model predictions.

$$\text{Mass } m_{B^0} = 5279.72 \pm 0.08 \text{ MeV}$$

$$m_{B^0} - m_{B^\pm} = 0.31 \pm 0.05 \text{ MeV}$$

$$\text{Mean life } \tau_{B^0} = (1.517 \pm 0.004) \times 10^{-12} \text{ s}$$

$$c\tau = 454.8 \text{ } \mu\text{m}$$

$$\tau_{B^+}/\tau_{B^0} = 1.076 \pm 0.004 \quad (\text{direct measurements})$$

### $B^0$ - $\overline{B}^0$ mixing parameters

$$\chi_d (B^0\text{-}\overline{B}^0 \text{ mixing probability}) = 0.1860 \pm 0.0011$$

$$\begin{aligned} \Delta m_{B^0} = m_{B_H^0} - m_{B_L^0} &= (0.5069 \pm 0.0019) \times 10^{12} \text{ } \hbar \text{ s}^{-1} \\ &= (3.336 \pm 0.013) \times 10^{-10} \text{ MeV} \end{aligned}$$

$$x_d = \Delta m_{B^0}/\Gamma_{B^0} = 0.7697 \pm 0.0035$$

$$\text{Re}(\lambda_{CP} / |\lambda_{CP}|) \text{ Re}(z) = 0.047 \pm 0.022$$

$$\Delta\Gamma \text{ Re}(z) = -0.007 \pm 0.004 \text{ ps}^{-1}$$

$$\text{Re}(z) = (-4 \pm 4) \times 10^{-2} \quad (S = 1.4)$$

$$\text{Im}(z) = (-0.8 \pm 0.4) \times 10^{-2}$$

### CP violation parameters

$$\text{Re}(\epsilon_{B^0})/(1+|\epsilon_{B^0}|^2) = (-0.5 \pm 0.4) \times 10^{-3}$$

$$A_{T/CP}(B^0 \leftrightarrow \overline{B}^0) = 0.005 \pm 0.018$$

$$\begin{aligned}
A_{CP}(B^0 \rightarrow D^*(2010)^+ D^-) &= 0.013 \pm 0.014 \\
A_{CP}(B^0 \rightarrow \bar{D}^0 \pi^0) &= (0.4 \pm 2.4) \times 10^{-2} \\
A_{CP}(B^0 \rightarrow [K^+ K^-]_D K^*(892)^0) &= -0.05 \pm 0.10 \\
A_{CP}(B^0 \rightarrow [K^+ \pi^-]_D K^*(892)^0) &= 0.047 \pm 0.029 \\
A_{CP}(B^0 \rightarrow [K^+ \pi^- \pi^+ \pi^-]_D K^*(892)^0) &= 0.037 \pm 0.034 \\
A_{CP}(B^0 \rightarrow [K^- \pi^+]_D K^*(892)^0) &= 0.19 \pm 0.19 \\
A_{CP}(B^0 \rightarrow [K^- \pi^+ \pi^+ \pi^-]_D K^*(892)^0) &= -0.01 \pm 0.24 \\
R_d^+ &= \Gamma(B^0 \rightarrow [\pi^+ K^-]_D K^{*0}) / \Gamma(B^0 \rightarrow [\pi^- K^+]_D K^{*0}) = \\
&0.064 \pm 0.021 \\
R_d^- &= \Gamma(\bar{B}^0 \rightarrow [\pi^- K^+]_D K^{*0}) / \Gamma(\bar{B}^0 \rightarrow [\pi^+ K^-]_D K^{*0}) = \\
&0.095 \pm 0.021 \\
A_{CP}(B^0 \rightarrow [\pi^+ \pi^-]_D K^*(892)^0) &= -0.18 \pm 0.14 \\
A_{CP}(B^0 \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D K^*(892)^0) &= -0.03 \pm 0.15 \\
R_d^+ &= \Gamma(B^0 \rightarrow [\pi^+ K^- \pi^+ \pi^-]_D K^{*0}) / \Gamma(B^0 \rightarrow \\
&[\pi^- K^+ \pi^+ \pi^-]_D K^{*0}) = 0.074 \pm 0.026 \\
R_d^- &= \Gamma(\bar{B}^0 \rightarrow [\pi^- K^+ \pi^+ \pi^-]_D K^{*0}) / \Gamma(\bar{B}^0 \rightarrow \\
&[\pi^+ K^- \pi^+ \pi^-]_D K^{*0}) = 0.072 \pm 0.025 \\
\mathbf{ACP}(B^0 \rightarrow K^+ \pi^-) &= -0.0831 \pm 0.0031 \\
A_{CP}(B^0 \rightarrow \eta' K^*(892)^0) &= -0.07 \pm 0.18 \\
A_{CP}(B^0 \rightarrow \eta' K_0^*(1430)^0) &= -0.19 \pm 0.17 \\
A_{CP}(B^0 \rightarrow \eta' K_2^*(1430)^0) &= 0.14 \pm 0.18 \\
\mathbf{ACP}(B^0 \rightarrow \eta K^*(892)^0) &= 0.19 \pm 0.05 \\
A_{CP}(B^0 \rightarrow \eta K_0^*(1430)^0) &= 0.06 \pm 0.13 \\
A_{CP}(B^0 \rightarrow \eta K_2^*(1430)^0) &= -0.07 \pm 0.19 \\
A_{CP}(B^0 \rightarrow b_1 K^+) &= -0.07 \pm 0.12 \\
A_{CP}(B^0 \rightarrow \omega K^{*0}) &= 0.45 \pm 0.25 \\
A_{CP}(B^0 \rightarrow \omega(K\pi)_0^{*0}) &= -0.07 \pm 0.09 \\
A_{CP}(B^0 \rightarrow \omega K_2^*(1430)^0) &= -0.37 \pm 0.17 \\
A_{CP}(B^0 \rightarrow K^+ \pi^- \pi^0) &= (0 \pm 6) \times 10^{-2} \\
A_{CP}(B^0 \rightarrow \rho^- K^+) &= 0.20 \pm 0.11 \\
A_{CP}(B^0 \rightarrow \rho(1450)^- K^+) &= -0.10 \pm 0.33 \\
A_{CP}(B^0 \rightarrow \rho(1700)^- K^+) &= -0.4 \pm 0.6 \\
A_{CP}(B^0 \rightarrow K^+ \pi^- \pi^0 \text{ nonresonant}) &= 0.10 \pm 0.18 \\
A_{CP}(B^0 \rightarrow K^0 \pi^+ \pi^-) &= -0.01 \pm 0.05 \\
\mathbf{ACP}(B^0 \rightarrow K^*(892)^+ \pi^-) &= -0.27 \pm 0.04 \\
A_{CP}(B^0 \rightarrow (K\pi)_0^{*+} \pi^-) &= 0.02 \pm 0.04 \\
A_{CP}(B^0 \rightarrow K_2^*(1430)^+ \pi^-) &= -0.29 \pm 0.24 \\
A_{CP}(B^0 \rightarrow K^*(1680)^+ \pi^-) &= -0.07 \pm 0.14 \\
A_{CP}(B^0 \rightarrow f_0(980) K_S^0) &= 0.28 \pm 0.31 \\
A_{CP}(B^0 \rightarrow (K\pi)_0^{*0} \pi^0) &= -0.15 \pm 0.11 \\
A_{CP}(B^0 \rightarrow K^{*0} \pi^0) &= -0.15 \pm 0.13 \\
A_{CP}(B^0 \rightarrow K^*(892)^0 \pi^+ \pi^-) &= 0.07 \pm 0.05 \\
A_{CP}(B^0 \rightarrow K^*(892)^0 \rho^0) &= -0.06 \pm 0.09 \\
A_{CP}(B^0 \rightarrow K^{*0} f_0(980)) &= 0.07 \pm 0.10 \\
A_{CP}(B^0 \rightarrow K^{*+} \rho^-) &= 0.21 \pm 0.15 \\
A_{CP}(B^0 \rightarrow K^*(892)^0 K^+ K^-) &= 0.01 \pm 0.05 \\
A_{CP}(B^0 \rightarrow a_1^- K^+) &= -0.16 \pm 0.12 \\
A_{CP}(B^0 \rightarrow K^0 K^0) &= -0.6 \pm 0.7 \\
A_{CP}(B^0 \rightarrow K^*(892)^0 \phi) &= 0.00 \pm 0.04 \\
A_{CP}(B^0 \rightarrow K^*(892)^0 K^- \pi^+) &= 0.2 \pm 0.4 \\
A_{CP}(B^0 \rightarrow \phi(K\pi)_0^{*0}) &= 0.12 \pm 0.08
\end{aligned}$$

$$\begin{aligned}
A_{CP}(B^0 \rightarrow \phi K_2^*(1430)^0) &= -0.11 \pm 0.10 \\
A_{CP}(B^0 \rightarrow K^*(892)^0 \gamma) &= -0.006 \pm 0.011 \\
A_{CP}(B^0 \rightarrow K_2^*(1430)^0 \gamma) &= -0.08 \pm 0.15 \\
A_{CP}(B^0 \rightarrow X_S \gamma) &= -0.009 \pm 0.018 \\
A_{CP}(B^0 \rightarrow \rho^+ \pi^-) &= 0.13 \pm 0.06 \quad (S = 1.1) \\
A_{CP}(B^0 \rightarrow \rho^- \pi^+) &= -0.08 \pm 0.08 \\
A_{CP}(B^0 \rightarrow a_1(1260)^\pm \pi^\mp) &= -0.07 \pm 0.06 \\
A_{CP}(B^0 \rightarrow b_1^- \pi^+) &= -0.05 \pm 0.10 \\
A_{CP}(B^0 \rightarrow \rho \bar{\rho} K^*(892)^0) &= 0.05 \pm 0.12 \\
A_{CP}(B^0 \rightarrow \rho \bar{\Lambda} \pi^-) &= 0.04 \pm 0.07 \\
A_{CP}(B^0 \rightarrow K^{*0} \ell^+ \ell^-) &= -0.05 \pm 0.10 \\
A_{CP}(B^0 \rightarrow K^{*0} e^+ e^-) &= -0.21 \pm 0.19 \\
A_{CP}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) &= -0.034 \pm 0.024 \\
C_{D^{*-} D^+} (B^0 \rightarrow D^*(2010)^- D^+) &= -0.02 \pm 0.08 \\
\mathbf{S}_{D^{*-} D^+} (B^0 \rightarrow D^*(2010)^- D^+) &= -0.83 \pm 0.09 \\
C_{D^{*+} D^-} (B^0 \rightarrow D^*(2010)^+ D^-) &= -0.03 \pm 0.09 \quad (S = 1.1) \\
\mathbf{S}_{D^{*+} D^-} (B^0 \rightarrow D^*(2010)^+ D^-) &= -0.80 \pm 0.09 \\
C_{D^{*+} D^{*-}} (B^0 \rightarrow D^{*+} D^{*-}) &= 0.01 \pm 0.09 \quad (S = 1.6) \\
\mathbf{S}_{D^{*+} D^{*-}} (B^0 \rightarrow D^{*+} D^{*-}) &= -0.59 \pm 0.14 \quad (S = 1.8) \\
C_+ (B^0 \rightarrow D^{*+} D^{*-}) &= 0.00 \pm 0.10 \quad (S = 1.6) \\
\mathbf{S}_+ (B^0 \rightarrow D^{*+} D^{*-}) &= -0.73 \pm 0.09 \\
C_- (B^0 \rightarrow D^{*+} D^{*-}) &= 0.19 \pm 0.31 \\
S_- (B^0 \rightarrow D^{*+} D^{*-}) &= 0.1 \pm 1.6 \quad (S = 3.5) \\
C (B^0 \rightarrow D^*(2010)^+ D^*(2010)^- K_S^0) &= 0.01 \pm 0.29 \\
S (B^0 \rightarrow D^*(2010)^+ D^*(2010)^- K_S^0) &= 0.1 \pm 0.4 \\
C_{D^+ D^-} (B^0 \rightarrow D^+ D^-) &= -0.22 \pm 0.24 \quad (S = 2.5) \\
\mathbf{S}_{D^+ D^-} (B^0 \rightarrow D^+ D^-) &= -0.76_{-0.13}^{+0.15} \quad (S = 1.2) \\
C_{J/\psi(1S) \pi^0} (B^0 \rightarrow J/\psi(1S) \pi^0) &= 0.03 \pm 0.17 \quad (S = 1.5) \\
\mathbf{S}_{J/\psi(1S) \pi^0} (B^0 \rightarrow J/\psi(1S) \pi^0) &= -0.88 \pm 0.32 \quad (S = 2.2) \\
C (B^0 \rightarrow J/\psi(1S) \rho^0) &= -0.06 \pm 0.06 \\
\mathbf{S} (B^0 \rightarrow J/\psi(1S) \rho^0) &= -0.66_{-0.12}^{+0.16} \\
C_{D_{CP}^* h^0} (B^0 \rightarrow D_{CP}^* h^0) &= -0.02 \pm 0.08 \\
\mathbf{S}_{D_{CP}^* h^0} (B^0 \rightarrow D_{CP}^* h^0) &= -0.66 \pm 0.12 \\
C_{K^0 \pi^0} (B^0 \rightarrow K^0 \pi^0) &= 0.00 \pm 0.08 \\
\mathbf{S}_{K^0 \pi^0} (B^0 \rightarrow K^0 \pi^0) &= 0.64 \pm 0.13 \\
C_{\eta'(958) K_S^0} (B^0 \rightarrow \eta'(958) K_S^0) &= -0.04 \pm 0.20 \quad (S = 2.5) \\
S_{\eta'(958) K_S^0} (B^0 \rightarrow \eta'(958) K_S^0) &= 0.43 \pm 0.17 \quad (S = 1.5) \\
C_{\eta' K^0} (B^0 \rightarrow \eta' K^0) &= -0.06 \pm 0.04 \\
\mathbf{S}_{\eta' K^0} (B^0 \rightarrow \eta' K^0) &= 0.63 \pm 0.06 \\
C_{\omega K_S^0} (B^0 \rightarrow \omega K_S^0) &= 0.0 \pm 0.4 \quad (S = 3.0) \\
S_{\omega K_S^0} (B^0 \rightarrow \omega K_S^0) &= 0.70 \pm 0.21 \\
C (B^0 \rightarrow K_S^0 \pi^0 \pi^0) &= -0.21 \pm 0.20 \\
S (B^0 \rightarrow K_S^0 \pi^0 \pi^0) &= 0.89_{-0.30}^{+0.27} \\
C_{\rho^0 K_S^0} (B^0 \rightarrow \rho^0 K_S^0) &= -0.04 \pm 0.20 \\
S_{\rho^0 K_S^0} (B^0 \rightarrow \rho^0 K_S^0) &= 0.50_{-0.21}^{+0.17} \\
C_{f_0 K_S^0} (B^0 \rightarrow f_0(980) K_S^0) &= 0.29 \pm 0.20
\end{aligned}$$

$$\begin{aligned}
S_{f_0 K_S^0} (B^0 \rightarrow f_0(980) K_S^0) &= -0.50 \pm 0.16 \\
S_{f_2 K_S^0} (B^0 \rightarrow f_2(1270) K_S^0) &= -0.5 \pm 0.5 \\
C_{f_2 K_S^0} (B^0 \rightarrow f_2(1270) K_S^0) &= 0.3 \pm 0.4 \\
S_{f_x K_S^0} (B^0 \rightarrow f_x(1300) K_S^0) &= -0.2 \pm 0.5 \\
C_{f_x K_S^0} (B^0 \rightarrow f_x(1300) K_S^0) &= 0.13 \pm 0.35 \\
S_{K^0 \pi^+ \pi^-} (B^0 \rightarrow K^0 \pi^+ \pi^- \text{ nonresonant}) &= -0.01 \pm 0.33 \\
C_{K^0 \pi^+ \pi^-} (B^0 \rightarrow K^0 \pi^+ \pi^- \text{ nonresonant}) &= 0.01 \pm 0.26 \\
C_{K_S^0 K_S^0} (B^0 \rightarrow K_S^0 K_S^0) &= 0.0 \pm 0.4 \quad (S = 1.4) \\
S_{K_S^0 K_S^0} (B^0 \rightarrow K_S^0 K_S^0) &= -0.8 \pm 0.5 \\
C_{K^+ K^- K_S^0} (B^0 \rightarrow K^+ K^- K_S^0 \text{ nonresonant}) &= 0.06 \pm 0.08 \\
\mathbf{S_{K^+ K^- K_S^0} (B^0 \rightarrow K^+ K^- K_S^0 \text{ nonresonant})} &= -0.66 \pm 0.11 \\
C_{K^+ K^- K_S^0} (B^0 \rightarrow K^+ K^- K_S^0 \text{ inclusive}) &= 0.01 \pm 0.09 \\
\mathbf{S_{K^+ K^- K_S^0} (B^0 \rightarrow K^+ K^- K_S^0 \text{ inclusive})} &= -0.65 \pm 0.12 \\
C_{\phi K_S^0} (B^0 \rightarrow \phi K_S^0) &= -0.09 \pm 0.12 \\
\mathbf{S_{\phi K_S^0} (B^0 \rightarrow \phi K_S^0)} &= 0.58 \pm 0.12 \\
C_{K_S K_S K_S} (B^0 \rightarrow K_S K_S K_S) &= -0.14 \pm 0.12 \\
S_{K_S K_S K_S} (B^0 \rightarrow K_S K_S K_S) &= -0.82 \pm 0.17 \\
C_{K_S^0 \pi^0 \gamma} (B^0 \rightarrow K_S^0 \pi^0 \gamma) &= 0.36 \pm 0.33 \\
S_{K_S^0 \pi^0 \gamma} (B^0 \rightarrow K_S^0 \pi^0 \gamma) &= -0.8 \pm 0.6 \\
C_{K_S^0 \pi^+ \pi^- \gamma} (B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma) &= -0.39 \pm 0.20 \\
S_{K_S^0 \pi^+ \pi^- \gamma} (B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma) &= 0.14 \pm 0.25 \\
C_{K^{*0} \gamma} (B^0 \rightarrow K^*(892)^0 \gamma) &= -0.04 \pm 0.16 \quad (S = 1.2) \\
S_{K^{*0} \gamma} (B^0 \rightarrow K^*(892)^0 \gamma) &= -0.15 \pm 0.22 \\
C_{\eta K^0 \gamma} (B^0 \rightarrow \eta K^0 \gamma) &= 0.1 \pm 0.4 \quad (S = 1.4) \\
S_{\eta K^0 \gamma} (B^0 \rightarrow \eta K^0 \gamma) &= -0.5 \pm 0.5 \quad (S = 1.2) \\
C_{K^0 \phi \gamma} (B^0 \rightarrow K^0 \phi \gamma) &= -0.3 \pm 0.6 \\
S_{K^0 \phi \gamma} (B^0 \rightarrow K^0 \phi \gamma) &= 0.7_{-1.1}^{+0.7} \\
C(B^0 \rightarrow K_S^0 \rho^0 \gamma) &= -0.05 \pm 0.19 \\
S(B^0 \rightarrow K_S^0 \rho^0 \gamma) &= -0.04 \pm 0.23 \\
C(B^0 \rightarrow \rho^0 \gamma) &= 0.4 \pm 0.5 \\
S(B^0 \rightarrow \rho^0 \gamma) &= -0.8 \pm 0.7 \\
\mathbf{C_{\pi \pi} (B^0 \rightarrow \pi^+ \pi^-)} &= -0.314 \pm 0.030 \\
\mathbf{S_{\pi \pi} (B^0 \rightarrow \pi^+ \pi^-)} &= -0.670 \pm 0.030 \\
C_{\pi^0 \pi^0} (B^0 \rightarrow \pi^0 \pi^0) &= -0.30 \pm 0.20 \\
C_{\rho \pi} (B^0 \rightarrow \rho^+ \pi^-) &= -0.03 \pm 0.07 \quad (S = 1.2) \\
S_{\rho \pi} (B^0 \rightarrow \rho^+ \pi^-) &= 0.05 \pm 0.07 \\
\mathbf{\Delta C_{\rho \pi} (B^0 \rightarrow \rho^+ \pi^-)} &= 0.27 \pm 0.06 \\
\mathbf{\Delta S_{\rho \pi} (B^0 \rightarrow \rho^+ \pi^-)} &= 0.01 \pm 0.08 \\
C_{\rho^0 \pi^0} (B^0 \rightarrow \rho^0 \pi^0) &= 0.27 \pm 0.24 \\
S_{\rho^0 \pi^0} (B^0 \rightarrow \rho^0 \pi^0) &= -0.23 \pm 0.34 \\
C_{a_1 \pi} (B^0 \rightarrow a_1(1260)^+ \pi^-) &= -0.05 \pm 0.11 \\
S_{a_1 \pi} (B^0 \rightarrow a_1(1260)^+ \pi^-) &= -0.2 \pm 0.4 \quad (S = 3.2) \\
\mathbf{\Delta C_{a_1 \pi} (B^0 \rightarrow a_1(1260)^+ \pi^-)} &= 0.43 \pm 0.14 \quad (S = 1.3)
\end{aligned}$$

$$\begin{aligned}
 \Delta S_{a_1 \pi} (B^0 \rightarrow a_1(1260)^+ \pi^-) &= -0.11 \pm 0.12 \\
 C (B^0 \rightarrow b_1^- K^+) &= -0.22 \pm 0.24 \\
 \Delta C (B^0 \rightarrow b_1^- \pi^+) &= -1.04 \pm 0.24 \\
 C_{\rho^0 \rho^0} (B^0 \rightarrow \rho^0 \rho^0) &= 0.2 \pm 0.9 \\
 S_{\rho^0 \rho^0} (B^0 \rightarrow \rho^0 \rho^0) &= 0.3 \pm 0.7 \\
 C_{\rho \rho} (B^0 \rightarrow \rho^+ \rho^-) &= 0.00 \pm 0.09 \\
 S_{\rho \rho} (B^0 \rightarrow \rho^+ \rho^-) &= -0.14 \pm 0.13 \\
 |\lambda| (B^0 \rightarrow J/\psi K^*(892)^0) &< 0.25, \text{ CL} = 95\% \\
 \cos 2\beta (B^0 \rightarrow J/\psi K^*(892)^0) &= 1.7_{-0.9}^{+0.7} \quad (S = 1.6) \\
 \cos 2\beta (B^0 \rightarrow [K_S^0 \pi^+ \pi^-]_{D^{(*)}} h^0) &= 0.91 \pm 0.25 \\
 (S_+ + S_-)/2 (B^0 \rightarrow D^{*-} \pi^+) &= -0.039 \pm 0.011 \\
 (S_- - S_+)/2 (B^0 \rightarrow D^{*-} \pi^+) &= -0.009 \pm 0.015 \\
 (S_+ + S_-)/2 (B^0 \rightarrow D^- \pi^+) &= -0.046 \pm 0.023 \\
 (S_- - S_+)/2 (B^0 \rightarrow D^- \pi^+) &= -0.022 \pm 0.021 \\
 S_+ (B^0 \rightarrow D^- \pi^+) &= 0.058 \pm 0.023 \\
 S_- (B^0 \rightarrow D^+ \pi^-) &= 0.038 \pm 0.021 \\
 (S_+ + S_-)/2 (B^0 \rightarrow D^- \rho^+) &= -0.024 \pm 0.032 \\
 (S_- - S_+)/2 (B^0 \rightarrow D^- \rho^+) &= -0.10 \pm 0.06 \\
 C_{\eta_c K_S^0} (B^0 \rightarrow \eta_c K_S^0) &= 0.08 \pm 0.13 \\
 S_{\eta_c K_S^0} (B^0 \rightarrow \eta_c K_S^0) &= 0.93 \pm 0.17 \\
 C_{c \bar{c} K^{(*)0}} (B^0 \rightarrow c \bar{c} K^{(*)0}) &= (-0.5 \pm 1.5) \times 10^{-2} \\
 \sin(2\beta) &= 0.709 \pm 0.011 \\
 C_{J/\psi(nS) K^0} (B^0 \rightarrow J/\psi(nS) K^0) &= (-0.8 \pm 1.7) \times 10^{-2} \\
 S_{J/\psi(nS) K^0} (B^0 \rightarrow J/\psi(nS) K^0) &= 0.701 \pm 0.017 \\
 C_{J/\psi K^{*0}} (B^0 \rightarrow J/\psi K^{*0}) &= 0.03 \pm 0.10 \\
 S_{J/\psi K^{*0}} (B^0 \rightarrow J/\psi K^{*0}) &= 0.60 \pm 0.25 \\
 C_{\chi_{c0} K_S^0} (B^0 \rightarrow \chi_{c0} K_S^0) &= -0.3_{-0.4}^{+0.5} \\
 S_{\chi_{c0} K_S^0} (B^0 \rightarrow \chi_{c0} K_S^0) &= -0.7 \pm 0.5 \\
 C_{\chi_{c1} K_S^0} (B^0 \rightarrow \chi_{c1} K_S^0) &= 0.06 \pm 0.07 \\
 S_{\chi_{c1} K_S^0} (B^0 \rightarrow \chi_{c1} K_S^0) &= 0.63 \pm 0.10 \\
 \sin(2\beta_{\text{eff}})(B^0 \rightarrow \phi K^0) &= 0.22 \pm 0.30 \\
 \sin(2\beta_{\text{eff}})(B^0 \rightarrow \phi K_0^*(1430)^0) &= 0.97_{-0.52}^{+0.03} \\
 \sin(2\beta_{\text{eff}})(B^0 \rightarrow K^+ K^- K_S^0) &= 0.77_{-0.12}^{+0.13} \\
 \sin(2\beta_{\text{eff}})(B^0 \rightarrow [K_S^0 \pi^+ \pi^-]_{D^{(*)}} h^0) &= 0.80 \pm 0.16 \\
 \beta_{\text{eff}}(B^0 \rightarrow [K_S^0 \pi^+ \pi^-]_{D^{(*)}} h^0) &= (22 \pm 5)^\circ \\
 2\beta_{\text{eff}}(B^0 \rightarrow J/\psi \rho^0) &= (42_{-11}^{+10})^\circ \\
 |\lambda| (B^0 \rightarrow [K_S^0 \pi^+ \pi^-]_{D^{(*)}} h^0) &= 1.01 \pm 0.08 \\
 |\sin(2\beta + \gamma)| &> 0.40, \text{ CL} = 90\% \\
 2\beta + \gamma &= (80 \pm 60)^\circ \\
 \alpha &= (84.1_{-3.8}^{+4.5})^\circ \\
 x_+ (B^0 \rightarrow DK^{*0}) &= 0.04 \pm 0.17 \\
 x_- (B^0 \rightarrow DK^{*0}) &= -0.16 \pm 0.14 \\
 y_+ (B^0 \rightarrow DK^{*0}) &= -0.68 \pm 0.22 \\
 y_- (B^0 \rightarrow DK^{*0}) &= 0.20 \pm 0.25 \quad (S = 1.2) \\
 r_{B^0}(B^0 \rightarrow DK^{*0}) &= 0.257_{-0.023}^{+0.021} \\
 \delta_{B^0}(B^0 \rightarrow DK^{*0}) &= (194.1_{-8.8}^{+9.6})^\circ
 \end{aligned}$$

$$a_{CP}(B^0 \rightarrow p\bar{p}K^+\pi^-) = (0.5 \pm 0.9)\%$$

$$a_P(B^0 \rightarrow p\bar{p}K^+\pi^-) = (1.5 \pm 0.9)\%$$

$\bar{B}^0$  modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing. Modes which do not identify the charge state of the  $B$  are listed in the  $B^\pm/B^0$  ADMIXTURE section.

The branching fractions listed below assume 50%  $B^0\bar{B}^0$  and 50%  $B^+B^-$  production at the  $\Upsilon(4S)$ . We have attempted to bring older measurements up to date by rescaling their assumed  $\Upsilon(4S)$  production ratio to 50:50 and their assumed  $D$ ,  $D_S$ ,  $D^*$ , and  $\psi$  branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

For inclusive branching fractions, e.g.,  $B \rightarrow D^\pm X$ , the values usually are multiplicities, not branching fractions. They can be greater than one.

$B^0$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$\ell^+ \nu_\ell X$	[hhh] ( 10.33 ± 0.28 ) %		—
$e^+ \nu_e X_c$	( 10.1 ± 0.4 ) %		—
$\ell^+ \nu_\ell X_u$	[hhh] ( 1.51 ± 0.19 ) × 10 <sup>-3</sup>		—
$D\ell^+ \nu_\ell X$	[hhh] ( 9.1 ± 0.8 ) %		—
$D^-\ell^+ \nu_\ell$	[hhh] ( 2.12 ± 0.06 ) %		2309
$D^-\tau^+ \nu_\tau$	( 9.9 ± 2.1 ) × 10 <sup>-3</sup>		1909
$D^*(2010)^-\ell^+ \nu_\ell$	[hhh] ( 4.90 ± 0.12 ) %		2257
$D^*(2010)^-\tau^+ \nu_\tau$	( 1.45 ± 0.10 ) %	S=1.3	1838
$\bar{D}^*(*)n\pi\ell^+ \nu_\ell (n \geq 1)$	[hhh] ( 2.3 ± 0.5 ) %		—
$\bar{D}^0\pi^-\ell^+ \nu_\ell$	[hhh] ( 3.64 ± 0.20 ) × 10 <sup>-3</sup>		2308
$D_0^*(2300)^-\ell^+ \nu_\ell, D_0^{*-} \rightarrow$	[hhh] < 4.4 × 10 <sup>-4</sup>	CL=90%	—
$\bar{D}^0\pi^-$			
$D_2^*(2460)^-\ell^+ \nu_\ell, D_2^{*-} \rightarrow$	[hhh] ( 1.41 ± 0.20 ) × 10 <sup>-3</sup>	S=1.7	2065
$\bar{D}^0\pi^-$			
$\bar{D}^{*0}\pi^-\ell^+ \nu_\ell$	[hhh] ( 5.44 ± 0.28 ) × 10 <sup>-3</sup>		2256
$D_1(2420)^-\ell^+ \nu_\ell, D_1^- \rightarrow$	[hhh] ( 2.85 ± 0.25 ) × 10 <sup>-3</sup>		—
$\bar{D}^{*0}\pi^-$			
$D_1(2420)^-\ell^+ \nu_\ell, D_1^- \rightarrow$	[hhh] ( 1.02 ± 0.16 ) × 10 <sup>-3</sup>		—
$D^-\pi^+\pi^-$			
$D_1'(2430)^-\ell^+ \nu_\ell, D_1'^- \rightarrow$	[hhh] ( 2.5 ± 0.6 ) × 10 <sup>-3</sup>		—
$\bar{D}^{*0}\pi^-$			
$D_2^*(2460)^-\ell^+ \nu_\ell, D_2^{*-} \rightarrow$	[hhh] ( 6.6 ± 1.1 ) × 10 <sup>-4</sup>		2065
$\bar{D}^{*0}\pi^-$			
$D^-\pi^+\pi^-\ell^+ \nu_\ell$	[hhh] ( 1.45 ± 0.22 ) × 10 <sup>-3</sup>		2299
$D^{*-}\pi^+\pi^-\ell^+ \nu_\ell$	[hhh] ( 5.1 ± 2.3 ) × 10 <sup>-4</sup>		2247
$\rho^-\ell^+ \nu_\ell$	[hhh] ( 2.94 ± 0.21 ) × 10 <sup>-4</sup>		2583
$\pi^-\ell^+ \nu_\ell$	[hhh] ( 1.50 ± 0.06 ) × 10 <sup>-4</sup>		2638
$\pi^-\tau^+ \nu_\tau$	< 2.5 × 10 <sup>-4</sup>	CL=90%	2339
<b>Inclusive modes</b>			
$K^\pm X$	( 78 ± 8 ) %		—
$D^0 X$	( 8.1 ± 1.5 ) %		—
$\bar{D}^0 X$	( 47.4 ± 2.8 ) %		—
$D^+ X$	< 3.9 %	CL=90%	—
$D^- X$	( 36.9 ± 3.3 ) %		—
$D_S^+ X$	( 10.3 ± 2.1 / 1.8 ) %		—



$D_s^- X$	< 2.6	%	CL=90%	-
$\Lambda_c^+ X$	< 3.1	%	CL=90%	-
$\bar{\Lambda}_c^- X$	( 5.0 $\pm$ 2.1 )	%		-
$\bar{c} X$	( 95 $\pm$ 5 )	%		-
$c X$	( 24.6 $\pm$ 3.1 )	%		-
$\bar{c}/c X$	(119 $\pm$ 6 )	%		-

**D, D\*, or D<sub>S</sub> modes**

$D^- \pi^+$	( 2.51 $\pm$ 0.08 )	$\times 10^{-3}$		2306
$D^- \rho^+$	( 7.6 $\pm$ 1.2 )	$\times 10^{-3}$		2235
$D^- K^0 \pi^+$	( 4.9 $\pm$ 0.9 )	$\times 10^{-4}$		2259
$D^- K^*(892)^+$	( 4.5 $\pm$ 0.7 )	$\times 10^{-4}$		2211
$D^- \omega \pi^+$	( 2.8 $\pm$ 0.6 )	$\times 10^{-3}$		2204
$D^- K^+$	( 2.05 $\pm$ 0.08 )	$\times 10^{-4}$		2279
$D^- K^+ \pi^+ \pi^-$	( 3.5 $\pm$ 0.8 )	$\times 10^{-4}$		2236
$D^- K^+ \bar{K}^0$	< 3.1	$\times 10^{-4}$	CL=90%	2188
$D^- K^+ \bar{K}^*(892)^0$	( 8.8 $\pm$ 1.9 )	$\times 10^{-4}$		2070
$\bar{D}^0 \pi^+ \pi^-$	( 8.8 $\pm$ 0.5 )	$\times 10^{-4}$		2301
$D^*(2010)^- \pi^+$	( 2.66 $\pm$ 0.07 )	$\times 10^{-3}$		2255
$\bar{D}^0 K^+ K^-$	( 6.1 $\pm$ 0.5 )	$\times 10^{-5}$		2191
$D^- \pi^+ \pi^+ \pi^-$	( 6.0 $\pm$ 0.6 )	$\times 10^{-3}$		2287
( $D^- \pi^+ \pi^+ \pi^-$ ) nonresonant	( 3.9 $\pm$ 1.9 )	$\times 10^{-3}$		2287
$D^- \pi^+ \rho^0$	( 1.1 $\pm$ 1.0 )	$\times 10^{-3}$		2206
$D^- a_1(1260)^+$	( 6.0 $\pm$ 3.3 )	$\times 10^{-3}$		2121
$D^*(2010)^- \pi^+ \pi^0$	( 1.5 $\pm$ 0.5 )	%		2248
$D^*(2010)^- \rho^+$	( 6.8 $\pm$ 0.9 )	$\times 10^{-3}$		2180
$D^*(2010)^- K^+$	( 2.16 $\pm$ 0.08 )	$\times 10^{-4}$		2226
$D^*(2010)^- K^0 \pi^+$	( 3.0 $\pm$ 0.8 )	$\times 10^{-4}$		2205
$D^*(2010)^- K^*(892)^+$	( 3.3 $\pm$ 0.6 )	$\times 10^{-4}$		2155
$D^*(2010)^- K^+ \bar{K}^0$	< 4.7	$\times 10^{-4}$	CL=90%	2131
$D^*(2010)^- K^+ \bar{K}^*(892)^0$	( 1.29 $\pm$ 0.33 )	$\times 10^{-3}$		2007
$D^*(2010)^- \pi^+ \pi^+ \pi^-$	( 7.21 $\pm$ 0.29 )	$\times 10^{-3}$		2235
( $D^*(2010)^- \pi^+ \pi^+ \pi^-$ ) nonresonant	( 0.0 $\pm$ 2.5 )	$\times 10^{-3}$		2235
$D^*(2010)^- \pi^+ \rho^0$	( 5.7 $\pm$ 3.2 )	$\times 10^{-3}$		2150
$D^*(2010)^- a_1(1260)^+$	( 1.30 $\pm$ 0.27 )	%		2061
$\bar{D}_1(2420)^0 \pi^- \pi^+, \bar{D}_1^0 \rightarrow$	( 1.47 $\pm$ 0.35 )	$\times 10^{-4}$		-
$D^{*-} \pi^+$				
$D^*(2010)^- K^+ \pi^- \pi^+$	( 4.7 $\pm$ 0.4 )	$\times 10^{-4}$		2181
$D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0$	( 1.76 $\pm$ 0.27 )	%		2218
$D^{*-} 3\pi^+ 2\pi^-$	( 4.7 $\pm$ 0.9 )	$\times 10^{-3}$		2195
$D^*(2010)^- \omega \pi^+$	( 2.46 $\pm$ 0.18 )	$\times 10^{-3}$	S=1.2	2148
$\bar{D}_1(2430)^0 \omega, \bar{D}_1^0 \rightarrow D^{*-} \pi^+$	( 2.7 $\pm$ 0.8 )	$\times 10^{-4}$		1992
$D^{*-} \rho(1450)^+, \rho^+ \rightarrow \omega \pi^+$	( 1.07 $\pm$ 0.40 )	$\times 10^{-3}$		-
$\bar{D}_1(2420)^0 \omega, \bar{D}_1^0 \rightarrow D^{*-} \pi^+$	( 7.0 $\pm$ 2.2 )	$\times 10^{-5}$		1995
$\bar{D}_2(2460)^0 \omega, \bar{D}_2^0 \rightarrow D^{*-} \pi^+$	( 4.0 $\pm$ 1.4 )	$\times 10^{-5}$		1975
$D^{*-} b_1(1235)^+, b_1^+ \rightarrow \omega \pi^+$	< 7	$\times 10^{-5}$	CL=90%	-
$\bar{D}^{*-} \pi^+$	[III] ( 1.9 $\pm$ 0.9 )	$\times 10^{-3}$		-
$D_1(2420)^- \pi^+, D_1^- \rightarrow$	( 9.9 $\pm$ 2.0 )	$\times 10^{-5}$		-
$D^- \pi^+ \pi^-$				
$D_1(2420)^- \pi^+, D_1^- \rightarrow$	< 3.3	$\times 10^{-5}$	CL=90%	-
$D^{*-} \pi^+ \pi^-$				
$\bar{D}_2(2460)^- \pi^+, D_2^{*-} \rightarrow D^0 \pi^-$	( 2.38 $\pm$ 0.16 )	$\times 10^{-4}$		2062

$\overline{D}_0^*(2400)^- \pi^+$ , $D_0^{*-} \rightarrow D^0 \pi^-$	$(7.6 \pm 0.8) \times 10^{-5}$		2090
$D_2^*(2460)^- \pi^+$ , $D_2^{*-} \rightarrow$ $D^{*-} \pi^+ \pi^-$	$< 2.4 \times 10^{-5}$	CL=90%	-
$\overline{D}_2^*(2460)^- \rho^+$	$< 4.9 \times 10^{-3}$	CL=90%	1974
$D_0^0 \overline{D}^0$	$(1.4 \pm 0.7) \times 10^{-5}$		1868
$D^{*0} \overline{D}^0$	$< 2.9 \times 10^{-4}$	CL=90%	1794
$D^- D^+$	$(2.11 \pm 0.18) \times 10^{-4}$		1864
$D^\pm D^{*\mp}$ (CP-averaged)	$(6.1 \pm 0.6) \times 10^{-4}$		-
$D^- D_s^+$	$(7.2 \pm 0.8) \times 10^{-3}$		1812
$D^*(2010)^- D_s^+$	$(8.0 \pm 1.1) \times 10^{-3}$		1735
$D^- D_s^{*+}$	$(7.4 \pm 1.6) \times 10^{-3}$		1732
$D^*(2010)^- D_s^{*+}$	$(1.77 \pm 0.14) \%$		1649
$D_{s0}(2317)^- K^+$ , $D_{s0}^- \rightarrow D_s^- \pi^0$	$(4.2 \pm 1.4) \times 10^{-5}$		2097
$D_{s0}(2317)^- \pi^+$ , $D_{s0}^- \rightarrow D_s^- \pi^0$	$< 2.5 \times 10^{-5}$	CL=90%	2128
$D_{sJ}(2457)^- K^+$ , $D_{sJ}^- \rightarrow D_s^- \pi^0$	$< 9.4 \times 10^{-6}$	CL=90%	-
$D_{sJ}(2457)^- \pi^+$ , $D_{sJ}^- \rightarrow D_s^- \pi^0$	$< 4.0 \times 10^{-6}$	CL=90%	-
$D_s^- D_s^+$	$< 3.6 \times 10^{-5}$	CL=90%	1759
$D_s^{*-} D_s^+$	$< 1.3 \times 10^{-4}$	CL=90%	1675
$D_s^{*-} D_s^{*+}$	$< 2.4 \times 10^{-4}$	CL=90%	1584
$D_{s0}^*(2317)^+ D^-$ , $D_{s0}^{*+} \rightarrow D_s^+ \pi^0$	$(1.06 \pm 0.16) \times 10^{-3}$	S=1.1	1602
$D_{s0}(2317)^+ D^-$ , $D_{s0}^+ \rightarrow D_s^{*+} \gamma$	$< 9.5 \times 10^{-4}$	CL=90%	-
$D_{s0}(2317)^+ D^*(2010)^-$ , $D_{s0}^+ \rightarrow$ $D_s^+ \pi^0$	$(1.5 \pm 0.6) \times 10^{-3}$		1509
$D_{sJ}(2457)^+ D^-$	$(3.5 \pm 1.1) \times 10^{-3}$		-
$D_{sJ}(2457)^+ D^-$ , $D_{sJ}^+ \rightarrow D_s^+ \gamma$	$(6.5 \pm_{1.4}^{1.7}) \times 10^{-4}$		-
$D_{sJ}(2457)^+ D^-$ , $D_{sJ}^+ \rightarrow D_s^{*+} \gamma$	$< 6.0 \times 10^{-4}$	CL=90%	-
$D_{sJ}(2457)^+ D^-$ , $D_{sJ}^+ \rightarrow$ $D_s^+ \pi^+ \pi^-$	$< 2.0 \times 10^{-4}$	CL=90%	-
$D_{sJ}(2457)^+ D^-$ , $D_{sJ}^+ \rightarrow D_s^+ \pi^0$	$< 3.6 \times 10^{-4}$	CL=90%	-
$D^*(2010)^- D_{sJ}(2457)^+$	$(9.3 \pm 2.2) \times 10^{-3}$		-
$D_{sJ}(2457)^+ D^*(2010)$ , $D_{sJ}^+ \rightarrow$ $D_s^+ \gamma$	$(2.3 \pm_{0.7}^{0.9}) \times 10^{-3}$		-
$D^- D_{s1}(2536)^+$ , $D_{s1}^+ \rightarrow$ $D^{*0} K^+ + D^{*+} K^0$	$(2.8 \pm 0.7) \times 10^{-4}$		1444
$D^- D_{s1}(2536)^+$ , $D_{s1}^+ \rightarrow$ $D^{*0} K^+$	$(1.7 \pm 0.6) \times 10^{-4}$		1444
$D^- D_{s1}(2536)^+$ , $D_{s1}^+ \rightarrow$ $D^{*+} K^0$	$(2.6 \pm 1.1) \times 10^{-4}$		1444
$D^*(2010)^- D_{s1}(2536)^+$ , $D_{s1}^+ \rightarrow$ $D^{*0} K^+ + D^{*+} K^0$	$(5.0 \pm 1.4) \times 10^{-4}$		1336
$D^*(2010)^- D_{s1}(2536)^+$ , $D_{s1}^+ \rightarrow D^{*0} K^+$	$(3.3 \pm 1.1) \times 10^{-4}$		1336
$D^{*-} D_{s1}(2536)^+$ , $D_{s1}^+ \rightarrow$ $D^{*+} K^0$	$(5.0 \pm 1.7) \times 10^{-4}$		1336
$D^- D_{sJ}(2573)^+$ , $D_{sJ}^+ \rightarrow$ $D^0 K^+$	$(3.4 \pm 1.8) \times 10^{-5}$		1414
$D^*(2010)^- D_{sJ}(2573)^+$ , $D_{sJ}^+ \rightarrow$ $D^0 K^+$	$< 2 \times 10^{-4}$	CL=90%	1304
$D^- D_{sJ}(2700)^+$ , $D_{sJ}^+ \rightarrow$ $D^0 K^+$	$(7.1 \pm 1.2) \times 10^{-4}$		-
$D^+ \pi^-$	$(7.3 \pm 1.2) \times 10^{-7}$		2306

$D_S^+ \pi^-$	$( 2.03 \pm 0.18 ) \times 10^{-5}$		2271
$D_S^{*+} \pi^-$	$( 2.1 \pm 0.4 ) \times 10^{-5}$	S=1.4	2215
$D_S^+ \rho^-$	$< 2.4 \times 10^{-5}$	CL=90%	2197
$D_S^{*+} \rho^-$	$( 4.1 \pm 1.3 ) \times 10^{-5}$		2138
$D_S^+ a_0^-$	$< 1.9 \times 10^{-5}$	CL=90%	—
$D_S^{*+} a_0^-$	$< 3.6 \times 10^{-5}$	CL=90%	—
$D_S^+ a_1(1260)^-$	$< 2.1 \times 10^{-3}$	CL=90%	2080
$D_S^{*+} a_1(1260)^-$	$< 1.7 \times 10^{-3}$	CL=90%	2015
$D_S^+ a_2^-$	$< 1.9 \times 10^{-4}$	CL=90%	—
$D_S^{*+} a_2^-$	$< 2.0 \times 10^{-4}$	CL=90%	—
$D_S^- K^+$	$( 2.7 \pm 0.5 ) \times 10^{-5}$	S=2.7	2242
$D_S^{*-} K^+$	$( 2.19 \pm 0.30 ) \times 10^{-5}$		2185
$D_{S1}(2536)^\mp K^\pm, D_{S1}^- \rightarrow \bar{D}^*(2007)^0 K^-$	$( 5.1 \pm 0.6 ) \times 10^{-6}$		—
$D_S^- K^*(892)^+$	$( 3.5 \pm 1.0 ) \times 10^{-5}$		2172
$D_S^{*-} K^*(892)^+$	$( 3.2 \pm 1.5 ) \times 10^{-5}$		2112
$D_S^- \pi^+ K^0$	$( 9.7 \pm 1.4 ) \times 10^{-5}$		2222
$D_S^{*-} \pi^+ K^0$	$< 1.10 \times 10^{-4}$	CL=90%	2164
$D_S^- K^+ \pi^+ \pi^-$	$( 1.7 \pm 0.5 ) \times 10^{-4}$		2198
$D_S^- \pi^+ K^*(892)^0$	$< 3.0 \times 10^{-3}$	CL=90%	2138
$D_S^{*-} \pi^+ K^*(892)^0$	$< 1.6 \times 10^{-3}$	CL=90%	2076
$\bar{D}^0 K^0$	$( 5.5 \pm 0.4 ) \times 10^{-5}$		2280
$\bar{D}^0 K^+ \pi^-$	$( 8.8 \pm 1.7 ) \times 10^{-5}$		2262
$\bar{D}^0 K^*(892)^0$	$( 4.5 \pm 0.6 ) \times 10^{-5}$		2213
$\bar{D}^0 K^*(1410)^0$	$< 6.7 \times 10^{-5}$	CL=90%	2062
$\bar{D}^0 K_0^*(1430)^0$	$( 7 \pm 7 ) \times 10^{-6}$		2058
$\bar{D}^0 K_2^*(1430)^0$	$( 2.1 \pm 0.9 ) \times 10^{-5}$		2057
$D_0^*(2300)^- K^+, D_0^{*-} \rightarrow \bar{D}^0 \pi^-$	$( 1.9 \pm 0.9 ) \times 10^{-5}$		—
$D_2^*(2460)^- K^+, D_2^{*-} \rightarrow \bar{D}^0 \pi^-$	$( 2.03 \pm 0.35 ) \times 10^{-5}$		2029
$D_3^*(2760)^- K^+, D_3^{*-} \rightarrow \bar{D}^0 \pi^-$	$< 1.0 \times 10^{-6}$	CL=90%	—
$\bar{D}^0 K^+ \pi^-$ nonresonant	$< 3.7 \times 10^{-5}$	CL=90%	2262
$[K^+ K^-]_D K^*(892)^0$	$( 4.2 \pm 0.7 ) \times 10^{-5}$		—
$[\pi^+ \pi^-]_D K^*(892)^0$	$( 6.0 \pm 1.1 ) \times 10^{-5}$		—
$[\pi^+ \pi^- \pi^+ \pi^-]_D K^{*0}$	$( 4.6 \pm 0.9 ) \times 10^{-5}$		—
$\bar{D}^0 \pi^0$	$( 2.67 \pm 0.09 ) \times 10^{-4}$		2308
$\bar{D}^0 \rho^0$	$( 3.21 \pm 0.21 ) \times 10^{-4}$		2237
$\bar{D}^0 f_2$	$( 1.56 \pm 0.21 ) \times 10^{-4}$		—
$\bar{D}^0 \eta$	$( 2.56 \pm 0.12 ) \times 10^{-4}$		2274
$\bar{D}^0 \eta'$	$( 1.38 \pm 0.16 ) \times 10^{-4}$	S=1.3	2198
$\bar{D}^0 \omega$	$( 2.54 \pm 0.16 ) \times 10^{-4}$		2235
$\bar{D}^0 \phi$	$( 7.7 \pm 2.3 ) \times 10^{-7}$		2183
$D^0 K^+ \pi^-$	$( 5.3 \pm 3.2 ) \times 10^{-6}$		2262
$D^0 K^*(892)^0$	$( 3.0 \pm 0.6 ) \times 10^{-6}$		2213
$\bar{D}^{*0} \gamma$	$< 2.5 \times 10^{-5}$	CL=90%	2258
$\bar{D}^*(2007)^0 \pi^0$	$( 2.2 \pm 0.6 ) \times 10^{-4}$	S=2.6	2256
$\bar{D}^*(2007)^0 \rho^0$	$< 5.1 \times 10^{-4}$	CL=90%	2182
$\bar{D}^*(2007)^0 \eta$	$( 2.3 \pm 0.6 ) \times 10^{-4}$	S=2.8	2220
$\bar{D}^*(2007)^0 \eta'$	$( 1.40 \pm 0.22 ) \times 10^{-4}$		2141
$\bar{D}^*(2007)^0 \pi^+ \pi^-$	$( 6.2 \pm 2.2 ) \times 10^{-4}$		2249

$\bar{D}^*(2007)^0 K^+ \pi^-$	$( 5.2 \pm 1.9 ) \times 10^{-5}$		2207
$\bar{D}^*(2007)^0 K^0$	$( 3.6 \pm 1.2 ) \times 10^{-5}$		2227
$\bar{D}^*(2007)^0 K^*(892)^0$	$< 6.9 \times 10^{-5}$	CL=90%	2157
$\bar{D}^*(2007)^0 \phi$	$( 2.2 \pm 0.6 ) \times 10^{-6}$		2125
$D^*(2007)^0 K^*(892)^0$	$< 4.0 \times 10^{-5}$	CL=90%	2157
$D^*(2007)^0 \pi^+ \pi^+ \pi^- \pi^-$	$( 2.7 \pm 0.5 ) \times 10^{-3}$		2219
$D^*(2010)^+ D^*(2010)^-$	$( 8.0 \pm 0.6 ) \times 10^{-4}$		1711
$\bar{D}^*(2007)^0 \omega$	$( 3.6 \pm 1.1 ) \times 10^{-4}$	S=3.1	2180
$D^*(2010)^+ D^-$	$( 6.1 \pm 1.5 ) \times 10^{-4}$	S=1.6	1790
$D^*(2007)^0 \bar{D}^*(2007)^0$	$< 9 \times 10^{-5}$	CL=90%	1715
$D^- D^0 K^+$	$( 1.07 \pm 0.11 ) \times 10^{-3}$		1574
$D^- D^*(2007)^0 K^+$	$( 3.5 \pm 0.4 ) \times 10^{-3}$		1478
$D^*(2010)^- D^0 K^+$	$( 2.47 \pm 0.21 ) \times 10^{-3}$		1479
$D^*(2010)^- D^*(2007)^0 K^+$	$( 1.06 \pm 0.09 ) \%$		1366
$D^- D^+ K^0$	$( 7.5 \pm 1.7 ) \times 10^{-4}$		1568
$D^*(2010)^- D^+ K^0 +$ $D^- D^*(2010)^+ K^0$	$( 6.4 \pm 0.5 ) \times 10^{-3}$		1473
$D^*(2010)^- D^*(2010)^+ K^0$	$( 8.1 \pm 0.7 ) \times 10^{-3}$		1360
$D^{*-} D_{s1}(2536)^+, D_{s1}^+ \rightarrow$ $D^{*+} K^0$	$( 8.0 \pm 2.4 ) \times 10^{-4}$		1336
$\bar{D}^0 D^0 K^0$	$( 2.7 \pm 1.1 ) \times 10^{-4}$		1575
$D^0 \bar{D}^0 K^+ \pi^-$	$( 3.5 \pm 0.5 ) \times 10^{-4}$		1476
$\bar{D}^0 D^*(2007)^0 K^0 +$ $\bar{D}^*(2007)^0 D^0 K^0$	$( 1.1 \pm 0.5 ) \times 10^{-3}$		1478
$\bar{D}^*(2007)^0 D^*(2007)^0 K^0$	$( 2.4 \pm 0.9 ) \times 10^{-3}$		1365
$(\bar{D} + \bar{D}^*)(D + D^*)K$	$( 3.68 \pm 0.26 ) \%$		-

## Charmonium modes

$\eta_c K^0$	$( 9.0 \pm 1.1 ) \times 10^{-4}$		1751
$\eta_c(1S) K^+ \pi^-$	$( 6.5 \pm 0.7 ) \times 10^{-4}$		1722
$\eta_c(1S) K^+ \pi^-$ (NR)	$( 6.7 \pm 1.4 ) \times 10^{-5}$		-
$T_{c\bar{c}}(4100)^- K^+, T_{c\bar{c}}^- \rightarrow$ $\eta_c \pi^-$	$( 2.2 \pm 1.1 ) \times 10^{-5}$		-
$\eta_c(1S) K^*(1410)^0$	$( 2.1 \pm 1.6 ) \times 10^{-4}$		1395
$\eta_c(1S) K_0^*(1430)^0$	$( 1.8 \pm 0.4 ) \times 10^{-4}$		1387
$\eta_c(1S) K_2^*(1430)^0$	$( 5.4 \pm_{-2.9}^{2.4} ) \times 10^{-5}$		1386
$\eta_c(1S) K^*(1680)^0$	$( 4 \pm 4 ) \times 10^{-5}$		1166
$\eta_c(1S) K_0^*(1950)^0$	$( 4.8 \pm_{-4.0}^{3.2} ) \times 10^{-5}$		-
$\eta_c K^*(892)^0$	$( 5.3 \pm_{-0.9}^{0.8} ) \times 10^{-4}$	S=1.7	1646
$\eta_c(2S) K_S^0, \eta_c \rightarrow p \bar{p} \pi^+ \pi^-$	$( 4.2 \pm_{-1.2}^{1.4} ) \times 10^{-7}$		-
$\eta_c(2S) K^{*0}$	$< 3.9 \times 10^{-4}$	CL=90%	1159
$h_c(1P) K_S^0$	$< 1.4 \times 10^{-5}$		1401
$h_c(1P) K^{*0}$	$< 4 \times 10^{-4}$	CL=90%	1253
$J/\psi(1S) K^0$	$( 8.91 \pm 0.21 ) \times 10^{-4}$		1683
$J/\psi(1S) K^+ \pi^-$	$( 1.15 \pm 0.05 ) \times 10^{-3}$		1652
$J/\psi(1S) K^*(892)^0$	$( 1.27 \pm 0.05 ) \times 10^{-3}$		1572
$J/\psi(1S) \eta K_S^0$	$( 5.4 \pm 0.9 ) \times 10^{-5}$		1508
$J/\psi(1S) \eta' K_S^0$	$< 2.5 \times 10^{-5}$	CL=90%	1271
$J/\psi(1S) \phi K^0$	$( 4.9 \pm 1.0 ) \times 10^{-5}$	S=1.3	1224
$J/\psi(1S) \omega K^0$	$( 2.3 \pm 0.4 ) \times 10^{-4}$		1386
$\chi_{c0}(3915), \chi_{c0} \rightarrow J/\psi \omega$	$( 2.1 \pm 0.9 ) \times 10^{-5}$		1102
$J/\psi(1S) K(1270)^0$	$( 1.3 \pm 0.5 ) \times 10^{-3}$		1402
$J/\psi(1S) \pi^0$	$( 1.66 \pm 0.10 ) \times 10^{-5}$		1728

$J/\psi(1S)\eta$	$(1.08 \pm 0.23) \times 10^{-5}$	S=1.5	1673
$J/\psi(1S)\pi^+\pi^-$	$(3.99 \pm 0.15) \times 10^{-5}$		1716
$J/\psi(1S)\pi^+\pi^-$ nonresonant	$< 1.2 \times 10^{-5}$	CL=90%	1716
$J/\psi(1S)f_0(500), f_0 \rightarrow \pi\pi$	$(8.8 \pm_{-1.6}^{+1.2}) \times 10^{-6}$		-
$J/\psi(1S)f_2$	$(3.3 \pm_{-0.6}^{+0.5}) \times 10^{-6}$	S=1.5	-
$J/\psi(1S)\rho^0$	$(2.55 \pm_{-0.16}^{+0.18}) \times 10^{-5}$		1612
$J/\psi(1S)f_0(980), f_0 \rightarrow \pi^+\pi^-$	$< 1.1 \times 10^{-6}$	CL=90%	-
$J/\psi(1S)\rho(1450)^0, \rho^0 \rightarrow \pi\pi$	$(2.9 \pm_{-0.7}^{+1.6}) \times 10^{-6}$		-
$J/\psi\rho(1700)^0, \rho^0 \rightarrow \pi^+\pi^-$	$(2.0 \pm 1.3) \times 10^{-6}$		-
$J/\psi(1S)\omega$	$(1.8 \pm_{-0.5}^{+0.7}) \times 10^{-5}$		1609
$J/\psi(1S)K^+K^-$	$(2.53 \pm 0.35) \times 10^{-6}$		1534
$J/\psi(1S)a_0(980), a_0 \rightarrow K^+K^-$	$(4.7 \pm 3.4) \times 10^{-7}$		-
$J/\psi(1S)\phi$	$< 1.1 \times 10^{-7}$	CL=90%	1520
$J/\psi(1S)\eta'(958)$	$(7.6 \pm 2.4) \times 10^{-6}$		1546
$J/\psi(1S)K^0\pi^+\pi^-$	$(4.5 \pm 0.4) \times 10^{-4}$		1611
$J/\psi(1S)K^0K^-\pi^+ + \text{c.c.}$	$< 2.1 \times 10^{-5}$	CL=90%	1468
$J/\psi(1S)K^0K^+K^-$	$(2.5 \pm 0.7) \times 10^{-5}$	S=1.8	1249
$J/\psi(1S)K^0\rho^0$	$(5.4 \pm 3.0) \times 10^{-4}$		1390
$J/\psi(1S)K^*(892)^+\pi^-$	$(8 \pm 4) \times 10^{-4}$		1515
$J/\psi(1S)\pi^+\pi^-\pi^+\pi^-$	$(1.44 \pm 0.12) \times 10^{-5}$		1670
$J/\psi(1S)f_1(1285)$	$(8.4 \pm 2.1) \times 10^{-6}$		1385
$J/\psi(1S)K^*(892)^0\pi^+\pi^-$	$(6.6 \pm 2.2) \times 10^{-4}$		1447
$\eta_{c2}(1D)K_S^0, \eta_{c2} \rightarrow h_c\gamma$	$< 3.5 \times 10^{-5}$	CL=90%	-
$\eta_{c2}(1D)\pi^-K^+, \eta_{c2} \rightarrow h_c\gamma$	$< 1.0 \times 10^{-4}$	CL=90%	-
$\chi_{c1}(3872)^-K^+$	$< 5 \times 10^{-4}$	CL=90%	-
$\chi_{c1}(3872)^-K^+,$ $\chi_{c1}(3872)^- \rightarrow J/\psi(1S)\pi^-\pi^0$	$[nnn] < 4.2 \times 10^{-6}$	CL=90%	-
$\chi_{c1}(3872)K^0$	$(1.4 \pm 0.4) \times 10^{-4}$	S=1.1	1140
$\chi_{c1}(3872)K^*(892)^0$	$(1.1 \pm 0.5) \times 10^{-4}$		940
$\chi_{c1}(3872)K^+\pi^-$	$(2.2 \pm 0.7) \times 10^{-4}$		1087
$\chi_{c1}(3872)\gamma$	$< 1.5 \times 10^{-5}$	CL=90%	1220
$T_{c\bar{c}1}(4430)^\pm K^\mp, T_{c\bar{c}1}^\pm \rightarrow \psi(2S)\pi^\pm$	$(6.0 \pm_{-2.4}^{+3.0}) \times 10^{-5}$		583
$T_{c\bar{c}1}(4430)^\pm K^\mp, T_{c\bar{c}1}^\pm \rightarrow J/\psi\pi^\pm$	$(5.4 \pm_{-1.2}^{+4.0}) \times 10^{-6}$		583
$T_{c\bar{c}1}(3900)^\pm K^\mp, T_{c\bar{c}1}^\pm \rightarrow J/\psi\pi^\pm$	$< 9 \times 10^{-7}$		-
$T_{c\bar{c}1}(4200)^\pm K^\mp, T_{c\bar{c}1}^\pm \rightarrow J/\psi\pi^\pm$	$(2.2 \pm_{-0.8}^{+1.3}) \times 10^{-5}$		-
$J/\psi(1S)p\bar{p}$	$(4.5 \pm 0.6) \times 10^{-7}$		862
$J/\psi(1S)\gamma$	$< 1.5 \times 10^{-6}$	CL=90%	1732
$J/\psi\mu^+\mu^-, J/\psi \rightarrow \mu^+\mu^-$	$< 1.0 \times 10^{-9}$	CL=95%	-
$J/\psi(1S)\bar{D}^0$	$< 1.3 \times 10^{-5}$	CL=90%	877
$\psi(2S)\pi^0$	$(1.17 \pm 0.19) \times 10^{-5}$		1348
$\psi(2S)K^0$	$(5.8 \pm 0.5) \times 10^{-4}$		1283
$\psi(2S)K^0\pi^+\pi^-$	$(2.81 \pm 0.30) \times 10^{-4}$		1177
$\psi(3770)K^0, \psi \rightarrow \bar{D}^0D^0$	$< 1.23 \times 10^{-4}$	CL=90%	1217
$\psi(3770)K^0, \psi \rightarrow D^-D^+$	$< 1.88 \times 10^{-4}$	CL=90%	1217

$\psi(2S)\pi^+\pi^-$	$(2.24 \pm 0.35) \times 10^{-5}$		1332
$\psi(2S)K^+\pi^-$	$(5.8 \pm 0.4) \times 10^{-4}$		1239
$\psi(2S)K^*(892)^0$	$(5.9 \pm 0.4) \times 10^{-4}$		1116
$\chi_{c0}K^0$	$(1.9 \pm 0.4) \times 10^{-4}$		1478
$\chi_{c0}K^*(892)^0$	$(1.7 \pm 0.4) \times 10^{-4}$		1342
$\chi_{c1}\pi^0$	$(1.12 \pm 0.28) \times 10^{-5}$		1468
$\chi_{c1}K^0$	$(3.95 \pm 0.27) \times 10^{-4}$		1411
$\chi_{c1}\pi^-K^+$	$(4.97 \pm 0.30) \times 10^{-4}$		1372
$\chi_{c1}K^*(892)^0$	$(2.38 \pm 0.19) \times 10^{-4}$	S=1.2	1265
$T_{c\bar{c}}(4050)^-K^+, T_{c\bar{c}}^- \rightarrow$	$(3.0 \begin{smallmatrix} + \\ - \end{smallmatrix} \begin{smallmatrix} 4.0 \\ 1.8 \end{smallmatrix}) \times 10^{-5}$		-
$\chi_{c1}\pi^-$			
$T_{c\bar{c}}(4250)^-K^+, T_{c\bar{c}}^- \rightarrow$	$(4.0 \begin{smallmatrix} + \\ - \end{smallmatrix} \begin{smallmatrix} 20.0 \\ 1.0 \end{smallmatrix}) \times 10^{-5}$		-
$\chi_{c1}\pi^-$			
$\chi_{c1}\pi^+\pi^-K^0$	$(3.2 \pm 0.5) \times 10^{-4}$		1318
$\chi_{c1}\pi^-\pi^0K^+$	$(3.5 \pm 0.6) \times 10^{-4}$		1321
$\chi_{c2}K^0$	$< 1.5 \times 10^{-5}$	CL=90%	1379
$\chi_{c2}K^*(892)^0$	$(4.9 \pm 1.2) \times 10^{-5}$	S=1.1	1228
$\chi_{c2}\pi^-K^+$	$(7.2 \pm 1.0) \times 10^{-5}$		1338
$\chi_{c2}\pi^+\pi^-K^0$	$< 1.70 \times 10^{-4}$	CL=90%	1282
$\chi_{c2}\pi^-\pi^0K^+$	$< 7.4 \times 10^{-5}$	CL=90%	1286
$\psi(4660)K^0, \psi \rightarrow \Lambda_c^+\Lambda_c^-$	$< 2.3 \times 10^{-4}$	CL=90%	-
$\psi(4230)^0K^0, \psi^0 \rightarrow J/\psi\pi^+\pi^-$	$< 1.7 \times 10^{-5}$	CL=90%	-
<b>K or K* modes</b>			
$K^+\pi^-$	$(2.00 \pm 0.04) \times 10^{-5}$		2615
$K^0\pi^0$	$(1.01 \pm 0.04) \times 10^{-5}$		2615
$\eta'K^0$	$(6.6 \pm 0.4) \times 10^{-5}$	S=1.4	2528
$\eta'K^*(892)^0$	$(2.8 \pm 0.6) \times 10^{-6}$		2472
$\eta'K_0^*(1430)^0$	$(6.3 \pm 1.6) \times 10^{-6}$		2346
$\eta'K_2^*(1430)^0$	$(1.37 \pm 0.32) \times 10^{-5}$		2346
$\eta K^0$	$(1.23 \begin{smallmatrix} + \\ - \end{smallmatrix} \begin{smallmatrix} 0.27 \\ 0.24 \end{smallmatrix}) \times 10^{-6}$		2587
$\eta K^*(892)^0$	$(1.59 \pm 0.10) \times 10^{-5}$		2534
$\eta K_0^*(1430)^0$	$(1.10 \pm 0.22) \times 10^{-5}$		2415
$\eta K_2^*(1430)^0$	$(9.6 \pm 2.1) \times 10^{-6}$		2414
$\omega K^0$	$(4.8 \pm 0.4) \times 10^{-6}$		2557
$a_0(980)^0K^0, a_0^0 \rightarrow \eta\pi^0$	$< 7.8 \times 10^{-6}$	CL=90%	-
$b_1^0K^0, b_1^0 \rightarrow \omega\pi^0$	$< 7.8 \times 10^{-6}$	CL=90%	-
$a_0(980)^\pm K^\mp, a_0^\pm \rightarrow \eta\pi^\pm$	$< 1.9 \times 10^{-6}$	CL=90%	-
$b_1^-K^+, b_1^- \rightarrow \omega\pi^-$	$(7.4 \pm 1.4) \times 10^{-6}$		-
$b_1^0K^{*0}, b_1^0 \rightarrow \omega\pi^0$	$< 8.0 \times 10^{-6}$	CL=90%	-
$b_1^-K^{*+}, b_1^- \rightarrow \omega\pi^-$	$< 5.0 \times 10^{-6}$	CL=90%	-
$a_0(1450)^\pm K^\mp, a_0^\pm \rightarrow \eta\pi^\pm$	$< 3.1 \times 10^{-6}$	CL=90%	-
$K_S^0 X^0$ (Familon)	$< 5.3 \times 10^{-5}$	CL=90%	-
$\omega K^*(892)^0$	$(2.0 \pm 0.5) \times 10^{-6}$		2503
$\omega(K\pi)_0^{*0}$	$(1.84 \pm 0.25) \times 10^{-5}$		-
$\omega K_0^*(1430)^0$	$(1.60 \pm 0.34) \times 10^{-5}$		2380
$\omega K_2^*(1430)^0$	$(1.01 \pm 0.23) \times 10^{-5}$		2380
$\omega K^+\pi^-$ nonresonant	$(5.1 \pm 1.0) \times 10^{-6}$		2542
$K^+\pi^-\pi^0$	$(3.78 \pm 0.32) \times 10^{-5}$		2610
$K^+\rho^-$	$(7.0 \pm 0.9) \times 10^{-6}$		2559
$K^+\rho(1450)^-$	$(2.4 \pm 1.2) \times 10^{-6}$		-
$K^+\rho(1700)^-$	$(6 \pm 7) \times 10^{-7}$		-
$(K^+\pi^-\pi^0)$ nonresonant	$(2.8 \pm 0.6) \times 10^{-6}$		2610

$(K\pi)_0^{*+} \pi^-, (K\pi)_0^{*+} \rightarrow$	$(3.4 \pm 0.5) \times 10^{-5}$		—
$K^+ \pi^0$			
$(K\pi)_0^{*0} \pi^0, (K\pi)_0^{*0} \rightarrow K^+ \pi^-$	$(8.6 \pm 1.7) \times 10^{-6}$		—
$K_2^*(1430)^0 \pi^0$	$< 4.0 \times 10^{-6}$	CL=90%	2445
$K^*(1680)^0 \pi^0$	$< 7.5 \times 10^{-6}$	CL=90%	2358
$K_x^{*0} \pi^0$	$(6.1 \pm 1.6) \times 10^{-6}$		—
$K^0 \pi^+ \pi^-$	$(4.97 \pm 0.18) \times 10^{-5}$		2609
$K^0 \pi^+ \pi^-$ nonresonant	$(1.39 \pm_{-0.18}^{+0.26}) \times 10^{-5}$	S=1.6	2609
$K^0 \rho^0$	$(3.4 \pm 1.1) \times 10^{-6}$	S=2.3	2558
$K^*(892)^+ \pi^-$	$(7.5 \pm 0.4) \times 10^{-6}$		2563
$K_0^*(1430)^+ \pi^-$	$(3.3 \pm 0.7) \times 10^{-5}$	S=2.0	—
$K_x^{*+} \pi^-$	$(5.1 \pm 1.6) \times 10^{-6}$		—
$K^*(1410)^+ \pi^-, K^{*+} \rightarrow$	$< 3.8 \times 10^{-6}$	CL=90%	—
$K^0 \pi^+$			
$(K\pi)_0^{*+} \pi^-, (K\pi)_0^{*+} \rightarrow$	$(1.62 \pm 0.13) \times 10^{-5}$		—
$K^0 \pi^+$			
$f_0(980) K^0, f_0 \rightarrow \pi^+ \pi^-$	$(8.1 \pm 0.8) \times 10^{-6}$	S=1.3	2522
$K^0 f_0(500)$	$(1.6 \pm_{-1.6}^{+2.5}) \times 10^{-7}$		—
$K^0 f_0(1500)$	$(1.3 \pm 0.8) \times 10^{-6}$		2393
$f_2(1270) K^0$	$(2.7 \pm_{-1.2}^{+1.3}) \times 10^{-6}$		2459
$f_x(1300) K^0, f_x \rightarrow \pi^+ \pi^-$	$(1.8 \pm 0.7) \times 10^{-6}$		—
$K^*(892)^0 \pi^0$	$(3.3 \pm 0.6) \times 10^{-6}$		2563
$K_2^*(1430)^+ \pi^-$	$(3.65 \pm 0.34) \times 10^{-6}$		2445
$K^*(1680)^+ \pi^-$	$(1.41 \pm 0.10) \times 10^{-5}$		2358
$K^+ \pi^- \pi^+ \pi^-$	$< 2.3 \times 10^{-4}$	CL=90%	2600
$\rho^0 K^+ \pi^-$	$(2.8 \pm 0.7) \times 10^{-6}$		2543
$f_0(980) K^+ \pi^-, f_0 \rightarrow \pi \pi$	$(1.4 \pm_{-0.6}^{+0.5}) \times 10^{-6}$		2506
$K^+ \pi^- \pi^+ \pi^-$ nonresonant	$< 2.1 \times 10^{-6}$	CL=90%	2600
$K^*(892)^0 \pi^+ \pi^-$	$(5.5 \pm 0.5) \times 10^{-5}$		2557
$K^*(892)^0 \rho^0$	$(3.9 \pm 1.3) \times 10^{-6}$	S=1.9	2504
$K^*(892)^0 f_0(980), f_0 \rightarrow \pi \pi$	$(3.9 \pm_{-1.8}^{+2.1}) \times 10^{-6}$	S=3.9	2466
$K_1(1270)^+ \pi^-$	$< 3.0 \times 10^{-5}$	CL=90%	2489
$K_1(1400)^+ \pi^-$	$< 2.7 \times 10^{-5}$	CL=90%	2451
$a_1(1260)^- K^+$	$(1.6 \pm 0.4) \times 10^{-5}$		2471
$K^*(892)^+ \rho^-$	$(1.03 \pm 0.26) \times 10^{-5}$		2504
$K_0^*(1430)^+ \rho^-$	$(2.8 \pm 1.2) \times 10^{-5}$		—
$K_1(1400)^0 \rho^0$	$< 3.0 \times 10^{-3}$	CL=90%	2388
$K_0^*(1430)^0 \rho^0$	$(2.7 \pm 0.6) \times 10^{-5}$		2381
$K_0^*(1430)^0 f_0(980), f_0 \rightarrow \pi \pi$	$(2.7 \pm 0.9) \times 10^{-6}$		—
$K_2^*(1430)^0 f_0(980), f_0 \rightarrow \pi \pi$	$(8.6 \pm 2.0) \times 10^{-6}$		—
$K^+ K^-$	$(7.8 \pm 1.5) \times 10^{-8}$		2593
$K^0 \bar{K}^0$	$(1.21 \pm 0.16) \times 10^{-6}$		2593
$K^0 K^- \pi^+$	$(6.7 \pm 0.5) \times 10^{-6}$		2578
$K^*(892)^\pm K^\mp$	$< 4 \times 10^{-7}$	CL=90%	2540
$\bar{K}^{*0} K^0 + K^{*0} \bar{K}^0$	$< 9.6 \times 10^{-7}$	CL=90%	—
$K^+ K^- \pi^0$	$(2.2 \pm 0.6) \times 10^{-6}$		2579
$K_S^0 K_S^0 \pi^0$	$< 9 \times 10^{-7}$	CL=90%	2578
$K_S^0 K_S^0 \eta$	$< 1.0 \times 10^{-6}$	CL=90%	2516
$K_S^0 K_S^0 \eta'$	$< 2.0 \times 10^{-6}$	CL=90%	2453
$K^0 K^+ K^-$	$(2.68 \pm 0.11) \times 10^{-5}$		2522
$K^0 \phi$	$(7.3 \pm 0.7) \times 10^{-6}$		2516

$f_0(980)K^0, f_0 \rightarrow K^+K^-$	$(7.0 \pm_{-3.0}^{+3.5}) \times 10^{-6}$		—
$f_0(1500)K^0$	$(1.3 \pm_{-0.5}^{+0.7}) \times 10^{-5}$		2393
$f'_2(1525)^0K^0$	$(3 \pm_{-4}^{+5}) \times 10^{-7}$		—
$f_0(1710)K^0, f_0 \rightarrow K^+K^-$	$(4.4 \pm 0.9) \times 10^{-6}$		—
$K^0K^+K^-$ nonresonant	$(3.3 \pm 1.0) \times 10^{-5}$		2522
$K_S^0K_S^0K_S^0, f_0 \rightarrow K_S^0K_S^0$	$(6.0 \pm 0.5) \times 10^{-6}$	S=1.1	2521
$f_0(980)K^0, f_0 \rightarrow K_S^0K_S^0$	$(2.7 \pm 1.8) \times 10^{-6}$		—
$f_0(1710)K^0, f_0 \rightarrow K_S^0K_S^0$	$(5.0 \pm_{-2.6}^{+5.0}) \times 10^{-7}$		—
$f_2(2010)K^0, f_2 \rightarrow K_S^0K_S^0$	$(5 \pm 6) \times 10^{-7}$		—
$K_S^0K_S^0K_S^0$ nonresonant	$(1.33 \pm 0.31) \times 10^{-5}$		2521
$K_S^0K_S^0K_L^0$	$< 1.6 \times 10^{-5}$	CL=90%	2521
$K^*(892)^0K^+K^-$	$(2.75 \pm 0.26) \times 10^{-5}$		2467
$K^*(892)^0\phi$	$(1.00 \pm 0.05) \times 10^{-5}$		2460
$K^+K^-\pi^+\pi^-$ nonresonant	$< 7.17 \times 10^{-5}$	CL=90%	2559
$K^*(892)^0K^-\pi^+$	$(4.5 \pm 1.3) \times 10^{-6}$		2524
$K^*(892)^0\bar{K}^*(892)^0$	$(8.3 \pm 2.4) \times 10^{-7}$	S=1.5	2485
$K^+K^+\pi^-\pi^-$ nonresonant	$< 6.0 \times 10^{-6}$	CL=90%	2559
$K^*(892)^0K^+\pi^-$	$< 2.2 \times 10^{-6}$	CL=90%	2524
$K^*(892)^0K^*(892)^0$	$< 2 \times 10^{-7}$	CL=90%	2485
$K^*(892)^+K^*(892)^-$	$< 2.0 \times 10^{-6}$	CL=90%	2485
$K_1(1400)^0\phi$	$< 5.0 \times 10^{-3}$	CL=90%	2340
$\phi(K\pi)_0^{*0}$	$(4.3 \pm 0.4) \times 10^{-6}$		—
$\phi(K\pi)_0^{*0} (1.60 < m_{K\pi} < 2.15)$ [sss]	$< 1.7 \times 10^{-6}$	CL=90%	—
$K_0^*(1430)^0K^-\pi^+$	$< 3.18 \times 10^{-5}$	CL=90%	2404
$K_0^*(1430)^0\bar{K}^*(892)^0$	$< 3.3 \times 10^{-6}$	CL=90%	2360
$K_0^*(1430)^0\bar{K}_0^*(1430)^0$	$< 8.4 \times 10^{-6}$	CL=90%	2222
$K_0^*(1430)^0\phi$	$(3.9 \pm 0.8) \times 10^{-6}$		2333
$K_0^*(1430)^0K^*(892)^0$	$< 1.7 \times 10^{-6}$	CL=90%	2360
$K_0^*(1430)^0K_0^*(1430)^0$	$< 4.7 \times 10^{-6}$	CL=90%	2222
$K^*(1680)^0\phi$	$< 3.5 \times 10^{-6}$	CL=90%	2238
$K^*(1780)^0\phi$	$< 2.7 \times 10^{-6}$	CL=90%	—
$K^*(2045)^0\phi$	$< 1.53 \times 10^{-5}$	CL=90%	—
$K_2^*(1430)^0\rho^0$	$< 1.1 \times 10^{-3}$	CL=90%	2381
$K_2^*(1430)^0\phi$	$(6.8 \pm 0.9) \times 10^{-6}$	S=1.2	2332
$K_0^0\phi\phi$	$(3.7 \pm 0.7) \times 10^{-6}$	S=1.3	2305
$\eta'\eta'K^0$	$< 3.1 \times 10^{-5}$	CL=90%	2338
$\eta K^0\gamma$	$(7.6 \pm 1.8) \times 10^{-6}$		2587
$\eta'K^0\gamma$	$< 6.4 \times 10^{-6}$	CL=90%	2528
$K^0\phi\gamma$	$(2.7 \pm 0.7) \times 10^{-6}$		2516
$K^+\pi^-\gamma$	$(4.6 \pm 1.4) \times 10^{-6}$		2615
$K^*(892)^0\gamma$	$(4.18 \pm 0.25) \times 10^{-5}$	S=2.1	2565
$K^*(1410)\gamma$	$< 1.3 \times 10^{-4}$	CL=90%	2451
$K^+\pi^-\gamma$ nonresonant	$< 2.6 \times 10^{-6}$	CL=90%	2615
$K^*(892)^0X(214), X \rightarrow \mu^+\mu^-$ [ttt]	$< 2.26 \times 10^{-8}$	CL=90%	—
$K^0\pi^+\pi^-\gamma$	$(1.99 \pm 0.18) \times 10^{-5}$		2609
$K^+\pi^-\pi^0\gamma$	$(4.1 \pm 0.4) \times 10^{-5}$		2610
$K_1(1270)^0\gamma$	$< 5.8 \times 10^{-5}$	CL=90%	2491
$K_1(1400)^0\gamma$	$< 1.2 \times 10^{-5}$	CL=90%	2454
$K_2^*(1430)^0\gamma$	$(1.24 \pm 0.24) \times 10^{-5}$		2447
$K^*(1680)^0\gamma$	$< 2.0 \times 10^{-3}$	CL=90%	2360
$K_3^*(1780)^0\gamma$	$< 8.3 \times 10^{-5}$	CL=90%	2340



$K_4^*(2045)^0\gamma$	< 4.3	$\times 10^{-3}$	CL=90%	2243
<b>Light unflavored meson modes</b>				
$\rho^0\gamma$	( 8.6 $\pm$ 1.5 )	$\times 10^{-7}$		2583
$\rho^0 X(214), X \rightarrow \mu^+\mu^-$	[ttt] < 1.73	$\times 10^{-8}$	CL=90%	—
$\omega\gamma$	( 4.4 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 1.8 )	$\times 10^{-7}$		2582
$\phi\gamma$	< 1.0	$\times 10^{-7}$	CL=90%	2541
$f_2(1270)\gamma, f_2 \rightarrow (KS)^0(KS)^0$	< 3.1	$\times 10^{-7}$		—
$f_2'(1525)\gamma, f_2' \rightarrow (KS)^0(KS)^0$	< 2.1	$\times 10^{-7}$		—
$\pi^+\pi^-$	( 5.37 $\pm$ 0.20 )	$\times 10^{-6}$	S=1.3	2636
$\pi^0\pi^0$	( 1.55 $\pm$ 0.17 )	$\times 10^{-6}$	S=1.1	2636
$\eta\pi^0$	( 4.1 $\pm$ 1.7 )	$\times 10^{-7}$		2610
$\eta\eta$	< 1.0	$\times 10^{-6}$	CL=90%	2582
$\eta'\pi^0$	( 1.2 $\pm$ 0.6 )	$\times 10^{-6}$	S=1.7	2551
$\eta'\eta'$	< 1.7	$\times 10^{-6}$	CL=90%	2460
$\eta'\eta$	< 1.2	$\times 10^{-6}$	CL=90%	2523
$\eta'\rho^0$	< 1.3	$\times 10^{-6}$	CL=90%	2492
$\eta'f_0(980), f_0 \rightarrow \pi^+\pi^-$	< 9	$\times 10^{-7}$	CL=90%	2454
$\eta\rho^0$	< 1.5	$\times 10^{-6}$	CL=90%	2553
$\eta f_0(980), f_0 \rightarrow \pi^+\pi^-$	< 4	$\times 10^{-7}$	CL=90%	2516
$\omega\eta$	( 9.4 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 4.0 )	$\times 10^{-7}$		2552
$\omega\eta'$	( 1.0 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.5 )	$\times 10^{-6}$		2491
$\omega\rho^0$	< 1.6	$\times 10^{-6}$	CL=90%	2522
$\omega f_0(980), f_0 \rightarrow \pi^+\pi^-$	< 1.5	$\times 10^{-6}$	CL=90%	2485
$\omega\omega$	( 1.2 $\pm$ 0.4 )	$\times 10^{-6}$		2521
$\phi\pi^0$	< 1.5	$\times 10^{-7}$	CL=90%	2540
$\phi\eta$	< 5	$\times 10^{-7}$	CL=90%	2511
$\phi\eta'$	< 5	$\times 10^{-7}$	CL=90%	2448
$\phi\pi^+\pi^-$	( 1.8 $\pm$ 0.5 )	$\times 10^{-7}$		2533
$\phi\rho^0$	< 3.3	$\times 10^{-7}$	CL=90%	2480
$\phi f_0(980), f_0 \rightarrow \pi^+\pi^-$	< 3.8	$\times 10^{-7}$	CL=90%	2441
$\phi\omega$	< 7	$\times 10^{-7}$	CL=90%	2479
$\phi\phi$	< 2.7	$\times 10^{-8}$	CL=90%	2435
$a_0(980)^\pm\pi^\mp, a_0^\pm \rightarrow \eta\pi^\pm$	< 3.1	$\times 10^{-6}$	CL=90%	—
$a_0(1450)^\pm\pi^\mp, a_0^\pm \rightarrow \eta\pi^\pm$	< 2.3	$\times 10^{-6}$	CL=90%	—
$\pi^+\pi^-\pi^0$	< 7.2	$\times 10^{-4}$	CL=90%	2631
$\rho^0\pi^0$	( 2.0 $\pm$ 0.5 )	$\times 10^{-6}$		2581
$\rho^\mp\pi^\pm$	[aa] ( 2.30 $\pm$ 0.23 )	$\times 10^{-5}$		2581
$\pi^+\pi^-\pi^+\pi^-$	< 1.12	$\times 10^{-5}$	CL=90%	2621
$\rho^0\pi^+\pi^-$	< 8.8	$\times 10^{-6}$	CL=90%	2575
$\rho^0\rho^0$	( 9.6 $\pm$ 1.5 )	$\times 10^{-7}$		2523
$f_0(980)\pi^+\pi^-, f_0 \rightarrow \pi^+\pi^-$	< 3.0	$\times 10^{-6}$	CL=90%	—
$\rho^0 f_0(980), f_0 \rightarrow \pi^+\pi^-$	( 7.8 $\pm$ 2.5 )	$\times 10^{-7}$		2486
$f_0(980)f_0(980), f_0 \rightarrow \pi^+\pi^-,$ $f_0 \rightarrow \pi^+\pi^-$	< 1.9	$\times 10^{-7}$	CL=90%	2447
$f_0(980)f_0(980), f_0 \rightarrow \pi^+\pi^-,$ $f_0 \rightarrow K^+K^-$	< 2.3	$\times 10^{-7}$	CL=90%	2447
$a_1(1260)^\mp\pi^\pm$	[aa] ( 2.6 $\pm$ 0.5 )	$\times 10^{-5}$	S=1.9	2495
$a_2(1320)^\mp\pi^\pm$	[aa] < 6.3	$\times 10^{-6}$	CL=90%	2473
$\pi^+\pi^-\pi^0\pi^0$	< 3.1	$\times 10^{-3}$	CL=90%	2622
$\rho^+\rho^-$	( 2.77 $\pm$ 0.19 )	$\times 10^{-5}$		2523
$a_1(1260)^0\pi^0$	< 1.1	$\times 10^{-3}$	CL=90%	2495
$\omega\pi^0$	< 5	$\times 10^{-7}$	CL=90%	2580

$\pi^+ \pi^+ \pi^- \pi^- \pi^0$	< 9.0	$\times 10^{-3}$	CL=90%	2609
$a_1(1260)^+ \rho^-$	< 6.1	$\times 10^{-5}$	CL=90%	2433
$a_1(1260)^0 \rho^0$	< 2.4	$\times 10^{-3}$	CL=90%	2433
$b_1^\mp \pi^\pm, b_1^\mp \rightarrow \omega \pi^\mp$	( 1.09 ± 0.15 )	$\times 10^{-5}$		—
$b_1^0 \pi^0, b_1^0 \rightarrow \omega \pi^0$	< 1.9	$\times 10^{-6}$	CL=90%	—
$b_1^- \rho^+, b_1^- \rightarrow \omega \pi^-$	< 1.4	$\times 10^{-6}$	CL=90%	—
$b_1^0 \rho^0, b_1^0 \rightarrow \omega \pi^0$	< 3.4	$\times 10^{-6}$	CL=90%	—
$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$	< 3.0	$\times 10^{-3}$	CL=90%	2592
$a_1(1260)^+ a_1(1260)^-, a_1^+ \rightarrow$ $2\pi^+ \pi^-, a_1^- \rightarrow 2\pi^- \pi^+$	( 1.18 ± 0.31 )	$\times 10^{-5}$		2336
$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0$	< 1.1	%	CL=90%	2572

**Baryon modes**

$p\bar{p}$	( 1.27 ± 0.14 )	$\times 10^{-8}$		2467
$p\bar{p}\pi^+ \pi^-$	( 2.87 ± 0.19 )	$\times 10^{-6}$		2406
$p\bar{p}K^+ \pi^-$	( 6.3 ± 0.5 )	$\times 10^{-6}$		2306
$p\bar{p}K^0$	( 2.66 ± 0.32 )	$\times 10^{-6}$		2347
$\Theta(1540)^+ \bar{p}, \Theta^+ \rightarrow pK_S^0$	[uuu] < 5	$\times 10^{-8}$	CL=90%	2318
$f_J(2220)K^0, f_J \rightarrow p\bar{p}$	< 4.5	$\times 10^{-7}$	CL=90%	2135
$p\bar{p}K^*(892)^0$	( 1.24 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.28 / 0.25 )	$\times 10^{-6}$		2216
$f_J(2220)K_0^*, f_J \rightarrow p\bar{p}$	< 1.5	$\times 10^{-7}$	CL=90%	—
$p\bar{p}K^+ K^-$	( 1.21 ± 0.32 )	$\times 10^{-7}$		2179
$p\bar{p}\pi^0$	( 5.0 ± 1.9 )	$\times 10^{-7}$		2440
$p\bar{p}p\bar{p}$	( 2.2 ± 0.4 )	$\times 10^{-8}$		1735
$p\bar{\Lambda}\pi^-$	( 3.16 ± 0.24 )	$\times 10^{-6}$		2401
$p\bar{\Lambda}\pi^- \gamma$	< 6.5	$\times 10^{-7}$	CL=90%	2401
$p\bar{\Sigma}^-(1385)^-$	< 2.6	$\times 10^{-7}$	CL=90%	2363
$\Delta(1232)^+ \bar{p} + \Delta(1232)^- p$	< 1.6	$\times 10^{-6}$		—
$\Delta^0 \bar{\Lambda}$	< 9.3	$\times 10^{-7}$	CL=90%	2364
$p\bar{\Lambda}K^-$	< 8.2	$\times 10^{-7}$	CL=90%	2308
$p\bar{\Lambda}D^-$	( 2.5 ± 0.4 )	$\times 10^{-5}$		1765
$p\bar{\Lambda}D^{*-}$	( 3.4 ± 0.8 )	$\times 10^{-5}$		1685
$p\bar{\Sigma}^0 \pi^-$	( 1.2 ± 0.4 )	$\times 10^{-6}$		2383
$\bar{\Lambda}\Lambda$	< 3.2	$\times 10^{-7}$	CL=90%	2393
$\bar{\Lambda}\Lambda K^0$	( 4.8 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 1.0 / 0.9 )	$\times 10^{-6}$		2250
$\bar{\Lambda}\Lambda K^{*0}$	( 2.5 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.9 / 0.8 )	$\times 10^{-6}$		2098
$\bar{\Lambda}\Lambda D^0$	( 1.00 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ 0.30 / 0.26 )	$\times 10^{-5}$		1662
$D^0 \Sigma^0 \bar{\Lambda} + c.c.$	< 3.1	$\times 10^{-5}$	CL=90%	1611
$\Delta^0 \bar{\Delta}^0$	< 1.5	$\times 10^{-3}$	CL=90%	2335
$\Delta^{++} \bar{\Delta}^{--}$	< 1.1	$\times 10^{-4}$	CL=90%	2335
$\bar{D}^0 p\bar{p}$	( 1.04 ± 0.07 )	$\times 10^{-4}$		1863
$D_S^- \bar{\Lambda} p$	( 2.8 ± 0.9 )	$\times 10^{-5}$		1710
$\bar{D}^*(2007)^0 p\bar{p}$	( 9.9 ± 1.1 )	$\times 10^{-5}$		1788
$D^*(2010)^- p\bar{n}$	( 1.4 ± 0.4 )	$\times 10^{-3}$		1785
$D^- p\bar{p}\pi^+$	( 3.32 ± 0.31 )	$\times 10^{-4}$		1786
$D^*(2010)^- p\bar{p}\pi^+$	( 4.7 ± 0.5 )	$\times 10^{-4}$	S=1.2	1708
$\bar{D}^0 p\bar{p}\pi^+ \pi^-$	( 3.0 ± 0.5 )	$\times 10^{-4}$		1708
$\bar{D}^{*0} p\bar{p}\pi^+ \pi^-$	( 1.9 ± 0.5 )	$\times 10^{-4}$		1623
$\Theta_c \bar{p}\pi^+, \Theta_c \rightarrow D^- p$	< 9	$\times 10^{-6}$	CL=90%	—
$\Theta_c \bar{p}\pi^+, \Theta_c \rightarrow D^{*-} p$	< 1.4	$\times 10^{-5}$	CL=90%	—
$\bar{\Sigma}_c^- \Delta^{++}$	< 8	$\times 10^{-4}$	CL=90%	1839
$\bar{\Lambda}_c^- p\pi^+ \pi^-$	( 1.02 ± 0.14 )	$\times 10^{-3}$	S=1.3	1934

$\bar{\Lambda}_c^- p$		$(1.55 \pm 0.17) \times 10^{-5}$		2021
$\bar{\Lambda}_c^- p \pi^0$		$(1.55 \pm 0.18) \times 10^{-4}$		1982
$\bar{\Sigma}_c(2455)^- p$		$< 2.4 \times 10^{-5}$		—
$\bar{\Lambda}_c^- p \pi^+ \pi^- \pi^0$		$< 5.07 \times 10^{-3}$	CL=90%	1883
$\bar{\Lambda}_c^- p \pi^+ \pi^- \pi^+ \pi^-$		$< 2.74 \times 10^{-3}$	CL=90%	1821
$\bar{\Lambda}_c^- p \pi^+ \pi^-$ (nonresonant)		$(5.5 \pm 1.0) \times 10^{-4}$	S=1.3	1934
$\bar{\Sigma}_c(2520)^{-} p \pi^+$		$(1.02 \pm 0.18) \times 10^{-4}$		1860
$\bar{\Sigma}_c(2520)^0 p \pi^-$		$< 3.1 \times 10^{-5}$	CL=90%	1860
$\bar{\Sigma}_c(2455)^0 p \pi^-$		$(1.08 \pm 0.09) \times 10^{-4}$		1895
$\bar{\Sigma}_c(2455)^0 N^0, N^0 \rightarrow p \pi^-$		$(6.4 \pm 1.7) \times 10^{-5}$		—
$\bar{\Sigma}_c(2455)^{-} p \pi^+$		$(1.89 \pm 0.15) \times 10^{-4}$		1895
$\Lambda_c^- p K^+ \pi^-$		$(3.5 \pm 0.7) \times 10^{-5}$		1786
$\bar{\Sigma}_c(2455)^{-} p K^+, \bar{\Sigma}_c^- \rightarrow \bar{\Lambda}_c^- \pi^-$		$(8.9 \pm 2.6) \times 10^{-6}$		1754
$\Lambda_c^- p K^*(892)^0$		$< 2.42 \times 10^{-5}$	CL=90%	1647
$\Lambda_c^- p K^+ K^-$		$(2.0 \pm 0.4) \times 10^{-5}$		1588
$\Lambda_c^- p \phi$		$< 1.0 \times 10^{-5}$	CL=90%	1567
$\Lambda_c^- p \bar{p} p$		$< 2.8 \times 10^{-6}$		677
$\bar{\Lambda}_c^- \Lambda K^+$		$(4.8 \pm 1.1) \times 10^{-5}$		1767
$\bar{\Lambda}_c^- \Lambda_c^+$		$< 1.6 \times 10^{-5}$	CL=95%	1319
$\bar{\Lambda}_c(2593)^- / \bar{\Lambda}_c(2625)^- p$		$< 1.1 \times 10^{-4}$	CL=90%	—
$\bar{\Xi}_c^- \Lambda_c^+$		$(1.2 \pm 0.8) \times 10^{-3}$		1147
$\bar{\Xi}_c^- \Lambda_c^+, \bar{\Xi}_c^- \rightarrow \bar{\Xi}^+ \pi^- \pi^-$		$(2.4 \pm 1.1) \times 10^{-5}$	S=1.8	1147
$\bar{\Xi}_c^- \Lambda_c^+, \bar{\Xi}_c^- \rightarrow \bar{p} K^+ \pi^-$		$(5.3 \pm 1.7) \times 10^{-6}$		—
$\Lambda_c^+ \Lambda_c^- K^0$		$(4.0 \pm 0.9) \times 10^{-4}$		732
$\bar{\Lambda}_c(2910)^- p, \bar{\Lambda}_c^- \rightarrow \bar{\Sigma}_c(2455)^{-} \pi^+$		$(1.2 \pm 0.4) \times 10^{-5}$		—
$\bar{\Lambda}_c(2910)^- p, \bar{\Lambda}_c^- \rightarrow \bar{\Sigma}_c(2455)^0 \pi^-$		$(10 \pm 4) \times 10^{-6}$		—
$\bar{\Xi}_c(2930)^- \Lambda_c^+, \bar{\Xi}_c^- \rightarrow \Lambda_c^- K^0$		$(2.4 \pm 0.6) \times 10^{-4}$		—
$\Lambda \psi_{DS}$	[vvv]	$< 0.13-5.2 \times 10^{-5}$		—

**Lepton Family number (LF) or Lepton number (L) or Baryon number (B) violating modes, or/and  $\Delta B = 1$  weak neutral current (B1) modes**

$\gamma \gamma$	B1	$< 3.2 \times 10^{-7}$	CL=90%	2640
$e^+ e^-$	B1	$< 2.5 \times 10^{-9}$	CL=90%	2640
$e^+ e^- \gamma$	B1	$< 1.2 \times 10^{-7}$	CL=90%	2640
$\mu^+ \mu^-$	B1	$< 1.5 \times 10^{-10}$	CL=90%	2638
$\mu^+ \mu^- \mu^+ \mu^-$	B1	$< 1.8 \times 10^{-10}$	CL=95%	2629
$SP, S \rightarrow \mu^+ \mu^-, P \rightarrow \mu^+ \mu^-$	B1 [xxx]	$< 6.0 \times 10^{-10}$	CL=95%	—
$aa, a \rightarrow \mu^+ \mu^-$	B1	$< 2.3 \times 10^{-10}$	CL=95%	—
$\tau^+ \tau^-$	B1	$< 2.1 \times 10^{-3}$	CL=95%	1952
$\pi^0 \ell^+ \ell^-$	B1 [hhh]	$< 5.3 \times 10^{-8}$	CL=90%	2638
$\pi^0 e^+ e^-$	B1	$< 8.4 \times 10^{-8}$	CL=90%	2638
$\pi^0 \mu^+ \mu^-$	B1	$< 6.9 \times 10^{-8}$	CL=90%	2634
$\eta \ell^+ \ell^-$	B1 [hhh]	$< 6.4 \times 10^{-8}$	CL=90%	2611
$\eta e^+ e^-$	B1	$< 1.08 \times 10^{-7}$	CL=90%	2611
$\eta \mu^+ \mu^-$	B1	$< 1.12 \times 10^{-7}$	CL=90%	2607
$\pi^0 \nu \bar{\nu}$	B1	$< 9 \times 10^{-6}$	CL=90%	2638
$K^0 \ell^+ \ell^-$	B1 [hhh]	$(3.3 \pm 0.6) \times 10^{-7}$		2616
$K^0 e^+ e^-$	B1	$(2.5 \pm 1.1 / 0.9) \times 10^{-7}$	S=1.3	2616

$K^0 \mu^+ \mu^-$	$BI$	$(3.39 \pm 0.35) \times 10^{-7}$	$S=1.1$	2612
$K^0 \nu \bar{\nu}$	$BI$	$< 2.6 \times 10^{-5}$	$CL=90\%$	2616
$\rho^0 \nu \bar{\nu}$	$BI$	$< 4.0 \times 10^{-5}$	$CL=90\%$	2583
$K^*(892)^0 \ell^+ \ell^-$	$BI$ [hhh]	$(9.9 \pm_{-1.1}^{+1.2}) \times 10^{-7}$		2565
$K^*(892)^0 e^+ e^-$	$BI$	$(1.03 \pm_{0.17}^{+0.19}) \times 10^{-6}$		2565
$K^*(892)^0 \mu^+ \mu^-$	$BI$	$(9.4 \pm 0.5) \times 10^{-7}$		2560
$K^*(892)^0 \tau^+ \tau^-$	$BI$	$< 3.1 \times 10^{-3}$	$CL=90\%$	1404
$\pi^+ \pi^- \mu^+ \mu^-$	$BI$	$(2.1 \pm 0.5) \times 10^{-8}$		2626
$K^*(892)^0 \nu \bar{\nu}$	$BI$	$< 1.8 \times 10^{-5}$	$CL=90\%$	2565
invisible	$BI$	$< 2.4 \times 10^{-5}$	$CL=90\%$	-
$\nu \bar{\nu} \gamma$	$BI$	$< 1.6 \times 10^{-5}$	$CL=90\%$	2640
$\phi \mu^+ \mu^-$	$BI$	$< 3.2 \times 10^{-9}$	$CL=90\%$	2537
$\phi \nu \bar{\nu}$	$BI$	$< 1.27 \times 10^{-4}$	$CL=90\%$	2541
$e^\pm \mu^\mp$	$LF$ [aa]	$< 1.0 \times 10^{-9}$	$CL=90\%$	2639
$\pi^0 e^\pm \mu^\mp$	$LF$	$< 1.4 \times 10^{-7}$	$CL=90\%$	2637
$K^0 e^\pm \mu^\mp$	$LF$	$< 3.8 \times 10^{-8}$	$CL=90\%$	2615
$K^*(892)^0 e^+ \mu^-$	$LF$	$< 6.8 \times 10^{-9}$	$CL=90\%$	2563
$K^*(892)^0 e^- \mu^+$	$LF$	$< 5.7 \times 10^{-9}$	$CL=90\%$	2563
$K^*(892)^0 e^\pm \mu^\mp$	$LF$	$< 1.01 \times 10^{-8}$	$CL=90\%$	2563
$K^*(892)^0 \tau^+ \mu^-$	$LF$	$< 1.0 \times 10^{-5}$	$CL=90\%$	2221
$K^*(892)^0 \tau^- \mu^+$	$LF$	$< 8.2 \times 10^{-6}$	$CL=90\%$	2221
$e^\pm \tau^\mp$	$LF$ [aa]	$< 1.6 \times 10^{-5}$	$CL=90\%$	2341
$\mu^\pm \tau^\mp$	$LF$ [aa]	$< 1.4 \times 10^{-5}$	$CL=95\%$	2340
$\rho \mu^-$	$L, B$	$< 2.6 \times 10^{-9}$	$CL=90\%$	2555
$\Lambda_c^+ \mu^-$	$L, B$	$< 1.4 \times 10^{-6}$	$CL=90\%$	2143
$\Lambda_c^+ e^-$	$L, B$	$< 4 \times 10^{-6}$	$CL=90\%$	2145

## B<sup>±</sup>/B<sup>0</sup> ADMIXTURE

### CP violation

$$A_{CP}(B \rightarrow K^*(892)\gamma) = -0.003 \pm 0.011$$

$$A_{CP}(B \rightarrow s\gamma) = 0.015 \pm 0.011$$

$$A_{CP}(B \rightarrow (s+d)\gamma) = 0.010 \pm 0.031$$

$$A_{CP}(B \rightarrow X_S \ell^+ \ell^-) = 0.04 \pm 0.11$$

$$A_{CP}(B \rightarrow X_S \ell^+ \ell^-) (1.0 < q^2 < 6.0 \text{ GeV}^2/c^4) = -0.06 \pm 0.22$$

$$A_{CP}(B \rightarrow X_S \ell^+ \ell^-) (10.1 < q^2 < 12.9 \text{ or } q^2 > 14.2 \text{ GeV}^2/c^4) = 0.19 \pm 0.18$$

$$A_{CP}(B \rightarrow K^* e^+ e^-) = -0.18 \pm 0.15$$

$$A_{CP}(B \rightarrow K^* \mu^+ \mu^-) = -0.03 \pm 0.13$$

$$A_{CP}(B \rightarrow K^* \ell^+ \ell^-) = -0.04 \pm 0.07$$

$$A_{CP}(B \rightarrow \eta \text{ anything}) = -0.13 \pm_{-0.05}^{+0.04}$$

$$\Delta A_{CP}(X_S \gamma) = A_{CP}(B^\pm \rightarrow X_S \gamma) - A_{CP}(B^0 \rightarrow X_S \gamma) = 0.041 \pm 0.023$$

$$\bar{A}_{CP}(B \rightarrow X_S \gamma) = (A_{CP}(B^+ \rightarrow X_S \gamma) + A_{CP}(B^0 \rightarrow X_S \gamma))/2 = 0.009 \pm 0.012$$

$$\Delta A_{CP}(B \rightarrow K^* \gamma) = A_{CP}(B^+ \rightarrow K^{*+} \gamma) - A_{CP}(B^0 \rightarrow K^{*0} \gamma) = 0.024 \pm 0.028$$

$$\bar{A}_{CP}(B \rightarrow K^* \gamma) = (A_{CP}(B^+ \rightarrow K^{*+} \gamma) + A_{CP}(B^0 \rightarrow K^{*0} \gamma))/2 = -0.001 \pm 0.014$$

The branching fraction measurements are for an admixture of  $B$  mesons at the  $\Upsilon(4S)$ . The values quoted assume that  $B(\Upsilon(4S) \rightarrow B\bar{B}) = 100\%$ .

For inclusive branching fractions, e.g.,  $B \rightarrow D^\pm \text{ anything}$ , the treatment of multiple  $D$ 's in the final state must be defined. One possibility would be to count the number of events with one-or-more  $D$ 's and divide by the total number of  $B$ 's. Another possibility would be to count the total number of  $D$ 's and divide by the total number of  $B$ 's, which is the definition of average multiplicity. The two definitions are identical if only one  $D$  is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the  $B$  sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross section.

$\bar{B}$  modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing.

B DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level (MeV/c)	$p$
<b>Semileptonic and leptonic modes</b>			
$\ell^+ \nu_\ell \text{ anything}$	[hhh,yyy] ( 10.82 ± 0.15 ) %		—
$D^- \ell^+ \nu_\ell \text{ anything}$	[hhh] ( 2.6 ± 0.5 ) %		—
$\bar{D}^0 \ell^+ \nu_\ell \text{ anything}$	[hhh] ( 7.2 ± 1.5 ) %		—
$\bar{D} \ell^+ \nu_\ell$	( 2.41 ± 0.12 ) %		2311
$D^{*-} \ell^+ \nu_\ell \text{ anything}$	[zzz] ( 6.7 ± 1.3 ) × 10 <sup>-3</sup>		—
$\bar{D}^* \ell^+ \nu_\ell$	[aaa] ( 4.95 ± 0.11 ) %		2257
$\bar{D}^{**} \ell^+ \nu_\ell$	[hhh,baaa] ( 2.7 ± 0.7 ) %		—
$\bar{D}_1(2420) \ell^+ \nu_\ell \text{ anything}$	( 3.8 ± 1.3 ) × 10 <sup>-3</sup>	S=2.4	—
$\bar{D} \pi \ell^+ \nu_\ell \text{ anything} +$ $\bar{D}^* \pi \ell^+ \nu_\ell \text{ anything}$	( 2.6 ± 0.5 ) %	S=1.5	—
$\bar{D} \pi \ell^+ \nu_\ell \text{ anything}$	( 1.5 ± 0.6 ) %		—
$\bar{D}^* \pi \ell^+ \nu_\ell \text{ anything}$	( 1.9 ± 0.4 ) %		—
$\bar{D}_2^*(2460) \ell^+ \nu_\ell \text{ anything}$	( 4.4 ± 1.6 ) × 10 <sup>-3</sup>		—
$D^{*-} \pi^+ \ell^+ \nu_\ell \text{ anything}$	( 1.00 ± 0.34 ) %		—
$\bar{D} \pi^+ \pi^- \ell^+ \nu_\ell$	( 1.62 ± 0.32 ) × 10 <sup>-3</sup>		2301
$\bar{D}^* \pi^+ \pi^- \ell^+ \nu_\ell$	( 9.4 ± 3.2 ) × 10 <sup>-4</sup>		2247
$D_S^- \ell^+ \nu_\ell \text{ anything}$	[hhh] < 7 × 10 <sup>-3</sup>	CL=90%	—
$D_S^- \ell^+ \nu_\ell K^+ \text{ anything}$	[hhh] < 5 × 10 <sup>-3</sup>	CL=90%	—
$D_S^- \ell^+ \nu_\ell K^0 \text{ anything}$	[hhh] < 7 × 10 <sup>-3</sup>	CL=90%	—
$X_c \ell^+ \nu_\ell$	( 10.63 ± 0.15 ) %		—
$X_u \ell^+ \nu_\ell$	( 1.88 ± 0.27 ) × 10 <sup>-3</sup>		—
$X_u e^+ \nu_e$	( 1.57 ± 0.19 ) × 10 <sup>-3</sup>		—
$X_u \mu^+ \nu_\mu$	( 1.62 ± 0.21 ) × 10 <sup>-3</sup>		—
$K^+ \ell^+ \nu_\ell \text{ anything}$	[hhh] ( 6.3 ± 0.5 ) %		—
$K^- \ell^+ \nu_\ell \text{ anything}$	[hhh] ( 10 ± 4 ) × 10 <sup>-3</sup>		—
$K^0/\bar{K}^0 \ell^+ \nu_\ell \text{ anything}$	[hhh] ( 4.6 ± 0.5 ) %		—
$\bar{D} \tau^+ \nu_\tau$	( 8.6 ± 0.8 ) × 10 <sup>-3</sup>		1911
$\bar{D}^* \tau^+ \nu_\tau$	( 1.40 ± 0.07 ) %		1838
<b>D, D*, or D<sub>S</sub> modes</b>			
$D^\pm \text{ anything}$	( 23.1 ± 1.2 ) %		—
$D^0/\bar{D}^0 \text{ anything}$	( 64.6 ± 2.1 ) %	S=1.5	—
$D^*(2010)^\pm \text{ anything}$	( 22.5 ± 1.5 ) %		—
$\bar{D}^*(2007)^0 \text{ anything}$	( 26.0 ± 2.7 ) %		—
$D_S^\pm \text{ anything}$	[aa] ( 10.6 ± 0.6 ) %	S=1.7	—

$D_S^{*\pm}$ anything	(	6.3 ± 1.0	) %		—
$D_S^{*\pm} \overline{D}^*$	(	3.4 ± 0.6	) %		—
$D^* \overline{D}^* K^0 + D^* \overline{D}^* K_{[aa,ccaa]}^0$	(	7.1 ± 2.7 — 1.7	) %		—
$b \rightarrow c \overline{c} s$	(	22 ± 4	) %		—
$D_S^* \overline{D}^*$	[aa,ccaa] (	5.0 ± 0.4	) %		—
$D^* D^*(2010)^\pm$	[aa] <	5.9	$\times 10^{-3}$	CL=90%	1711
$D D^*(2010)^\pm + D^* D^\pm$	[aa] <	5.5	$\times 10^{-3}$	CL=90%	—
$D D^\pm$	[aa] <	3.1	$\times 10^{-3}$	CL=90%	1866
$D_S^* (\pm \overline{D}^*) X (n\pi^\pm)$	[aa,ccaa] (	9 ± 5 — 4	) %		—
$\overline{D}^*(2010)\gamma$	<	1.1	$\times 10^{-3}$	CL=90%	2257
$D_S^+ \pi^-, D_S^{*+} \pi^-, D_S^+ \rho^-,$ $D_S^{*+} \rho^-, D_S^+ \pi^0, D_S^{*+} \pi^0,$ $D_S^+ \eta, D_S^{*+} \eta, D_S^+ \rho^0,$ $D_S^{*+} \rho^0, D_S^+ \omega, D_S^{*+} \omega$	[aa] <	4	$\times 10^{-4}$	CL=90%	—
$D_{S1}(2536)^+$ anything	<	9.5	$\times 10^{-3}$	CL=90%	—

**Charmonium modes**

$J/\psi(1S)$ anything	(	1.094 ± 0.032	) %	S=1.1	—
$J/\psi(1S)$ (direct) anything	(	7.8 ± 0.4	) $\times 10^{-3}$	S=1.1	—
$\psi(2S)$ anything	(	3.07 ± 0.21	) $\times 10^{-3}$		—
$\chi_{c1}(1P)$ anything	(	3.55 ± 0.27	) $\times 10^{-3}$	S=1.3	—
$\chi_{c1}(1P)$ (direct) anything	(	3.08 ± 0.19	) $\times 10^{-3}$		—
$\chi_{c2}(1P)$ anything	(	9.9 ± 1.7	) $\times 10^{-4}$	S=1.6	—
$\chi_{c2}(1P)$ (direct) anything	(	7.5 ± 1.1	) $\times 10^{-4}$		—
$\eta_c(1S)$ anything	<	9	$\times 10^{-3}$	CL=90%	—
$K \chi_{c1}(3872)$	(	2.5 ± 0.9	) $\times 10^{-4}$		1141
$K X(3940), X \rightarrow D^{*0} D^0$	<	6.7	$\times 10^{-5}$	CL=90%	1084
$K \chi_{c0}(3915), \chi_{c0} \rightarrow \omega J/\psi$	[ddaa] (	7.1 ± 3.4	) $\times 10^{-5}$		1103

**K or K\* modes**

$K^\pm$ anything	[aa] (	78.9 ± 2.5	) %		—
$K^+$ anything	(	66 ± 5	) %		—
$K^-$ anything	(	13 ± 4	) %		—
$K^0 / \overline{K}^0$ anything	[aa] (	64 ± 4	) %		—
$K^*(892)^\pm$ anything	(	18 ± 6	) %		—
$K^*(892)^0 / \overline{K}^*(892)^0$ anything	[aa] (	14.6 ± 2.6	) %		—
$K^*(892)\gamma$	(	4.2 ± 0.6	) $\times 10^{-5}$		2565
$\eta K \gamma$	(	8.5 ± 1.8 — 1.6	) $\times 10^{-6}$		2588
$K_1(1400)\gamma$	<	1.27	$\times 10^{-4}$	CL=90%	2454
$K_2^*(1430)\gamma$	(	1.7 ± 0.6 — 0.5	) $\times 10^{-5}$		2447
$K_2(1770)\gamma$	<	1.2	$\times 10^{-3}$	CL=90%	2342
$K_3^*(1780)\gamma$	<	3.7	$\times 10^{-5}$	CL=90%	2340
$K_4^*(2045)\gamma$	<	1.0	$\times 10^{-3}$	CL=90%	2243
$K \eta'(958)$	(	8.3 ± 1.1	) $\times 10^{-5}$		2528
$K^*(892)\eta'(958)$	(	4.1 ± 1.1	) $\times 10^{-6}$		2472
$K \eta$	<	5.2	$\times 10^{-6}$	CL=90%	2588
$K^*(892)\eta$	(	1.8 ± 0.5	) $\times 10^{-5}$		2534
$K \phi \phi$	(	2.3 ± 0.9	) $\times 10^{-6}$		2306
$\overline{b} \rightarrow \overline{s} \gamma$	(	3.49 ± 0.19	) $\times 10^{-4}$		—
$\overline{b} \rightarrow \overline{d} \gamma$	(	9.2 ± 3.0	) $\times 10^{-6}$		—
$\overline{b} \rightarrow \overline{s} g$ gluon	<	6.8	%	CL=90%	—
$\eta$ anything	(	2.6 ± 0.5 — 0.8	) $\times 10^{-4}$		—

$\eta'$ anything	(	$4.2 \pm 0.9$	) $\times 10^{-4}$		—
$K^+$ gluon (charmless)	<	1.87	$\times 10^{-4}$	CL=90%	—
$K^0$ gluon (charmless)	(	$1.9 \pm 0.7$	) $\times 10^{-4}$		—

### Light unflavored meson modes

$\rho\gamma$	(	$1.39 \pm 0.25$	) $\times 10^{-6}$	S=1.2	2583
$\rho/\omega\gamma$	(	$1.30 \pm 0.23$	) $\times 10^{-6}$	S=1.2	—
$\pi^\pm$ anything	[ <i>aa,eeaa</i> ]	(	$358 \pm 7$	) %	—
$\pi^0$ anything	(	$235 \pm 11$	) %		—
$\eta$ anything	(	$17.6 \pm 1.6$	) %		—
$\rho^0$ anything	(	$21 \pm 5$	) %		—
$\omega$ anything	<	81	%	CL=90%	—
$\phi$ anything	(	$3.43 \pm 0.12$	) %		—
$\phi K^*(892)$	<	2.2	$\times 10^{-5}$	CL=90%	2460
$\pi^+$ gluon (charmless)	(	$3.7 \pm 0.8$	) $\times 10^{-4}$		—

### Baryon modes

$\Lambda_c^+ / \bar{\Lambda}_c^-$ anything	(	$3.6 \pm 0.4$	) %		—
$\Lambda_c^+$ anything	<	1.3	%	CL=90%	—
$\bar{\Lambda}_c^-$ anything	<	7	%	CL=90%	—
$\bar{\Lambda}_c^- \ell^+$ anything	<	9	$\times 10^{-4}$	CL=90%	—
$\bar{\Lambda}_c^- e^+$ anything	<	1.8	$\times 10^{-3}$	CL=90%	—
$\bar{\Lambda}_c^- \mu^+$ anything	<	1.4	$\times 10^{-3}$	CL=90%	—
$\bar{\Lambda}_c^- p$ anything	(	$2.06 \pm 0.33$	) %		—
$\bar{\Lambda}_c^- p e^+ \nu_e$	<	8	$\times 10^{-4}$	CL=90%	2021
$\bar{\Sigma}_c^-$ anything	(	$3.4 \pm 1.7$	) $\times 10^{-3}$		—
$\bar{\Sigma}_c^-$ anything	<	8	$\times 10^{-3}$	CL=90%	—
$\bar{\Sigma}_c^0$ anything	(	$3.7 \pm 1.7$	) $\times 10^{-3}$		—
$\bar{\Sigma}_c^0 N$ ( $N = p$ or $n$ )	<	1.2	$\times 10^{-3}$	CL=90%	1938
$\Xi_c^0$ anything, $\Xi_c^0 \rightarrow \Xi^- \pi^+$	(	$1.93 \pm 0.30$	) $\times 10^{-4}$	S=1.1	—
$\Xi_c^+, \Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$	(	$4.5 \pm 1.3$ $- 1.2$	) $\times 10^{-4}$		—
$p/\bar{p}$ anything	[ <i>aa</i> ]	(	$8.0 \pm 0.4$	) %	—
$p/\bar{p}$ (direct) anything	[ <i>aa</i> ]	(	$5.5 \pm 0.5$	) %	—
$\bar{p} e^+ \nu_e$ anything	<	5.9	$\times 10^{-4}$	CL=90%	—
$\Lambda/\bar{\Lambda}$ anything	[ <i>aa</i> ]	(	$4.0 \pm 0.5$	) %	—
$\Xi^-/\bar{\Xi}^+$ anything	[ <i>aa</i> ]	(	$2.7 \pm 0.6$	) $\times 10^{-3}$	—
baryons anything	(	$6.8 \pm 0.6$	) %		—
$p\bar{p}$ anything	(	$2.47 \pm 0.23$	) %		—
$\Lambda\bar{p}/\bar{\Lambda}p$ anything	[ <i>aa</i> ]	(	$2.5 \pm 0.4$	) %	—
$\Lambda\bar{\Lambda}$ anything	<	5	$\times 10^{-3}$	CL=90%	—

### Lepton Family number (*LF*) violating modes or $\Delta B = 1$ weak neutral current (*B1*) modes

$s e^+ e^-$	<i>B1</i>	(	$6.7 \pm 1.7$	) $\times 10^{-6}$	S=2.0	—
$s \mu^+ \mu^-$	<i>B1</i>	(	$4.3 \pm 1.0$	) $\times 10^{-6}$		—
$s \ell^+ \ell^-$	<i>B1</i> [ <i>hhh</i> ]	(	$5.8 \pm 1.3$	) $\times 10^{-6}$	S=1.8	—
$\pi \ell^+ \ell^-$	<i>B1</i>	<	5.9	$\times 10^{-8}$	CL=90%	2638
$\pi e^+ e^-$	<i>B1</i>	<	1.10	$\times 10^{-7}$	CL=90%	2638
$\pi \mu^+ \mu^-$	<i>B1</i>	<	5.0	$\times 10^{-8}$	CL=90%	2634
$K e^+ e^-$	<i>B1</i>	(	$4.4 \pm 0.6$	) $\times 10^{-7}$		2617
$K^*(892) e^+ e^-$	<i>B1</i>	(	$1.19 \pm 0.20$	) $\times 10^{-6}$	S=1.2	2565
$K \mu^+ \mu^-$	<i>B1</i>	(	$4.4 \pm 0.4$	) $\times 10^{-7}$		2612
$K^*(892) \mu^+ \mu^-$	<i>B1</i>	(	$1.06 \pm 0.09$	) $\times 10^{-6}$		2560

$K\ell^+\ell^-$	$B1$	(	$4.8 \pm 0.4$	)	$\times 10^{-7}$		2617	
$K^*(892)\ell^+\ell^-$	$B1$	(	$1.05 \pm 0.10$	)	$\times 10^{-6}$		2565	
$K\nu\bar{\nu}$	$B1$	<	1.6		$\times 10^{-5}$	CL=90%	2617	
$K^*\nu\bar{\nu}$	$B1$	<	2.7		$\times 10^{-5}$	CL=90%	—	
$\pi\nu\bar{\nu}$	$B1$	<	8		$\times 10^{-6}$	CL=90%	2638	
$\rho\nu\bar{\nu}$	$B1$	<	2.8		$\times 10^{-5}$	CL=90%	2583	
$se^{\pm}\mu^{\mp}$	$LF$	[ $a\bar{a}$ ]	<	2.2		$\times 10^{-5}$	CL=90%	—
$\pi e^{\pm}\mu^{\mp}$	$LF$	<	9.2		$\times 10^{-8}$	CL=90%	2637	
$\rho e^{\pm}\mu^{\mp}$	$LF$	<	3.2		$\times 10^{-6}$	CL=90%	2582	
$Ke^{\pm}\mu^{\mp}$	$LF$	<	3.8		$\times 10^{-8}$	CL=90%	2616	
$K^*(892)e^{\pm}\mu^{\mp}$	$LF$	<	5.1		$\times 10^{-7}$	CL=90%	2563	

See Particle Listings for 4 decay modes that have been seen / not seen.

### $B^{\pm}/B^0/B_s^0/b$ -baryon ADMIXTURE

These measurements are for an admixture of bottom particles at high energy (LHC, LEP, Tevatron,  $S\bar{p}\bar{p}S$ ).

$$\text{Mean life } \tau = (1.5673 \pm 0.0029) \times 10^{-12} \text{ s}$$

$$\text{Mean life } \tau = (1.72 \pm 0.10) \times 10^{-12} \text{ s} \quad \text{Charged } b\text{-hadron admixture}$$

$$\text{Mean life } \tau = (1.58 \pm 0.14) \times 10^{-12} \text{ s} \quad \text{Neutral } b\text{-hadron admixture}$$

$$\tau_{\text{charged } b\text{-hadron}}/\tau_{\text{neutral } b\text{-hadron}} = 1.09 \pm 0.13$$

$$|\Delta\tau_b|/\tau_{b,\bar{b}} = -0.001 \pm 0.014$$

The branching fraction measurements are for an admixture of  $B$  mesons and baryons at energies above the  $\Upsilon(4S)$ . Only the highest energy results (LHC, LEP, Tevatron,  $S\bar{p}\bar{p}S$ ) are used in the branching fraction averages. In the following, we assume that the production fractions are the same at the LHC, LEP, and at the Tevatron.

For inclusive branching fractions, e.g.,  $B \rightarrow D^{\pm}$  anything, the values usually are multiplicities, not branching fractions. They can be greater than one.

The modes below are listed for a  $\bar{b}$  initial state.  $b$  modes are their charge conjugates. Reactions indicate the weak decay vertex and do not include mixing.

#### $\bar{b}$ DECAY MODES

Fraction ( $\Gamma_i/\Gamma$ )

Scale factor/  
Confidence level

$p$   
(MeV/c)

### PRODUCTION FRACTIONS

The production fractions for weakly decaying  $b$ -hadrons at high energy have been calculated from the best values of mean lives, mixing parameters, and branching fractions in this edition by the Heavy Flavor Averaging Group (HFLAV) as described in the note “ $B^0$ - $\bar{B}^0$  Mixing” in the  $B^0$  Particle Listings. We no longer provide world averages of the  $b$ -hadron production fractions, where results from LEP, Tevatron and LHC are averaged together; indeed the available data (from CDF and LHCb) shows that the fractions depend on the kinematics (in particular the  $p_T$ ) of the produced  $b$  hadron. Hence we would like to list the fractions in  $Z$  decays instead, which are well-defined physics observables. The production fractions in  $p\bar{p}$  collisions at the Tevatron are also listed at the end of the section. Values assume

$$B(\bar{b} \rightarrow B^+) = B(\bar{b} \rightarrow B^0)$$

$$B(\bar{b} \rightarrow B^+) + B(\bar{b} \rightarrow B^0) + B(\bar{b} \rightarrow B_s^0) + B(b \rightarrow b\text{-baryon}) = 100\%.$$

The correlation coefficients between production fractions are also reported:

$$\text{cor}(B_s^0, b\text{-baryon}) = 0.064$$

$$\text{cor}(B_s^0, B^{\pm}=B^0) = -0.633$$

$$\text{cor}(b\text{-baryon}, B^{\pm}=B^0) = -0.813.$$



The notation for production fractions varies in the literature ( $f_d$ ,  $d_{B^0}$ ,  $f(b \rightarrow \bar{B}^0)$ ,  $\text{Br}(b \rightarrow \bar{B}^0)$ ). We use our own branching fraction notation here,  $\text{B}(\bar{b} \rightarrow B^0)$ .

Note these production fractions are  $b$ -hadronization fractions, not the conventional branching fractions of  $b$ -quark to a  $B$ -hadron, which may have considerable dependence on the initial and final state kinematic and production environment.

$B^+$	( 40.8 ± 0.7 ) %	—
$B^0$	( 40.8 ± 0.7 ) %	—
$B_S^0$	( 10.0 ± 0.8 ) %	—
$b$ -baryon	( 8.4 ± 1.1 ) %	—

## DECAY MODES

### Semileptonic and leptonic modes

$\nu$ anything	( 23.1 ± 1.5 ) %	—
$\ell^+ \nu_\ell$ anything	[ $hhh$ ] ( 10.69 ± 0.22 ) %	—
$e^+ \nu_e$ anything	( 10.86 ± 0.35 ) %	—
$\mu^+ \nu_\mu$ anything	( 10.95 $^{+0.29}_{-0.25}$ ) %	—
$D^- \ell^+ \nu_\ell$ anything	[ $hhh$ ] ( 2.2 ± 0.4 ) %	S=1.9
$D^- \pi^+ \ell^+ \nu_\ell$ anything	( 4.9 ± 1.9 ) × 10 <sup>-3</sup>	—
$D^- \pi^- \ell^+ \nu_\ell$ anything	( 2.6 ± 1.6 ) × 10 <sup>-3</sup>	—
$\bar{D}^0 \ell^+ \nu_\ell$ anything	[ $hhh$ ] ( 6.79 ± 0.34 ) %	—
$\bar{D}^0 \pi^- \ell^+ \nu_\ell$ anything	( 1.07 ± 0.27 ) %	—
$\bar{D}^0 \pi^+ \ell^+ \nu_\ell$ anything	( 2.3 ± 1.6 ) × 10 <sup>-3</sup>	—
$D^{*-} \ell^+ \nu_\ell$ anything	[ $hhh$ ] ( 2.75 ± 0.19 ) %	—
$D^{*-} \pi^- \ell^+ \nu_\ell$ anything	( 6 ± 7 ) × 10 <sup>-4</sup>	—
$D^{*-} \pi^+ \ell^+ \nu_\ell$ anything	( 4.8 ± 1.0 ) × 10 <sup>-3</sup>	—
$\bar{D}_j^0 \ell^+ \nu_\ell$ anything × $\text{B}(\bar{D}_j^0 \rightarrow [hhh, f\bar{a}a])$	( 2.6 ± 0.9 ) × 10 <sup>-3</sup>	—
$D^{*+} \pi^-$		
$D_j^- \ell^+ \nu_\ell$ anything × $\text{B}(D_j^- \rightarrow D^0 \pi^-)$	[ $hhh, f\bar{a}a$ ] ( 7.0 ± 2.3 ) × 10 <sup>-3</sup>	—
$\bar{D}_2^*(2460)^0 \ell^+ \nu_\ell$ anything × $\text{B}(\bar{D}_2^*(2460)^0 \rightarrow D^{*-} \pi^+)$	< 1.4 × 10 <sup>-3</sup>	CL=90%
$D_2^*(2460)^- \ell^+ \nu_\ell$ anything × $\text{B}(D_2^*(2460)^- \rightarrow D^0 \pi^-)$	( 4.2 $^{+1.5}_{-1.8}$ ) × 10 <sup>-3</sup>	—
$\bar{D}_2^*(2460)^0 \ell^+ \nu_\ell$ anything × $\text{B}(\bar{D}_2^*(2460)^0 \rightarrow D^- \pi^+)$	( 1.6 ± 0.8 ) × 10 <sup>-3</sup>	—
charmless $\ell \bar{\nu}_\ell$	[ $hhh$ ] ( 1.7 ± 0.5 ) × 10 <sup>-3</sup>	—
$\tau^+ \nu_\tau$ anything	( 2.41 ± 0.23 ) %	—
$D^{*-} \tau \nu_\tau$ anything	( 9 ± 4 ) × 10 <sup>-3</sup>	—
$\bar{c} \rightarrow \ell^- \bar{\nu}_\ell$ anything	[ $hhh$ ] ( 8.02 ± 0.19 ) %	—
$c \rightarrow \ell^+ \nu$ anything	( 1.6 $^{+0.4}_{-0.5}$ ) %	—

### Charmed meson and baryon modes

$\bar{D}^0$ anything	( 58.7 ± 2.8 ) %	—
$D^0 D_S^\pm$ anything	[ $aa$ ] ( 9.1 $^{+4.0}_{-2.8}$ ) %	—
$D^\mp D_S^\pm$ anything	[ $aa$ ] ( 4.0 $^{+2.3}_{-1.8}$ ) %	—
$\bar{D}^0 D^0$ anything	[ $aa$ ] ( 5.1 $^{+2.0}_{-1.8}$ ) %	—

$D^0 D^\pm$ anything	[aa]	( 2.7 $\pm$ 1.8 ) %	-
$D^\pm D^\mp$ anything	[aa]	< 9 $\times 10^{-3}$	CL=90%
$D^-$ anything		( 22.7 $\pm$ 1.6 ) %	-
$D^*(2010)^+$ anything		( 17.3 $\pm$ 2.0 ) %	-
$D_1(2420)^0$ anything		( 5.0 $\pm$ 1.5 ) %	-
$D^*(2010)^\mp D_S^\pm$ anything	[aa]	( 3.3 $\pm$ 1.6 ) %	-
$D^0 D^*(2010)^\pm$ anything	[aa]	( 3.0 $\pm$ 1.1 ) %	-
$D^*(2010)^\pm D^\mp$ anything	[aa]	( 2.5 $\pm$ 1.2 ) %	-
$D^*(2010)^\pm D^*(2010)^\mp$ anything	[aa]	( 1.2 $\pm$ 0.4 ) %	-
$\bar{D} D$ anything		( 10 $\pm$ 11 ) %	-
$D_2^*(2460)^0$ anything		( 4.7 $\pm$ 2.7 ) %	-
$D_S^-$ anything		( 14.7 $\pm$ 2.1 ) %	-
$D_S^+$ anything		( 10.1 $\pm$ 3.1 ) %	-
$\Lambda_c^+$ anything		( 7.8 $\pm$ 1.1 ) %	-
$\bar{c}/c$ anything	[eeaa]	(116.2 $\pm$ 3.2 ) %	-

**Charmonium modes**

$J/\psi(1S)$ anything		( 1.16 $\pm$ 0.10 ) %	-
$\psi(2S)$ anything		( 3.06 $\pm$ 0.30 ) $\times 10^{-3}$	-
$\chi_{c0}(1P)$ anything		( 1.4 $\pm$ 0.5 ) %	-
$\chi_{c1}(1P)$ anything		( 1.4 $\pm$ 0.4 ) %	-
$\chi_{c2}(1P)$ anything		( 5.5 $\pm$ 2.4 ) $\times 10^{-3}$	-
$\chi_c(2P)$ anything, $\chi_c \rightarrow \phi\phi$	<	2.8 $\times 10^{-7}$	CL=95%
$\eta_c(1S)$ anything		( 5.6 $\pm$ 0.9 ) $\times 10^{-3}$	-
$\eta_c(2S)$ anything, $\eta_c \rightarrow \phi\phi$		( 4.1 $\pm$ 1.7 ) $\times 10^{-7}$	-
$\chi_{c1}(3872)$ anything, $\chi_{c1} \rightarrow \phi\phi$	<	4.5 $\times 10^{-7}$	CL=95%
$\chi_{c0}(3915)$ anything, $\chi_{c0} \rightarrow \phi\phi$	<	3.1 $\times 10^{-7}$	CL=95%

**K or K\* modes**

$\bar{S}\gamma$		( 3.1 $\pm$ 1.1 ) $\times 10^{-4}$	-
$\bar{S}\bar{D}\nu$	B1	< 6.4 $\times 10^{-4}$	CL=90%
$K^\pm$ anything		( 74 $\pm$ 6 ) %	-
$K_S^0$ anything		( 29.0 $\pm$ 2.9 ) %	-

**Pion modes**

$\pi^\pm$ anything		(397 $\pm$ 21 ) %	-
$\pi^0$ anything	[eeaa]	(280 $\pm$ 60 ) %	-
$\phi$ anything		( 2.82 $\pm$ 0.23 ) %	-

**Baryon modes**

$p/\bar{p}$ anything		( 13.1 $\pm$ 1.1 ) %	-
$\Lambda/\bar{\Lambda}$ anything		( 5.9 $\pm$ 0.6 ) %	-
$b$ -baryon anything		( 10.2 $\pm$ 2.8 ) %	-

**Other modes**

charged anything	[eeaa]	(497 $\pm$ 7 ) %	-
hadron <sup>+</sup> hadron <sup>-</sup>		( 1.7 $\pm$ 1.0 ) $\times 10^{-5}$	-
charmless		( 7 $\pm$ 21 ) $\times 10^{-3}$	-

 **$\Delta B = 1$  weak neutral current (B1) modes**

$\mu^+ \mu^-$ anything	B1	< 3.2 $\times 10^{-4}$	CL=90%
------------------------	----	------------------------	--------

**B\***

$$I(J^P) = \frac{1}{2}(1^-)$$

$I, J, P$  need confirmation.

Quantum numbers shown are quark-model predictions.

$$\text{Mass } m_{B^*} = 5324.75 \pm 0.20 \text{ MeV}$$

$$m_{B^*} - m_B = 45.18 \pm 0.20 \text{ MeV}$$

$$m_{B^{*+}} - m_{B^+} = 45.34 \pm 0.20 \text{ MeV}$$

**B<sub>1</sub>(5721)**

$$I(J^P) = \frac{1}{2}(1^+)$$

$I, J, P$  need confirmation.

$$B_1(5721)^+ \text{ mass} = 5726.0^{+2.5}_{-2.7} \text{ MeV}$$

$$m_{B_1^+} - m_{B^{*0}} = 401.2^{+2.4}_{-2.7} \text{ MeV}$$

$$B_1(5721)^0 \text{ mass} = 5726.1 \pm 1.2 \text{ MeV} \quad (S = 1.2)$$

$$m_{B_1^0} - m_{B^+} = 446.7 \pm 1.2 \text{ MeV} \quad (S = 1.2)$$

$$m_{B_1^0} - m_{B^{*+}} = 401.4 \pm 1.2 \text{ MeV} \quad (S = 1.2)$$

$$\text{Full width } \Gamma(B_1(5721)^+) = 31 \pm 6 \text{ MeV} \quad (S = 1.1)$$

$$\text{Full width } \Gamma(B_1(5721)^0) = 27.5 \pm 3.4 \text{ MeV} \quad (S = 1.1)$$

**B<sub>2</sub><sup>\*</sup>(5747)**

$$I(J^P) = \frac{1}{2}(2^+)$$

$I, J, P$  need confirmation.

$$B_2^*(5747)^+ \text{ mass} = 5737.3 \pm 0.7 \text{ MeV}$$

$$m_{B_2^{*+}} - m_{B^0} = 457.5 \pm 0.7 \text{ MeV}$$

$$B_2^*(5747)^0 \text{ mass} = 5739.6 \pm 0.7 \text{ MeV} \quad (S = 1.4)$$

$$m_{B_2^{*0}} - m_{B_1^0} = 13.5 \pm 1.4 \text{ MeV} \quad (S = 1.3)$$

$$m_{B_2^{*0}} - m_{B^+} = 460.2 \pm 0.6 \text{ MeV} \quad (S = 1.4)$$

$$\text{Full width } \Gamma(B_2^*(5747)^+) = 20 \pm 5 \text{ MeV} \quad (S = 2.2)$$

$$\text{Full width } \Gamma(B_2^*(5747)^0) = 24.2 \pm 1.7 \text{ MeV}$$

**B<sub>J</sub>(5970)**

$$I(J^P) = \frac{1}{2}(?^?)$$

$I, J, P$  need confirmation.

$$B_J(5970)^+ \text{ mass } m = 5965 \pm 5 \text{ MeV}$$

$$m_{B_J(5970)^+} - m_{B^0} = 685 \pm 5 \text{ MeV}$$

$$B_J(5970)^0 \text{ mass } m = 5971 \pm 5 \text{ MeV}$$

$$m_{B_J(5970)^0} - m_{B^+} = 691 \pm 5 \text{ MeV}$$

$$B_J(5970)^+ \text{ full width } \Gamma = 62 \pm 20 \text{ MeV}$$

$$B_J(5970)^0 \text{ full width } \Gamma = 81 \pm 12 \text{ MeV}$$

# BOTTOM, STRANGE MESONS

## ( $B = \pm 1, S = \mp 1$ )

$$B_S^0 = s\bar{b}, \bar{B}_S^0 = \bar{s}b, \quad \text{similarly for } B_S^{*+}s$$

 **$B_S^0$** 

$$I(J^P) = 0(0^-)$$

$I, J, P$  need confirmation. Quantum numbers shown are quark-model predictions.

$$\text{Mass } m_{B_S^0} = 5366.93 \pm 0.10 \text{ MeV}$$

$$m_{B_S^0} - m_B = 87.37 \pm 0.12 \text{ MeV}$$

$$\text{Mean life } \tau = (1.520 \pm 0.005) \times 10^{-12} \text{ s}$$

$$c\tau = 455.7 \mu\text{m}$$

$$\Delta\Gamma_{B_S^0} = \Gamma_{B_{S_L}^0} - \Gamma_{B_{S_H}^0} = (0.083 \pm 0.005) \times 10^{12} \text{ s}^{-1} \quad (S = 1.8)$$

### $B_S^0$ - $\bar{B}_S^0$ mixing parameters

$$\Delta m_{B_S^0} = m_{B_{S_H}^0} - m_{B_{S_L}^0} = (17.765 \pm 0.006) \times 10^{12} \hbar \text{ s}^{-1}$$

$$= (1.1693 \pm 0.0004) \times 10^{-8} \text{ MeV}$$

$$x_S = \Delta m_{B_S^0} / \Gamma_{B_S^0} = 26.99 \pm 0.09$$

$$\chi_S (\text{CP violation parameter}) = 0.499318 \pm 0.000005$$

### CP violation parameters in $B_S^0$

$$\text{Re}(\epsilon_{B_S^0}) / (1 + |\epsilon_{B_S^0}|^2) = (-0.15 \pm 0.70) \times 10^{-3}$$

$$C_{KK}(B_S^0 \rightarrow K^+ K^-) = 0.162 \pm 0.035$$

$$S_{KK}(B_S^0 \rightarrow K^+ K^-) = 0.14 \pm 0.05 \quad (S = 1.3)$$

$$r_B(B_S^0 \rightarrow D_S^\mp K^\pm) = 0.37_{-0.09}^{+0.10}$$

$$r_B(B_S^0 \rightarrow D_S^\mp K^\pm \pi^\pm \pi^\mp) = 0.47 \pm 0.08$$

$$\delta_B(B_S^0 \rightarrow D_S^\pm K^\mp) = (358 \pm 14)^\circ$$

$$\delta_B(B_S^0 \rightarrow D_S^\pm K^\mp \pi^\pm \pi^\mp) = (-6_{-13}^{+10})^\circ$$

$$\text{CP Violation phase } \beta_s (b \rightarrow c\bar{s}) = (2.0 \pm 0.8) \times 10^{-2} \text{ rad}$$

$$\text{CP Violation phase } \beta_s (b \rightarrow s\bar{s}) = (3.7 \pm 3.5) \times 10^{-2} \text{ rad}$$

$$|\lambda| (B_S^0 \rightarrow J/\psi(1S)\phi) = 0.988 \pm 0.009$$

$$|\lambda| (b \rightarrow c\bar{s}) = 0.989 \pm 0.008$$

$$A, \text{ CP violation parameter} = -0.79 \pm 0.08$$

$$C, \text{ CP violation parameter} = 0.19 \pm 0.06$$

$$S, \text{ CP violation parameter} = 0.17 \pm 0.06$$

$$A_{CP}^{\perp}(B_S \rightarrow J/\psi \bar{K}^*(892)^0) = -0.05 \pm 0.06$$

$$A_{CP}^{\parallel}(B_S \rightarrow J/\psi \bar{K}^*(892)^0) = 0.17 \pm 0.15$$

$$A_{CP}^{\perp}(B_S \rightarrow J/\psi \bar{K}^*(892)^0) = -0.05 \pm 0.10$$

$$\mathbf{A}_{CP}(B_S \rightarrow \pi^+ K^-) = 0.224 \pm 0.012$$

$$A_{CP}(B_S^0 \rightarrow [K^+ K^-]_D \bar{K}^*(892)^0) = -0.04 \pm 0.07$$

$$A_{CP}(B_S^0 \rightarrow [\pi^+ K^-]_D K^*(892)^0) = -0.01 \pm 0.04$$

$$A_{CP}(B_S^0 \rightarrow [\pi^+ \pi^-]_D K^*(892)^0) = 0.06 \pm 0.13$$

$$S(B_S^0 \rightarrow \phi\gamma) = 0.43 \pm 0.32$$

$$C(B_S^0 \rightarrow \phi\gamma) = 0.11 \pm 0.31$$

$$A^\Delta(B_S^0 \rightarrow \phi\gamma) = -0.7 \pm 0.4$$

$$\Delta a_{\perp} < 1.2 \times 10^{-12} \text{ GeV}, \text{ CL} = 95\%$$

$$\begin{aligned}\Delta a_{\parallel} &= (-0.9 \pm 1.5) \times 10^{-14} \text{ GeV} \\ \Delta a_{\perp} &= (1.0 \pm 2.2) \times 10^{-14} \text{ GeV} \\ \Delta a_{\gamma} &= (-3.8 \pm 2.2) \times 10^{-14} \text{ GeV} \\ \text{Re}(\xi) &= -0.022 \pm 0.033 \\ \text{Im}(\xi) &= 0.004 \pm 0.011\end{aligned}$$

These branching fractions all scale with  $B(\bar{b} \rightarrow B_S^0)$ .

The branching fraction  $B(B_S^0 \rightarrow D_S^- \ell^+ \nu_{\ell} \text{ anything})$  is not a pure measurement since the measured product  $B(\bar{b} \rightarrow B_S^0) \times B(B_S^0 \rightarrow D_S^- \ell^+ \nu_{\ell} \text{ anything})$  was used to determine  $B(\bar{b} \rightarrow B_S^0)$ , as described in the note on “ $B^0$ - $\bar{B}^0$  Mixing”

For inclusive branching fractions, e.g.,  $B \rightarrow D^{\pm} \text{ anything}$ , the values usually are multiplicities, not branching fractions. They can be greater than one.

$B_S^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$D_S^-$ anything	(62 ± 6) %		—
$D_S^{\pm}$ anything	(92 ± 11) %		—
$D^0/\bar{D}^0$ anything	(38 ± 10) %		—
$\ell \nu_{\ell} X$	(9.6 ± 0.8) %		—
$e^+ \nu X^-$	(9.1 ± 0.8) %		—
$\mu^+ \nu X^-$	(10.2 ± 1.0) %		—
$D_S^- \ell^+ \nu_{\ell}$ anything	[ $ggaa$ ] (8.1 ± 1.3) %		—
$D_S^{*-} \ell^+ \nu_{\ell}$ anything	(5.4 ± 1.1) %		—
$D_S^- \mu^+ \nu_{\mu}$	(2.31 ± 0.21) %		2321
$D_S^{*-} \mu^+ \nu_{\mu}$	(5.2 ± 0.5) %		2266
$D_{S1}(2536)^- \mu^+ \nu_{\mu}, D_{S1}^- \rightarrow D^{*-} K_S^0$	(2.7 ± 0.7) × 10 <sup>-3</sup>		—
$D_{S1}(2536)^- X \mu^+ \nu, D_{S1}^- \rightarrow \bar{D}^0 K^+$	(4.4 ± 1.3) × 10 <sup>-3</sup>		—
$D_{S2}(2573)^- X \mu^+ \nu, D_{S2}^- \rightarrow \bar{D}^0 K^+$	(2.7 ± 1.0) × 10 <sup>-3</sup>		—
$K^- \mu^+ \nu_{\mu}$	(1.06 ± 0.09) × 10 <sup>-4</sup>		2660
$D_S^- \pi^+$	(2.98 ± 0.14) × 10 <sup>-3</sup>		2320
$D_S^- \rho^+$	(6.8 ± 1.4) × 10 <sup>-3</sup>		2249
$D_S^- \pi^+ \pi^+ \pi^-$	(6.1 ± 1.0) × 10 <sup>-3</sup>		2301
$D_{S1}(2536)^- \pi^+, D_{S1}^- \rightarrow D_S^- \pi^+ \pi^-$	(2.4 ± 0.8) × 10 <sup>-5</sup>		—
$D_S^{\mp} K^{\pm}$	(2.25 ± 0.12) × 10 <sup>-4</sup>		2293
$D_{S1}(2536)^{\mp} K^{\pm}, D_{S1}^- \rightarrow \bar{D}^*(2007)^0 K^-$	(2.48 ± 0.28) × 10 <sup>-5</sup>		—
$D_S^- K^+ \pi^+ \pi^-$	(3.2 ± 0.6) × 10 <sup>-4</sup>		2249
$D_S^+ D_S^-$	(4.4 ± 0.5) × 10 <sup>-3</sup>		1824
$D_S^- D^+$	(2.8 ± 0.5) × 10 <sup>-4</sup>		1875
$D^+ D^-$	(2.2 ± 0.6) × 10 <sup>-4</sup>		1925
$D^{*+} D^{*-}$	(2.14 ± 0.32) × 10 <sup>-4</sup>		1778
$D^0 \bar{D}^0$	(1.9 ± 0.5) × 10 <sup>-4</sup>		1930
$D_S^{*-} \pi^+$	(1.9 ± 0.4) × 10 <sup>-3</sup>		2265
$D_S^{*+} K^{\pm}$	(1.32 ± 0.40 / 0.32) × 10 <sup>-4</sup>		—
$D_S^{*-} \rho^+$	(9.5 ± 2.0) × 10 <sup>-3</sup>		2191

$D_s^{*+} D_s^- + D_s^{*-} D_s^+$	( 1.39 ± 0.17 ) %		1742
$D_s^{*+} D_s^{*-}$	( 1.44 ± 0.21 ) %	S=1.1	1655
$D_s^{(*)+} D_s^{(*)-}$	( 4.5 ± 1.4 ) %		—
$D_s^{*-} D_s^+$	( 3.9 ± 0.8 ) × 10 <sup>-4</sup>		1801
$\overline{D}^{*0} \overline{K}^0$	( 2.8 ± 1.1 ) × 10 <sup>-4</sup>		2278
$\overline{D}^0 \overline{K}^0$	( 4.3 ± 0.9 ) × 10 <sup>-4</sup>		2330
$\overline{D}^0 K^- \pi^+$	( 1.04 ± 0.13 ) × 10 <sup>-3</sup>		2312
$\overline{D}^*(2007)^0 K^- \pi^+$	( 7.3 ± 2.6 ) × 10 <sup>-4</sup>		2259
$\overline{D}^0 \overline{K}^*(892)^0$	( 4.4 ± 0.6 ) × 10 <sup>-4</sup>		2264
$\overline{D}^0 \overline{K}^*(1410)$	( 3.9 ± 3.5 ) × 10 <sup>-4</sup>		2117
$\overline{D}^0 \overline{K}_0^*(1430)$	( 3.0 ± 0.7 ) × 10 <sup>-4</sup>		2113
$\overline{D}^0 \overline{K}_2^*(1430)$	( 1.1 ± 0.4 ) × 10 <sup>-4</sup>		2112
$\overline{D}^0 \overline{K}^*(1680)$	< 7.8 × 10 <sup>-5</sup>	CL=90%	1997
$\overline{D}^0 \overline{K}_0^*(1950)$	< 1.1 × 10 <sup>-4</sup>	CL=90%	1884
$\overline{D}^0 \overline{K}_3^*(1780)$	< 2.6 × 10 <sup>-5</sup>	CL=90%	1970
$\overline{D}^0 \overline{K}_4^*(2045)$	< 3.1 × 10 <sup>-5</sup>	CL=90%	1835
$\overline{D}^0 K^- \pi^+$ (non-resonant)	( 2.1 ± 0.8 ) × 10 <sup>-4</sup>		2312
$D_{s2}^*(2573)^- \pi^+, D_{s2}^* \rightarrow \overline{D}^0 K^-$	( 2.6 ± 0.4 ) × 10 <sup>-4</sup>		—
$D_{s1}^*(2700)^- \pi^+, D_{s1}^* \rightarrow \overline{D}^0 K^-$	( 1.6 ± 0.8 ) × 10 <sup>-5</sup>		—
$D_{s1}^*(2860)^- \pi^+, D_{s1}^* \rightarrow \overline{D}^0 K^-$	( 5 ± 4 ) × 10 <sup>-5</sup>		—
$D_{s3}^*(2860)^- \pi^+, D_{s3}^* \rightarrow \overline{D}^0 K^-$	( 2.2 ± 0.6 ) × 10 <sup>-5</sup>		—
$\overline{D}^0 K^+ K^-$	( 5.6 ± 0.9 ) × 10 <sup>-5</sup>		2243
$\overline{D}^0 f_0(980)$	< 3.1 × 10 <sup>-6</sup>	CL=90%	2242
$\overline{D}^0 \phi$	( 2.30 ± 0.25 ) × 10 <sup>-5</sup>		2235
$\overline{D}^{*0} \phi$	( 3.2 ± 0.4 ) × 10 <sup>-5</sup>		2178
$D^{*\mp} \pi^\pm$	< 6.1 × 10 <sup>-6</sup>	CL=90%	—
$\eta_c \phi$	( 5.0 ± 0.9 ) × 10 <sup>-4</sup>		1663
$\eta_c \pi^+ \pi^-$	( 1.8 ± 0.7 ) × 10 <sup>-4</sup>		1840
$J/\psi(1S) \phi$	( 1.04 ± 0.04 ) × 10 <sup>-3</sup>		1588
$J/\psi(1S) \phi \phi$	( 1.20 <sup>+</sup> <sub>-0.16</sub> ) × 10 <sup>-5</sup>		764
$J/\psi(1S) \pi^0$	< 1.2 × 10 <sup>-3</sup>	CL=90%	1787
$J/\psi(1S) \eta$	( 4.0 ± 0.7 ) × 10 <sup>-4</sup>	S=1.4	1733
$J/\psi(1S) K_S^0$	( 1.92 ± 0.14 ) × 10 <sup>-5</sup>		1743
$J/\psi(1S) \overline{K}^*(892)^0$	( 4.1 ± 0.4 ) × 10 <sup>-5</sup>		1637
$J/\psi(1S) \eta'$	( 3.3 ± 0.4 ) × 10 <sup>-4</sup>		1612
$J/\psi(1S) \pi^+ \pi^-$	( 2.02 ± 0.17 ) × 10 <sup>-4</sup>	S=1.7	1775
$J/\psi(1S) f_0(500), f_0 \rightarrow \pi^+ \pi^-$	< 4 × 10 <sup>-6</sup>	CL=90%	—
$J/\psi(1S) \rho, \rho \rightarrow \pi^+ \pi^-$	< 3.4 × 10 <sup>-6</sup>	CL=90%	—
$J/\psi(1S) f_0(980), f_0 \rightarrow \pi^+ \pi^-$	( 1.24 ± 0.15 ) × 10 <sup>-4</sup>	S=2.1	—
$J/\psi(1S) f_2(1270), f_2 \rightarrow \pi^+ \pi^-$	( 1.0 ± 0.4 ) × 10 <sup>-6</sup>		—
$J/\psi(1S) f_2(1270)_0, f_2 \rightarrow \pi^+ \pi^-$	( 7.3 ± 1.7 ) × 10 <sup>-7</sup>		—
$J/\psi(1S) f_2(1270)_\parallel, f_2 \rightarrow \pi^+ \pi^-$	( 1.05 ± 0.33 ) × 10 <sup>-6</sup>		—
$J/\psi(1S) f_2(1270)_\perp, f_2 \rightarrow \pi^+ \pi^-$	( 1.3 ± 0.7 ) × 10 <sup>-6</sup>		—
$J/\psi(1S) f_0(1370), f_0 \rightarrow \pi^+ \pi^-$	( 4.4 <sup>+</sup> <sub>-4.0</sub> ) × 10 <sup>-5</sup>		—

$J/\psi(1S) f_0(1500), f_0 \rightarrow \pi^+ \pi^-$	$(2.04^{+0.32}_{-0.24}) \times 10^{-5}$		—
$J/\psi(1S) f'_2(1525)_0, f'_2 \rightarrow \pi^+ \pi^-$	$(1.03 \pm 0.22) \times 10^{-6}$		—
$J/\psi(1S) f'_2(1525)_{  }, f'_2 \rightarrow \pi^+ \pi^-$	$(1.2^{+2.6}_{-0.8}) \times 10^{-7}$		—
$J/\psi(1S) f'_2(1525)_{\perp}, f'_2 \rightarrow \pi^+ \pi^-$	$(5 \pm 4) \times 10^{-7}$		—
$J/\psi(1S) f_0(1790), f_0 \rightarrow \pi^+ \pi^-$	$(4.9^{+10.0}_{-1.0}) \times 10^{-6}$		—
$J/\psi(1S) \pi^+ \pi^-$ (nonresonant)	$(1.74^{+1.10}_{-0.34}) \times 10^{-5}$		1775
$J/\psi(1S) \bar{K}^0 \pi^+ \pi^-$	$< 4.4 \times 10^{-5}$	CL=90%	1675
$J/\psi(1S) K^+ K^-$	$(7.9 \pm 0.7) \times 10^{-4}$		1601
$J/\psi(1S) K^0 K^- \pi^+ + \text{c.c.}$	$(9.5 \pm 1.3) \times 10^{-4}$		1538
$J/\psi(1S) \bar{K}^0 K^+ K^-$	$< 1.2 \times 10^{-5}$	CL=90%	1333
$J/\psi K^*(892)^0 \bar{K}^*(892)^0$	$(1.10 \pm 0.09) \times 10^{-4}$		1083
$J/\psi(1S) f'_2(1525)$	$(2.6 \pm 0.6) \times 10^{-4}$		1310
$J/\psi(1S) \rho \bar{\rho}$	$(3.6 \pm 0.4) \times 10^{-6}$		982
$J/\psi(1S) \gamma$	$< 7.3 \times 10^{-6}$	CL=90%	1790
$J/\psi \mu^+ \mu^-, J/\psi \rightarrow \mu^+ \mu^-$	$< 2.6 \times 10^{-9}$	CL=95%	—
$J/\psi(1S) \pi^+ \pi^- \pi^+ \pi^-$	$(7.5 \pm 0.8) \times 10^{-5}$		1731
$J/\psi(1S) f_1(1285)$	$(7.2 \pm 1.4) \times 10^{-5}$		1460
$\psi(2S) \eta$	$(3.3 \pm 0.9) \times 10^{-4}$		1338
$\psi(2S) \eta'$	$(1.29 \pm 0.35) \times 10^{-4}$		1158
$\psi(2S) \pi^+ \pi^-$	$(6.9 \pm 1.2) \times 10^{-5}$		1397
$\psi(2S) \phi$	$(5.3 \pm 0.4) \times 10^{-4}$		1120
$\psi(2S) K^0$	$(1.9 \pm 0.5) \times 10^{-5}$		1352
$\psi(2S) K^- \pi^+$	$(3.1 \pm 0.4) \times 10^{-5}$		1310
$\psi(2S) \bar{K}^*(892)^0$	$(3.3 \pm 0.5) \times 10^{-5}$		1196
$\chi_{c1} \phi$	$(1.97 \pm 0.25) \times 10^{-4}$		1275
$\chi_{c1}(3872) \phi$	$(1.22 \pm 0.35) \times 10^{-4}$		936
$\chi_{c1}(3872) (K^+ K^-)_{non-\phi}$	$(9.4 \pm 3.4) \times 10^{-5}$		961
$\chi_{c1}(3872) \pi^+ \pi^-$	$(4.6 \pm 1.6) \times 10^{-5}$		1264
$\pi^+ \pi^-$	$(7.2 \pm 1.0) \times 10^{-7}$		2680
$\pi^0 \pi^0$	$< 7.7 \times 10^{-6}$	CL=90%	2680
$\eta \pi^0$	$< 1.0 \times 10^{-3}$	CL=90%	2654
$\eta \eta$	$< 1.43 \times 10^{-4}$	CL=90%	2627
$\rho^0 \rho^0$	$< 3.20 \times 10^{-4}$	CL=90%	2569
$\eta' K^0_S$	$< 8.16 \times 10^{-6}$	CL=90%	2573
$\eta' \eta$	$< 6.5 \times 10^{-5}$	CL=90%	2568
$\eta' \eta'$	$(3.3 \pm 0.7) \times 10^{-5}$		2507
$\eta' \phi$	$< 8.2 \times 10^{-7}$	CL=90%	2495
$\phi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-$	$(1.12 \pm 0.21) \times 10^{-6}$		—
$\phi f_2(1270), f_2(1270) \rightarrow \pi^+ \pi^-$	$(6.1^{+1.8}_{-1.5}) \times 10^{-7}$		—
$\phi \rho^0$	$(2.7 \pm 0.8) \times 10^{-7}$		2526
$\phi \pi^+ \pi^-$	$(3.5 \pm 0.5) \times 10^{-6}$		2579
$\phi \phi$	$(1.85 \pm 0.14) \times 10^{-5}$		2482
$\phi \phi \phi$	$(2.2 \pm 0.6) \times 10^{-6}$		2165
$\pi^+ K^-$	$(5.9 \pm 0.7) \times 10^{-6}$		2659
$K^+ K^-$	$(2.72 \pm 0.23) \times 10^{-5}$		2638
$K^0 \bar{K}^0$	$(1.76 \pm 0.31) \times 10^{-5}$		2637
$K^0 \pi^+ \pi^-$	$(9.5 \pm 2.1) \times 10^{-6}$		2653
$K^0 K^{\pm} \pi^{\mp}$	$(8.4 \pm 0.9) \times 10^{-5}$		2622

$K^*(892)^- \pi^+$		$(2.9 \pm 1.1) \times 10^{-6}$		2607
$K^*(892)^\pm K^\mp$		$(1.9 \pm 0.5) \times 10^{-5}$		2585
$K_0^*(1430)^\pm K^\mp$		$(3.1 \pm 2.5) \times 10^{-5}$		—
$K_2^*(1430)^\pm K^\mp$		$(1.0 \pm 1.7) \times 10^{-5}$		—
$K^*(892)^0 \bar{K}^0 + \text{c.c.}$		$(2.0 \pm 0.6) \times 10^{-5}$		2585
$K_0^*(1430) \bar{K}^0 + \text{c.c.}$		$(3.3 \pm 1.0) \times 10^{-5}$		2468
$K_2^*(1430)^0 \bar{K}^0 + \text{c.c.}$		$(1.7 \pm 2.2) \times 10^{-5}$		2467
$K_S^0 \bar{K}^*(892)^0 + \text{c.c.}$		$(1.6 \pm 0.4) \times 10^{-5}$		2585
$K^0 K^+ K^-$		$(1.3 \pm 0.6) \times 10^{-6}$		2568
$\bar{K}^*(892)^0 \rho^0$	<	7.67	$\times 10^{-4}$	CL=90% 2550
$\bar{K}^*(892)^0 K^*(892)^0$		$(1.11 \pm 0.27) \times 10^{-5}$		2531
$\phi K^*(892)^0$		$(1.14 \pm 0.30) \times 10^{-6}$		2507
$\rho \bar{\rho}$	<	4.4	$\times 10^{-9}$	CL=90% 2514
$\rho \bar{\rho} K^+ K^-$		$(4.5 \pm 0.5) \times 10^{-6}$		2231
$\rho \bar{\rho} K^+ \pi^-$		$(1.39 \pm 0.26) \times 10^{-6}$		2355
$\rho \bar{\rho} \pi^+ \pi^-$		$(4.3 \pm 2.0) \times 10^{-7}$		2454
$\rho \bar{\rho} \rho \bar{\rho}$		$(2.3 \pm 1.0) \times 10^{-8}$		1797
$\rho \bar{\Lambda} K^- + \text{c.c.}$		$(5.5 \pm 1.0) \times 10^{-6}$		2358
$\Lambda_c^- \Lambda \pi^+$		$(3.6 \pm 1.6) \times 10^{-4}$		1979
$\Lambda_c^- \Lambda_c^+$	<	8.0	$\times 10^{-5}$	CL=95% 1405

**Lepton Family number (LF) violating modes or  
 $\Delta B = 1$  weak neutral current (BI) modes**

$\gamma \gamma$	BI	<	3.1	$\times 10^{-6}$	CL=90%	2683
$\phi \gamma$	BI		$(3.4 \pm 0.4) \times 10^{-5}$			2587
$\mu^+ \mu^-$	BI		$(3.34 \pm 0.27) \times 10^{-9}$			2681
$e^+ e^-$	BI	<	9.4	$\times 10^{-9}$	CL=90%	2683
$\tau^+ \tau^-$	BI	<	6.8	$\times 10^{-3}$	CL=95%	2011
$\mu^+ \mu^- \gamma$	BI	<	2.0	$\times 10^{-9}$		2681
$\mu^+ \mu^- \mu^+ \mu^-$	BI	<	8.6	$\times 10^{-10}$	CL=95%	2673
$SP, S \rightarrow \mu^+ \mu^-,$ $P \rightarrow \mu^+ \mu^-$	BI	[xxx]	<	$2.2 \times 10^{-9}$	CL=95%	—
$aa, a \rightarrow \mu^+ \mu^-$	BI	<	5.8	$\times 10^{-10}$	CL=95%	—
$\phi(1020) \mu^+ \mu^-$	BI		$(8.4 \pm 0.4) \times 10^{-7}$			2582
$f_2'(1525) \mu^+ \mu^-$	BI		$(1.62 \pm 0.22) \times 10^{-7}$			2464
$\bar{K}^*(892)^0 \mu^+ \mu^-$	BI		$(2.9 \pm 1.1) \times 10^{-8}$			2605
$\pi^+ \pi^- \mu^+ \mu^-$	BI		$(8.4 \pm 1.7) \times 10^{-8}$			2670
$\phi \nu \bar{\nu}$	BI	<	5.4	$\times 10^{-3}$	CL=90%	2587
$e^\pm \mu^\mp$	LF	[aa]	<	$5.4 \times 10^{-9}$	CL=90%	2682
$e^\pm \tau^\mp$	LF		<	$1.4 \times 10^{-3}$	CL=90%	2389
$\mu^\pm \tau^\mp$	LF		<	$4.2 \times 10^{-5}$	CL=95%	2388
$\phi \mu^\pm e^\mp$	LF		<	$1.6 \times 10^{-8}$	CL=90%	2586
$\rho \mu^-$	L,B	<	1.21	$\times 10^{-8}$	CL=90%	2600

**$B_s^*$**

$$I(J^P) = 0(1^-)$$

$I, J, P$  need confirmation. Quantum numbers shown are quark-model predictions.

$$\text{Mass } m = 5415.4 \pm 1.4 \text{ MeV} \quad (S = 2.6)$$

$$m_{B_s^*} - m_{B_s} = 48.5 \pm 1.4 \text{ MeV} \quad (S = 2.6)$$



**$B_{s1}(5830)^0$** 

$$I(J^P) = 0(1^+)$$

 $I, J, P$  need confirmation.Mass  $m = 5828.73 \pm 0.20$  MeV $m_{B_{s1}^0} - m_{B^{*+}} = 503.98 \pm 0.17$  MeVFull width  $\Gamma = 0.5 \pm 0.4$  MeV **$B_{s2}^*(5840)^0$** 

$$I(J^P) = 0(2^+)$$

 $I, J, P$  need confirmation.Mass  $m = 5839.88 \pm 0.12$  MeV $m_{B_{s2}^{*0}} - m_{B^{*+}} = 560.48 \pm 0.12$  MeVFull width  $\Gamma = 1.49 \pm 0.27$  MeVBranching fractions are given relative to the one **DEFINED AS 1**. **$B_{s2}^*(5840)^0$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ ) $p$  (MeV/c)

<b><math>B_{s2}^*(5840)^0</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$B^+ K^-$	<b>DEFINED AS 1</b>	252
$B^{*+} K^-$	$0.093 \pm 0.018$	141
$B^0 K_S^0$	$0.43 \pm 0.11$	245
$B^{*0} K_S^0$	$0.04 \pm 0.04$	—

## BOTTOM, CHARMED MESONS ( $B = C = \pm 1$ )

$$B_c^+ = c\bar{b}, B_c^- = \bar{c}b, \quad \text{similarly for } B_c^{* \prime}s$$

 **$B_c^+$** 

$$I(J^P) = 0(0^-)$$

 $I, J, P$  need confirmation.

Quantum numbers shown are quark-model predictions.

Mass  $m = 6274.47 \pm 0.32$  MeV $m_{B_c^+} - m_{B_s^0} = 907.8 \pm 0.5$  MeVMean life  $\tau = (0.510 \pm 0.009) \times 10^{-12}$  sThe following quantities are not pure branching ratios; rather the fractions  $\Gamma_i/\Gamma \times B(\bar{b} \rightarrow B_c)$ .  $B_c^-$  modes are charge conjugates of the modes below. **$B_c^+$  DECAY MODES  $\times B(\bar{b} \rightarrow B_c)$** Fraction ( $\Gamma_i/\Gamma$ )

Confidence level

 $p$ 

(MeV/c)

<b><math>B_c^+</math> DECAY MODES <math>\times B(\bar{b} \rightarrow B_c)</math></b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\chi_{c0} \pi^+$	$(2.4^{+0.9}_{-0.8}) \times 10^{-5}$		2205
$D_S^+ \bar{D}^0$	$< 7.2 \times 10^{-4}$	90%	2483
$D_S^+ D^0$	$< 3.0 \times 10^{-4}$	90%	2483
$D^+ \bar{D}^0$	$< 1.9 \times 10^{-4}$	90%	2521
$D^+ D^0$	$< 1.4 \times 10^{-4}$	90%	2521
$D_S^{*+} \bar{D}^0$	$< 5.3 \times 10^{-4}$	90%	2425
$D_S^+ \bar{D}^*(2007)^0$	$< 4.6 \times 10^{-4}$	90%	2427
$D_S^{*+} D^0$	$< 9 \times 10^{-4}$	90%	2425
$D_S^+ D^*(2007)^0$	$< 6.6 \times 10^{-4}$	90%	2427
$D^*(2010)^+ \bar{D}^0$	$< 3.8 \times 10^{-4}$	90%	2467

$D^+ \bar{D}^*(2007)^0$	< 6.5	$\times 10^{-4}$	90%	2466
$D^*(2007)^+ D^0$	< 2.0	$\times 10^{-4}$	90%	—
$D^+ D^*(2007)^0$	< 3.7	$\times 10^{-4}$	90%	2466
$D_S^{*+} \bar{D}^*(2007)^0$	< 1.3	$\times 10^{-3}$	90%	2366
$D_S^{*+} D^*(2007)^0$	< 1.3	$\times 10^{-3}$	90%	2366
$D^*(2010)^+ \bar{D}^*(2007)^0$	< 1.0	$\times 10^{-3}$	90%	2410
$D^*(2010)^+ D^*(2007)^0$	< 7.7	$\times 10^{-4}$	90%	2410

See Particle Listings for 31 decay modes that have been seen / not seen.

**$B_c(2S)^\pm$**

$$I(J^P) = 0(0^-)$$

Mass  $m = 6871.2 \pm 1.0$  MeV

**$c\bar{c}$  MESONS**  
(including possibly non- $q\bar{q}$  states)

**$\eta_c(1S)$**

$$I^G(J^{PC}) = 0^+(0^{-+})$$

Mass  $m = 2984.1 \pm 0.4$  MeV ( $S = 1.2$ )

Full width  $\Gamma = 30.5 \pm 0.5$  MeV ( $S = 1.2$ )

$\eta_c(1S)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Decays involving hadronic resonances</b>			
$\eta'(958)\pi\pi$	( 2.0 $\pm$ 0.4 ) %	S=1.4	1323
$\eta'(958)K\bar{K}$	( 1.73 $\pm$ 0.35) %		1131
$\eta'(958)\eta\eta$	( 3.4 $\pm$ 0.6 ) $\times 10^{-3}$		1081
$\rho\rho$	( 1.8 $\pm$ 0.4 ) %		1275
$K^*(892)^0 K^- \pi^+ +$ c.c.	( 1.8 $\pm$ 0.5 ) %		1278
$K^*(892)\bar{K}^*(892)$	( 7.0 $\pm$ 1.2 ) $\times 10^{-3}$		1196
$K^*(892)^0 \bar{K}^*(892)^0 \pi^+ \pi^-$	( 1.4 $\pm$ 0.6 ) %		1074
$\phi K^+ K^-$	( 3.3 $^{+1.2}_{-1.1}$ ) $\times 10^{-3}$		1104
$\phi\phi$	( 1.8 $\pm$ 0.4 ) $\times 10^{-3}$	S=2.3	1089
$\phi 2(\pi^+ \pi^-)$	< 4 $\times 10^{-3}$	CL=90%	1251
$K^*(892)\bar{K} +$ c.c.	< 1.28 %	CL=90%	1310
$\omega\omega$	( 2.7 $\pm$ 0.9 ) $\times 10^{-3}$	S=2.1	1270
$\omega\phi$	< 2.5 $\times 10^{-4}$	CL=90%	1185
$f_2(1270)f_2(1270)$	( 1.08 $\pm$ 0.27) %		774
$f_2(1270)f_2'(1525)$	( 9.7 $\pm$ 3.2 ) $\times 10^{-3}$		524
<b>Decays into stable hadrons</b>			
$K\bar{K}\pi$	( 7.1 $\pm$ 0.4 ) %	S=1.1	1381
$K\bar{K}\eta$	( 1.32 $\pm$ 0.15) %		1265
$\eta\pi^+\pi^-$	( 1.6 $\pm$ 0.4 ) %		1428
$\eta 2(\pi^+ \pi^-)$	( 4.3 $\pm$ 1.3 ) %		1386
$K^+ K^- \pi^+ \pi^-$	( 8.3 $\pm$ 1.8 ) $\times 10^{-3}$	S=1.9	1345
$K^+ K^- \pi^+ \pi^- \pi^0$	( 3.4 $\pm$ 0.6 ) %		1304
$K^0 K^- \pi^+ \pi^- \pi^+ +$ c.c.	( 5.4 $\pm$ 1.5 ) %		1302
$K^+ K^- 2(\pi^+ \pi^-)$	( 8.4 $\pm$ 2.4 ) $\times 10^{-3}$		1254
$2(K^+ K^-)$	( 1.4 $\pm$ 0.4 ) $\times 10^{-3}$	S=1.4	1056
$\pi^+ \pi^- \pi^0$	< 4 $\times 10^{-4}$	CL=90%	1476

$\pi^+ \pi^- \pi^0 \pi^0$	( 4.6 ± 1.0 ) %		1461
$2(\pi^+ \pi^-)$	( 9.6 ± 1.5 ) × 10 <sup>-3</sup>	S=1.4	1459
$2(\pi^+ \pi^- \pi^0)$	(15.9 ± 2.0 ) %		1409
$3(\pi^+ \pi^-)$	( 1.89 ± 0.34 ) %		1407
$\rho \bar{\rho}$	( 1.33 ± 0.11 ) × 10 <sup>-3</sup>	S=1.1	1160
$\rho \bar{\rho} \pi^0$	( 3.4 ± 1.3 ) × 10 <sup>-3</sup>		1101
$\rho \bar{\rho} \pi^+ \pi^-$	( 3.7 ± 0.5 ) × 10 <sup>-3</sup>		1027
$\Lambda \bar{\Lambda}$	( 1.10 ± 0.28 ) × 10 <sup>-3</sup>	S=1.5	991
$K^+ \bar{p} \Lambda + \text{c.c.}$	( 2.5 ± 0.4 ) × 10 <sup>-3</sup>		773
$\bar{\Lambda}(1520) \Lambda + \text{c.c.}$	( 3.0 ± 1.3 ) × 10 <sup>-3</sup>		694
$\Sigma^+ \bar{\Sigma}^-$	( 2.6 ± 0.5 ) × 10 <sup>-3</sup>		901
$\Xi^- \bar{\Xi}^+$	( 1.07 ± 0.24 ) × 10 <sup>-3</sup>		692

## Radiative decays

$\gamma \gamma$	( 1.66 ± 0.13 ) × 10 <sup>-4</sup>	S=1.2	1492
-----------------	------------------------------------	-------	------

Charge conjugation (C), Parity (P),  
Lepton Family number (LF) violating modes

$\pi^+ \pi^-$	$P, CP < 1.3$	× 10 <sup>-4</sup>	CL=90%	1485
$\pi^0 \pi^0$	$P, CP < 4$	× 10 <sup>-5</sup>	CL=90%	1486
$K^+ K^-$	$P, CP < 7$	× 10 <sup>-4</sup>	CL=90%	1408
$K_S^0 K_S^0$	$P, CP < 4$	× 10 <sup>-4</sup>	CL=90%	1407

See Particle Listings for 21 decay modes that have been seen / not seen.

**J/ψ(1S)**

$$J^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 3096.900 \pm 0.006$  MeVFull width  $\Gamma = 92.6 \pm 1.7$  keV (S = 1.1)

J/ψ(1S) DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level (MeV/c)	$p$
hadrons	(87.7 ± 0.5 ) %		—
virtual $\gamma \rightarrow$ hadrons	(13.46 ± 0.07 ) %		—
$g g g$	(64.1 ± 1.0 ) %		—
$\gamma g g$	( 8.8 ± 1.1 ) %		—
$e^+ e^-$	( 5.971 ± 0.032 ) %		1548
$e^+ e^- \gamma$	[hhaa] ( 8.8 ± 1.4 ) × 10 <sup>-3</sup>		1548
$\mu^+ \mu^-$	( 5.961 ± 0.033 ) %		1545

## Decays involving hadronic resonances

$\rho \pi$	( 1.88 ± 0.12 ) %	S=2.6	1448
$\rho^0 \pi^0$	( 6.2 ± 0.6 ) × 10 <sup>-3</sup>		1448
$a_2(1320)^0 \pi^+ \pi^- \rightarrow$ $2(\pi^+ \pi^-) \pi^0$	( 2.8 ± 0.6 ) × 10 <sup>-3</sup>		—
$a_2(1320)^+ \pi^- \pi^0 + \text{c.c.} \rightarrow$ $2(\pi^+ \pi^-) \pi^0$	( 3.7 ± 0.7 ) × 10 <sup>-3</sup>		—
$a_2(1320) \rho$	( 1.09 ± 0.22 ) %		1123
$\eta \pi^+ \pi^-$	( 3.8 ± 0.7 ) × 10 <sup>-4</sup>		1487
$\eta \rho$	( 1.93 ± 0.23 ) × 10 <sup>-4</sup>		1396
$\eta \pi^+ \pi^- \pi^0$	( 1.17 ± 0.20 ) %		1470
$\eta \pi^+ \pi^- 3\pi^0$	( 4.9 ± 1.0 ) × 10 <sup>-3</sup>		1419
$\eta \phi(2170) \rightarrow \eta \phi f_0(980) \rightarrow$ $\eta \phi \pi^+ \pi^-$	( 1.2 ± 0.4 ) × 10 <sup>-4</sup>		628
$\eta \phi(2170) \rightarrow$ $\eta K^*(892)^0 \bar{K}^*(892)^0$	< 2.52 × 10 <sup>-4</sup>	CL=90%	—
$\eta K^+ K^-$	( 8.6 ± 3.0 ) × 10 <sup>-4</sup>		1331

$\eta K^\pm K_S^0 \pi^\mp$	[aa]	$(2.2 \pm 0.4) \times 10^{-3}$		1278
$\eta K^*(892)^0 \bar{K}^*(892)^0$		$(1.15 \pm 0.26) \times 10^{-3}$		1003
$\rho \eta'(958)$		$(8.1 \pm 0.8) \times 10^{-5}$	S=1.6	1281
$\rho^\pm \pi^\mp \pi^+ \pi^- 2\pi^0$		$(2.8 \pm 0.8) \%$		1364
$\rho^+ \rho^- \pi^+ \pi^- \pi^0$		$(6 \pm 4) \times 10^{-3}$		1186
$\rho^+ K^+ K^- \pi^- + \text{c.c.} \rightarrow$		$(3.5 \pm 0.8) \times 10^{-3}$		-
$\rho^\mp K^\pm K_S^0 \pi^\mp$		$(1.9 \pm 0.4) \times 10^{-3}$		1269
$\rho(1450) \pi \rightarrow \pi^+ \pi^- \pi^0$		$(2.2 \pm 1.1) \times 10^{-4}$		-
$\rho(1450)^\pm \pi^\mp \rightarrow K_S^0 K^\pm \pi^\mp$		$(3.3 \pm 0.6) \times 10^{-4}$		-
$\rho(1450)^0 \pi^0 \rightarrow K^+ K^- \pi^0$		$(2.7 \pm 0.6) \times 10^{-4}$		-
$\rho(1450) \eta'(958) \rightarrow$		$(3.3 \pm 0.7) \times 10^{-6}$		-
$\pi^+ \pi^- \eta'(958)$				
$\rho(1700) \pi \rightarrow \pi^+ \pi^- \pi^0$		$(1.6 \pm 1.1) \times 10^{-4}$		-
$\rho(2150) \pi \rightarrow \pi^+ \pi^- \pi^0$		$(10 \pm 40) \times 10^{-6}$		-
$\omega \pi^0$		$(4.5 \pm 0.5) \times 10^{-4}$	S=1.4	1446
$\omega \pi^0 \rightarrow \pi^+ \pi^- \pi^0$		$(1.6 \pm 0.7) \times 10^{-5}$		-
$\omega \pi^+ \pi^-$		$(8.5 \pm 1.0) \times 10^{-3}$	S=1.3	1435
$\omega \pi^0 \pi^0$		$(3.4 \pm 0.8) \times 10^{-3}$		1436
$\omega 3\pi^0$		$(1.9 \pm 0.6) \times 10^{-3}$		1419
$\omega f_2(1270)$		$(4.3 \pm 0.6) \times 10^{-3}$		1142
$\omega \eta$		$(1.74 \pm 0.20) \times 10^{-3}$	S=1.6	1394
$\omega \pi^+ \pi^- \pi^0$		$(4.0 \pm 0.7) \times 10^{-3}$		1418
$\omega \pi^0 \eta$		$(3.4 \pm 1.7) \times 10^{-4}$		1363
$\omega \pi^+ \pi^+ \pi^- \pi^-$		$(8.5 \pm 3.4) \times 10^{-3}$		1392
$\omega \pi^+ \pi^- 2\pi^0$		$(3.3 \pm 0.5) \%$		1394
$\omega \eta' \pi^+ \pi^-$		$(1.12 \pm 0.13) \times 10^{-3}$		1173
$\omega \eta'(958)$		$(1.89 \pm 0.18) \times 10^{-4}$		1279
$\omega f_0(980)$		$(1.4 \pm 0.5) \times 10^{-4}$		1267
$\omega f_0(1710) \rightarrow \omega K \bar{K}$		$(4.8 \pm 1.1) \times 10^{-4}$		878
$\omega f_1(1420)$		$(6.8 \pm 2.4) \times 10^{-4}$		1060
$\omega f_2'(1525)$		$< 2.2 \times 10^{-4}$	CL=90%	1007
$\omega X(1835) \rightarrow \omega p \bar{p}$		$< 3.9 \times 10^{-6}$	CL=95%	-
$\omega X(1835), X \rightarrow \eta' \pi^+ \pi^-$		$< 6.2 \times 10^{-5}$		-
$\omega K^+ K^-$		$(1.52 \pm 0.31) \times 10^{-3}$		1268
$\omega K^\pm K_S^0 \pi^\mp$	[aa]	$(3.4 \pm 0.5) \times 10^{-3}$		1210
$\omega K \bar{K}$		$(1.9 \pm 0.4) \times 10^{-3}$		1268
$\omega K^*(892) \bar{K} + \text{c.c.}$		$(6.1 \pm 0.9) \times 10^{-3}$		1097
$\eta' K^{*\pm} K^\mp$		$(1.48 \pm 0.13) \times 10^{-3}$		-
$\eta' K^{*0} \bar{K}^0 + \text{c.c.}$		$(1.66 \pm 0.21) \times 10^{-3}$		1000
$\eta' h_1(1415) \rightarrow \eta' K^* \bar{K} + \text{c.c.}$		$(2.16 \pm 0.31) \times 10^{-4}$		-
$\eta' h_1(1415) \rightarrow \eta' K^{*\pm} K^\mp$		$(1.51 \pm 0.23) \times 10^{-4}$		-
$\eta' h_1(1415) \rightarrow \gamma \eta' \eta'$		$(4.7 \pm \frac{1.1}{2.0}) \times 10^{-7}$		-
$\bar{K} K^*(892) + \text{c.c.} \rightarrow$		$(4.8 \pm 0.5) \times 10^{-3}$		-
$K_S^0 K^\pm \pi^\mp$				
$K^+ K^*(892)^- + \text{c.c.}$		$(6.0 \pm \frac{0.8}{1.0}) \times 10^{-3}$	S=2.9	1373
$K^+ K^*(892)^- + \text{c.c.} \rightarrow$		$(2.69 \pm \frac{0.13}{0.20}) \times 10^{-3}$		-
$K^+ K^- \pi^0$				
$K^+ K^*(892)^- + \text{c.c.} \rightarrow$		$(3.0 \pm 0.4) \times 10^{-3}$		-
$K^0 K^\pm \pi^\mp + \text{c.c.}$				
$K^0 \bar{K}^*(892)^0 + \text{c.c.}$		$(4.2 \pm 0.4) \times 10^{-3}$		1373
$K^0 \bar{K}^*(892)^0 + \text{c.c.} \rightarrow$		$(3.2 \pm 0.4) \times 10^{-3}$		-
$K^0 K^\pm \pi^\mp + \text{c.c.}$				
$\bar{K}^*(892)^0 K^+ \pi^- + \text{c.c.}$		$(5.7 \pm 0.8) \times 10^{-3}$		1343

$K^*(892)^\pm K^\mp \pi^0$	$(4.1 \pm 1.3) \times 10^{-3}$		1344
$K^*(892)^+ K_S^0 \pi^- + \text{c.c.}$	$(2.0 \pm 0.5) \times 10^{-3}$		1342
$K^*(892)^+ K_S^0 \pi^- + \text{c.c.} \rightarrow$ $K_S^0 K_S^0 \pi^+ \pi^-$	$(6.7 \pm 2.2) \times 10^{-4}$		-
$K^*(892)^0 K^- \pi^+ + \text{c.c.} \rightarrow$ $K^+ K^- \pi^+ \pi^-$	$(3.8 \pm 0.5) \times 10^{-3}$		-
$K^*(892)^0 K_S^0 \rightarrow \gamma K_S^0 K_S^0$	$(6.3 \pm_{-0.5}^{+0.6}) \times 10^{-6}$		-
$K^*(892)^0 K_S^0 \pi^0$	$(7 \pm 4) \times 10^{-4}$		1343
$K^*(892)^\pm K^*(700)^\mp$	$(1.1 \pm_{-0.6}^{+1.0}) \times 10^{-3}$		-
$K^*(892)^0 \bar{K}^*(892)^0$	$(2.3 \pm 0.6) \times 10^{-4}$		1266
$K^*(892)^\pm K^*(892)^\mp$	$(1.00 \pm_{-0.40}^{+0.22}) \times 10^{-3}$		1266
$K_1(1400)^\pm K^\mp$	$(3.8 \pm 1.4) \times 10^{-3}$		1170
$K^*(1410) \bar{K} + \text{c.c.} \rightarrow$ $K^\pm K^\mp \pi^0$	$(7 \pm 4) \times 10^{-5}$		-
$K^*(1410) \bar{K} + \text{c.c.} \rightarrow$ $K_S^0 K^\pm \pi^\mp$	$(8 \pm 5) \times 10^{-5}$		-
$K_2^*(1430) \bar{K} + \text{c.c.} \rightarrow$ $K^\pm K^\mp \pi^0$	$(1.0 \pm 0.5) \times 10^{-4}$		-
$K_2^*(1430) \bar{K} + \text{c.c.} \rightarrow$ $K_S^0 K^\pm \pi^\mp$	$(3.8 \pm 1.0) \times 10^{-4}$		-
$\bar{K}_2^*(1430) K + \text{c.c.}$	$< 4.0 \times 10^{-3}$	CL=90%	1158
$K_2^*(1430)^+ K^- + \text{c.c.} \rightarrow$ $K^+ K^- \pi^0$	$(2.69 \pm_{-0.19}^{+0.25}) \times 10^{-4}$		-
$K_2^*(1430)^0 K^- \pi^+ + \text{c.c.} \rightarrow$ $K^+ K^- \pi^+ \pi^-$	$(2.6 \pm 0.9) \times 10^{-3}$		-
$K_2^*(1430)^+ K_S^0 \pi^- + \text{c.c.}$	$(3.6 \pm 1.8) \times 10^{-3}$		1116
$\bar{K}_2^*(1430)^0 K^*(892)^0 + \text{c.c.}$	$(4.67 \pm 0.29) \times 10^{-3}$		1011
$K_2^*(1430)^- K^*(892)^+ + \text{c.c.}$	$(3.4 \pm 2.9) \times 10^{-3}$		1011
$K_2^*(1430)^- K^*(892)^+ +$ $\text{c.c.} \rightarrow K^*(892)^+ K_S^0 \pi^- +$ $\text{c.c.}$	$(4 \pm 4) \times 10^{-4}$		-
$K_2^*(1430)^0 \bar{K}_2^*(1430)^0$	$< 2.9 \times 10^{-3}$	CL=90%	601
$\bar{K}_2^*(1770)^0 K^*(892)^0 + \text{c.c.} \rightarrow$ $K^*(892)^0 K^- \pi^+ + \text{c.c.}$	$(6.9 \pm 0.9) \times 10^{-4}$		-
$K_2^*(1980)^+ K^- + \text{c.c.} \rightarrow$ $K^+ K^- \pi^0$	$(1.10 \pm_{-0.14}^{+0.60}) \times 10^{-5}$		-
$K_4^*(2045)^+ K^- + \text{c.c.} \rightarrow$ $K^+ K^- \pi^0$	$(6.2 \pm_{-1.6}^{+2.9}) \times 10^{-6}$		-
$K_1(1270)^\pm K^\mp$	$< 3.0 \times 10^{-3}$	CL=90%	1240
$K_1(1270) K_S^0 \rightarrow \gamma K_S^0 K_S^0$	$(8.5 \pm 2.5) \times 10^{-7}$		-
$a_2(1320)^\pm \pi^\mp$	$[a\bar{a}] < 4.3 \times 10^{-3}$	CL=90%	1263
$\phi \pi^0$	$3 \times 10^{-6} \text{ or } 1 \times 10^{-7}$		1377
$\phi \pi^+ \pi^-$	$(9.4 \pm 1.5) \times 10^{-4}$	S=1.7	1365
$\phi \pi^0 \pi^0$	$(5.0 \pm 1.0) \times 10^{-4}$		1366
$\phi 2(\pi^+ \pi^-)$	$(1.60 \pm 0.32) \times 10^{-3}$		1318
$\phi \eta$	$(7.4 \pm 0.6) \times 10^{-4}$	S=1.2	1320
$\phi \eta'(958)$	$(4.6 \pm 0.5) \times 10^{-4}$	S=2.2	1192
$\phi \eta \eta'$	$(2.32 \pm 0.17) \times 10^{-4}$		885
$\phi f_0(980)$	$(3.2 \pm 0.9) \times 10^{-4}$	S=1.9	1178
$\phi f_0(980) \rightarrow \phi \pi^+ \pi^-$	$(2.60 \pm 0.34) \times 10^{-4}$		-
$\phi f_0(980) \rightarrow \phi \pi^0 \pi^0$	$(1.8 \pm 0.5) \times 10^{-4}$		-
$\phi \pi^0 f_0(980) \rightarrow \phi \pi^0 \pi^+ \pi^-$	$(4.5 \pm 1.0) \times 10^{-6}$		-

$\phi\pi^0 f_0(980) \rightarrow \phi\pi^0\rho^0\pi^0$	$(1.7 \pm 0.6) \times 10^{-6}$		1045
$\phi f_0(980)\eta \rightarrow \eta\phi\pi^+\pi^-$	$(3.2 \pm 1.0) \times 10^{-4}$		—
$\phi a_0(980)^0 \rightarrow \phi\eta\pi^0$	$(4.4 \pm 1.4) \times 10^{-6}$		—
$\phi f_2(1270)$	$(3.2 \pm 0.6) \times 10^{-4}$		1036
$\phi f_1(1285)$	$(2.6 \pm 0.5) \times 10^{-4}$		1032
$\phi f_1(1285) \rightarrow \phi\pi^0 f_0(980) \rightarrow \phi\pi^0\pi^+\pi^-$	$(9.4 \pm 2.8) \times 10^{-7}$		952
$\phi f_1(1285) \rightarrow \phi\pi^0 f_0(980) \rightarrow \phi 3\pi^0$	$(2.1 \pm 2.2) \times 10^{-7}$		955
$\phi\eta(1405) \rightarrow \phi\eta\pi^+\pi^-$	$(2.0 \pm 1.0) \times 10^{-5}$		946
$\phi f_2'(1525)$	$(8 \pm 4) \times 10^{-4}$	S=2.7	877
$\phi X(1835) \rightarrow \phi\rho\bar{\rho}$	$< 2.1 \times 10^{-7}$	CL=90%	—
$\phi X(1835) \rightarrow \phi\eta\pi^+\pi^-$	$< 2.8 \times 10^{-4}$	CL=90%	578
$\phi X(1870) \rightarrow \phi\eta\pi^+\pi^-$	$< 6.13 \times 10^{-5}$	CL=90%	—
$\phi K\bar{K}$	$(1.77 \pm 0.16) \times 10^{-3}$	S=1.3	1179
$\phi f_0(1710) \rightarrow \phi K\bar{K}$	$(3.6 \pm 0.6) \times 10^{-4}$		875
$\phi K^+ K^-$	$(8.3 \pm 1.1) \times 10^{-4}$		1179
$\phi K_S^0 K_S^0$	$(5.9 \pm 1.5) \times 10^{-4}$		1176
$\phi K^\pm K_S^0 \pi^\mp$ [aa]	$(7.2 \pm 0.8) \times 10^{-4}$		1114
$\phi K^*(892)\bar{K} + c.c.$	$(2.18 \pm 0.23) \times 10^{-3}$		969
$b_1(1235)^\pm \pi^\mp$ [aa]	$(3.0 \pm 0.5) \times 10^{-3}$		1300
$b_1(1235)^0 \pi^0$	$(2.3 \pm 0.6) \times 10^{-3}$		1300
$f_2'(1525)K^+ K^-$	$(1.04 \pm 0.35) \times 10^{-3}$		897
$\Delta(1232)^+ \bar{p}$	$< 1 \times 10^{-4}$	CL=90%	1100
$\Delta(1232)^{++} \bar{p}\pi^-$	$(1.6 \pm 0.5) \times 10^{-3}$		1030
$\Delta(1232)^{++} \bar{\Delta}(1232)^{--}$	$(1.10 \pm 0.29) \times 10^{-3}$		938
$\bar{\Sigma}(1385)^0 \rho K^-$	$(5.1 \pm 3.2) \times 10^{-4}$		646
$\Sigma(1385)^0 \bar{\Lambda} + c.c.$	$< 8.2 \times 10^{-6}$	CL=90%	911
$\Sigma(1385)^- \bar{\Sigma}^+ + c.c.$ [aa]	$(3.0 \pm 0.7) \times 10^{-4}$		855
$\Sigma(1385)^+ \bar{\Sigma}^- + c.c.$	$(3.3 \pm 0.8) \times 10^{-4}$		861
$\Sigma(1385)^- \bar{\Sigma}(1385)^+ + c.c.$ [aa]	$(1.08 \pm 0.06) \times 10^{-3}$		697
$\Sigma(1385)^+ \bar{\Sigma}(1385)^- + c.c.$	$(1.25 \pm 0.07) \times 10^{-3}$		697
$\Sigma(1385)^0 \bar{\Sigma}(1385)^0$	$(1.07 \pm 0.08) \times 10^{-3}$		697
$\Lambda(1520)\bar{\Lambda} + c.c. \rightarrow \gamma\Lambda\bar{\Lambda}$	$< 4.1 \times 10^{-6}$	CL=90%	—
$\bar{\Lambda}(1520)\Lambda + c.c.$	$< 1.80 \times 10^{-3}$	CL=90%	807
$\Xi^0 \Xi^0$	$(1.17 \pm 0.04) \times 10^{-3}$		818
$\Xi(1530)^- \Xi^+ + c.c.$	$(3.18 \pm 0.08) \times 10^{-4}$		600
$\Xi(1530)^0 \Xi^0$	$(3.2 \pm 1.4) \times 10^{-4}$		608
$\Theta(1540)\bar{\Theta}(1540) \rightarrow K_S^0 \rho K^- \bar{n} + c.c.$ [iiaa]	$< 1.1 \times 10^{-5}$	CL=90%	—
$\Theta(1540)K^- \bar{n} \rightarrow K_S^0 \rho K^- \bar{n}$ [iiaa]	$< 2.1 \times 10^{-5}$	CL=90%	—
$\Theta(1540)K_S^0 \bar{p} \rightarrow K_S^0 \bar{p} K^+ n$ [iiaa]	$< 1.6 \times 10^{-5}$	CL=90%	—
$\bar{\Theta}(1540)K^+ n \rightarrow K_S^0 \bar{p} K^+ n$ [iiaa]	$< 5.6 \times 10^{-5}$	CL=90%	—
$\bar{\Theta}(1540)K_S^0 \rho \rightarrow K_S^0 \rho K^- \bar{n}$ [iiaa]	$< 1.1 \times 10^{-5}$	CL=90%	—

**Decays into stable hadrons**

$2(\pi^+\pi^-)\pi^0$	$(4.2 \pm 0.4) \%$	S=2.1	1496
$3(\pi^+\pi^-)\pi^0$	$(2.9 \pm 0.6) \%$		1433
$\pi^+\pi^- 3\pi^0$	$(1.9 \pm 0.9) \%$		1497
$\rho^\pm \pi^\mp \pi^0 \pi^0$	$(1.41 \pm 0.22) \%$		1421
$\rho^+ \rho^- \pi^0$	$(6.0 \pm 1.1) \times 10^{-3}$		1298
$\pi^+\pi^- 4\pi^0$	$(6.5 \pm 1.3) \times 10^{-3}$		1470
$\pi^+\pi^- \pi^0$	$(2.00 \pm 0.07) \%$	S=2.0	1533
$2(\pi^+\pi^-\pi^0)$	$(1.61 \pm 0.20) \%$		1468
$\pi^+\pi^-\pi^0 K^+ K^-$	$(1.52 \pm 0.27) \%$	S=1.4	1368

$\pi^+ \pi^-$	$(1.47 \pm 0.14) \times 10^{-4}$		1542
$2(\pi^+ \pi^-)$	$(3.20 \pm 0.25) \times 10^{-3}$	S=1.2	1517
$3(\pi^+ \pi^-)$	$(4.3 \pm 0.4) \times 10^{-3}$		1466
$2(\pi^+ \pi^-) 3\pi^0$	$(6.2 \pm 0.9) \%$		1435
$4(\pi^+ \pi^-) \pi^0$	$(9.0 \pm 3.0) \times 10^{-3}$		1345
$2(\pi^+ \pi^-) \eta$	$(2.29 \pm 0.28) \times 10^{-3}$		1446
$3(\pi^+ \pi^-) \eta$	$(7.2 \pm 1.5) \times 10^{-4}$		1379
$2(\pi^+ \pi^- \pi^0) \eta$	$(1.6 \pm 0.5) \times 10^{-3}$		1381
$\pi^+ \pi^- \pi^0 \pi^0 \eta$	$(2.4 \pm 0.5) \times 10^{-3}$		1448
$\rho^\pm \pi^\mp \pi^0 \eta$	$(1.9 \pm 0.8) \times 10^{-3}$		1326
$K^+ K^-$	$(2.86 \pm 0.21) \times 10^{-4}$		1468
$K_S^0 K_L^0$	$(1.95 \pm 0.11) \times 10^{-4}$	S=2.4	1466
$K_S^0 K_S^0$	$< 1.4 \times 10^{-8}$	CL=95%	1466
$K \bar{K} \pi$	$(6.1 \pm 1.0) \times 10^{-3}$		1442
$K^+ K^- \pi^0$	$(2.88 \pm 0.12) \times 10^{-3}$		1442
$K_S^0 K^\pm \pi^\mp$	$(5.3 \pm 0.5) \times 10^{-3}$		1440
$K_S^0 K_L^0 \pi^0$	$(2.06 \pm 0.26) \times 10^{-3}$		1440
$K^*(892)^0 \bar{K}^0 + \text{c.c.} \rightarrow$ $K_S^0 K_L^0 \pi^0$	$(1.21 \pm 0.18) \times 10^{-3}$		-
$K_2^*(1430)^0 \bar{K}^0 + \text{c.c.} \rightarrow$ $K_S^0 K_L^0 \pi^0$	$(4.3 \pm 1.3) \times 10^{-4}$		-
$K^+ K^- \pi^+ \pi^-$	$(7.0 \pm 1.0) \times 10^{-3}$		1407
$K^+ K^- \pi^0 \pi^0$	$(2.13 \pm 0.22) \times 10^{-3}$		1410
$K^+ K^- \pi^0 \pi^0 \pi^0$	$(1.61 \pm 0.29) \times 10^{-3}$		1371
$K_S^0 K^\pm \pi^\mp \pi^0 \pi^0$	$(5.3 \pm 0.7) \times 10^{-3}$		1369
$K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$	$(6.3 \pm 0.4) \times 10^{-3}$		1366
$K_S^0 K^\pm \rho(770)^\pm \pi^0$	$(2.9 \pm 0.8) \times 10^{-3}$		-
$K_S^0 K_L^0 \pi^+ \pi^-$	$(3.8 \pm 0.6) \times 10^{-3}$		1406
$K_S^0 K_L^0 \pi^0 \pi^0$	$(1.9 \pm 0.4) \times 10^{-3}$		1408
$K_S^0 K_L^0 \eta$	$(1.45 \pm 0.33) \times 10^{-3}$		1328
$K_S^0 K_S^0 \pi^+ \pi^-$	$(1.68 \pm 0.19) \times 10^{-3}$		1406
$K^\mp K_S^0 \pi^\pm \pi^0$	$(5.7 \pm 0.5) \times 10^{-3}$		1408
$K_S^0 K^\pm \pi^\mp \rho(770)^0$	$(3.1 \pm 0.5) \times 10^{-3}$		-
$K^+ K^- 2(\pi^+ \pi^-)$	$(3.1 \pm 1.3) \times 10^{-3}$		1320
$K^+ K^- \pi^+ \pi^- \eta$	$(4.7 \pm 0.7) \times 10^{-3}$		1221
$2(K^+ K^-)$	$(7.2 \pm 0.8) \times 10^{-4}$		1131
$K^+ K^- K_S^0 K_S^0$	$(4.2 \pm 0.7) \times 10^{-4}$		1127
$K_S^0 K^*(892)^0 \pi^+ \pi^-$	$(1.7 \pm 0.6) \times 10^{-3}$		1304
$K_S^0 K^*(892)^0 \pi^0 \pi^0$	$(1.01 \pm 0.18) \times 10^{-3}$		1306
$K^\mp K^*(892)^\pm \pi^+ \pi^-$	$(3.4 \pm 1.2) \times 10^{-3}$		1305
$K^*(892)^\pm K^*(892)^0 \pi^\mp$	$(4.8 \pm 1.0) \times 10^{-3}$		1213
$K^\mp K^*(892)^\pm \pi^0 \pi^0$	$(1.57 \pm 0.32) \times 10^{-3}$		1308
$K^*(892)^+ K^*(892)^- \pi^0$	$(1.12 \pm 0.23) \%$		1214
$\rho \bar{\rho}$	$(2.120 \pm 0.029) \times 10^{-3}$		1232
$\rho \bar{\rho} \pi^0$	$(1.19 \pm 0.08) \times 10^{-3}$	S=1.1	1176
$\rho \bar{\rho} \pi^+ \pi^-$	$(6.0 \pm 0.5) \times 10^{-3}$	S=1.3	1107
$\rho \bar{\rho} \pi^+ \pi^- \pi^0$	$(2.3 \pm 0.9) \times 10^{-3}$	S=1.9	1033
$\rho \bar{\rho} \eta$	$(2.00 \pm 0.12) \times 10^{-3}$		948
$\rho \bar{\rho} \rho$	$< 3.1 \times 10^{-4}$	CL=90%	774
$\rho \bar{\rho} \omega$	$(9.8 \pm 1.0) \times 10^{-4}$	S=1.3	768
$\rho \bar{\rho} \eta'(958)$	$(1.29 \pm 0.14) \times 10^{-4}$	S=2.0	596
$\rho \bar{\rho} a_0(980) \rightarrow \rho \bar{\rho} \pi^0 \eta$	$(6.8 \pm 1.8) \times 10^{-5}$		-
$\rho \bar{\rho} \phi$	$(5.19 \pm 0.33) \times 10^{-5}$		527

$\rho\bar{n}\pi^-$	$(2.12 \pm 0.09) \times 10^{-3}$		1174
$n\bar{n}$	$(2.09 \pm 0.16) \times 10^{-3}$		1231
$n\bar{n}\pi^+\pi^-$	$(4 \pm 4) \times 10^{-3}$		1106
$\Lambda\bar{\Lambda}$	$(1.88 \pm 0.08) \times 10^{-3}$	S=2.6	1074
$\Lambda\bar{\Lambda}\pi^0$	$(3.8 \pm 0.4) \times 10^{-5}$		998
$\Lambda\bar{\Lambda}\pi^+\pi^-$	$(4.3 \pm 1.0) \times 10^{-3}$		903
$\Lambda\bar{\Lambda}\eta$	$(1.62 \pm 0.17) \times 10^{-4}$		672
$\Lambda\bar{\Sigma}^-\pi^+ + \text{c.c.}$	$(1.26 \pm 0.05) \times 10^{-3}$	S=1.2	950
$\Lambda\bar{\Sigma}^+\pi^- + \text{c.c.}$	$(1.21 \pm 0.07) \times 10^{-3}$	S=1.8	945
$\rho K^-\bar{\Lambda} + \text{c.c.}$	$(8.6 \pm 1.1) \times 10^{-4}$		876
$\rho K^-\bar{\Sigma}^0$	$(2.9 \pm 0.8) \times 10^{-4}$		819
$\bar{\Lambda}nK_S^0 + \text{c.c.}$	$(6.5 \pm 1.1) \times 10^{-4}$		872
$\Lambda\bar{\Sigma}^+ + \text{c.c.}$	$(2.83 \pm 0.23) \times 10^{-5}$		1034
$\Sigma^+\bar{\Sigma}^-$	$(1.07 \pm 0.04) \times 10^{-3}$		992
$\Sigma^0\bar{\Sigma}^0$	$(1.172 \pm 0.032) \times 10^{-3}$	S=1.4	988
$\Sigma^+\bar{\Sigma}^-\eta$	$(6.3 \pm 0.4) \times 10^{-5}$		498
$\Xi^-\bar{\Xi}^+$	$(9.7 \pm 0.8) \times 10^{-4}$	S=1.4	807

**Radiative decays**

$\gamma\eta_c(1S)$	$(1.41 \pm 0.14) \%$	S=1.3	111
$3\gamma$	$(1.16 \pm 0.22) \times 10^{-5}$		1548
$4\gamma$	$< 9 \times 10^{-6}$	CL=90%	1548
$5\gamma$	$< 1.5 \times 10^{-5}$	CL=90%	1548
$\gamma\pi^0$	$(3.39 \pm 0.08) \times 10^{-5}$		1546
$\gamma\pi^0\pi^0$	$(1.15 \pm 0.05) \times 10^{-3}$		1543
$\gamma 2\pi^+ 2\pi^-$	$(2.8 \pm 0.5) \times 10^{-3}$	S=1.9	1517
$\gamma f_2(1270) f_2(1270)$	$(9.5 \pm 1.7) \times 10^{-4}$		878
$\gamma f_2(1270) f_2(1270) (\text{non resonant})$	$(8.2 \pm 1.9) \times 10^{-4}$		-
$\gamma\pi^+\pi^- 2\pi^0$	$(8.3 \pm 3.1) \times 10^{-3}$		1518
$\gamma K_S^0 K_S^0$	$(8.1 \pm 0.4) \times 10^{-4}$		1466
$\gamma(K\bar{K}\pi) [J^{PC} = 0^{-+}]$	$(7 \pm 4) \times 10^{-4}$	S=2.1	1442
$\gamma K^+ K^- \pi^+ \pi^-$	$(2.1 \pm 0.6) \times 10^{-3}$		1407
$\gamma K^*(892) \bar{K}^*(892)$	$(4.0 \pm 1.3) \times 10^{-3}$		1266
$\gamma\eta$	$(1.090 \pm 0.013) \times 10^{-3}$		1500
$\gamma\eta\pi^0$	$(2.14 \pm 0.31) \times 10^{-5}$		1497
$\gamma a_0(980)^0 \rightarrow \gamma\eta\pi^0$	$< 2.5 \times 10^{-6}$	CL=95%	-
$\gamma a_2(1320)^0 \rightarrow \gamma\eta\pi^0$	$< 6.6 \times 10^{-6}$	CL=95%	-
$\gamma\eta\pi\pi$	$(6.1 \pm 1.0) \times 10^{-3}$		1487
$\gamma\eta_2(1870) \rightarrow \gamma\eta\pi^+\pi^-$	$(6.2 \pm 2.4) \times 10^{-4}$		-
$\gamma\eta'(958)$	$(5.28 \pm 0.06) \times 10^{-3}$	S=1.3	1400
$\gamma\rho\rho$	$(4.5 \pm 0.8) \times 10^{-3}$		1340
$\gamma\rho\omega$	$< 5.4 \times 10^{-4}$	CL=90%	1338
$\gamma\rho\phi$	$< 8.8 \times 10^{-5}$	CL=90%	1258
$\gamma\omega\omega$	$(1.61 \pm 0.33) \times 10^{-3}$		1336
$\gamma\phi\phi$	$(4.0 \pm 1.2) \times 10^{-4}$	S=2.1	1166
$\gamma\eta(1405/1475) \rightarrow \gamma K\bar{K}\pi$	$(2.8 \pm 0.6) \times 10^{-3}$	S=1.6	1223
$\gamma\eta(1405/1475) \rightarrow \gamma\gamma\rho^0$	$(7.8 \pm 2.0) \times 10^{-5}$	S=1.8	1223
$\gamma\eta(1405/1475) \rightarrow \gamma\eta\pi^+\pi^-$	$(3.0 \pm 0.5) \times 10^{-4}$		-
$\gamma\eta(1405/1475) \rightarrow \gamma\rho^0\rho^0$	$(1.7 \pm 0.4) \times 10^{-3}$	S=1.3	1223
$\gamma\eta(1405/1475) \rightarrow \gamma\gamma\phi$	$< 8.2 \times 10^{-5}$	CL=95%	-
$\gamma\eta(1405) \rightarrow \gamma\gamma\gamma$	$< 2.63 \times 10^{-6}$	CL=90%	-
$\gamma\eta(1475) \rightarrow \gamma\gamma\gamma$	$< 1.86 \times 10^{-6}$	CL=90%	-
$\gamma\eta(1760) \rightarrow \gamma\rho^0\rho^0$	$(1.3 \pm 0.9) \times 10^{-4}$		1048
$\gamma\eta(1760) \rightarrow \gamma\omega\omega$	$(1.98 \pm 0.33) \times 10^{-3}$		-



$\gamma\eta(1760) \rightarrow \gamma\gamma\gamma$	$< 4.80$	$\times 10^{-6}$	CL=90%	-
$\gamma\eta(2225)$	$(3.14 \pm 0.50)$	$\times 10^{-4}$		752
$\gamma f_2(1270)$	$(1.63 \pm 0.12)$	$\times 10^{-3}$	S=1.3	1286
$\gamma f_2(1270) \rightarrow \gamma K_S^0 K_S^0$	$(2.58 \pm 0.60)$	$\times 10^{-5}$		-
$\gamma f_1(1285)$	$(6.1 \pm 0.8)$	$\times 10^{-4}$		1283
$\gamma f_0(1370) \rightarrow \gamma K \bar{K}$	$(4.2 \pm 1.5)$	$\times 10^{-4}$		-
$\gamma f_0(1370) \rightarrow \gamma K_S^0 K_S^0$	$(1.1 \pm 0.4)$	$\times 10^{-5}$		-
$\gamma f_1(1420) \rightarrow \gamma K \bar{K} \pi$	$(7.9 \pm 1.3)$	$\times 10^{-4}$		1220
$\gamma f_0(1500) \rightarrow \gamma \pi \pi$	$(1.09 \pm 0.24)$	$\times 10^{-4}$		1183
$\gamma f_0(1500) \rightarrow \gamma \eta \eta$	$(1.7 \pm 0.6)$	$\times 10^{-5}$		-
$\gamma f_0(1500) \rightarrow \gamma K_S^0 K_S^0$	$(1.59 \pm 0.24)$	$\times 10^{-5}$		-
$\gamma f_1(1510) \rightarrow \gamma \eta \pi^+ \pi^-$	$(4.5 \pm 1.2)$	$\times 10^{-4}$		-
$\gamma f'_2(1525)$	$(5.7 \pm 0.8)$	$\times 10^{-4}$	S=1.5	1177
$\gamma f'_2(1525) \rightarrow \gamma K_S^0 K_S^0$	$(8.0 \pm 0.7)$	$\times 10^{-5}$		-
$\gamma f'_2(1525) \rightarrow \gamma \eta \eta$	$(3.4 \pm 1.4)$	$\times 10^{-5}$		-
$\gamma f_2(1640) \rightarrow \gamma \omega \omega$	$(2.8 \pm 1.8)$	$\times 10^{-4}$		-
$\gamma f_0(1710) \rightarrow \gamma \pi \pi$	$(3.8 \pm 0.5)$	$\times 10^{-4}$		-
$\gamma f_0(1710) \rightarrow \gamma K \bar{K}$	$(9.5 \pm 1.0)$	$\times 10^{-4}$	S=1.5	1075
$\gamma f_0(1710) \rightarrow \gamma \omega \omega$	$(3.1 \pm 1.0)$	$\times 10^{-4}$		-
$\gamma f_0(1710) \rightarrow \gamma \eta \eta$	$(2.4 \pm 1.2)$	$\times 10^{-4}$		-
$\gamma f_0(1710) \rightarrow \gamma \omega \phi$	$(2.5 \pm 0.6)$	$\times 10^{-4}$		-
$\gamma f_0(1770) \rightarrow \gamma K_S^0 K_S^0$	$(1.11 \pm 0.20)$	$\times 10^{-5}$		-
$\gamma f_2(1810) \rightarrow \gamma \eta \eta$	$(5.4 \pm 3.5)$	$\times 10^{-5}$		-
$\gamma \eta_1(1855) \rightarrow \gamma \eta \eta'$	$(2.7 \pm 0.4)$	$\times 10^{-6}$		-
$\gamma f_2(1910) \rightarrow \gamma \omega \omega$	$(2.0 \pm 1.4)$	$\times 10^{-4}$		-
$\gamma f_2(1950) \rightarrow$ $\gamma K^*(892) \bar{K}^*(892)$	$(7.0 \pm 2.2)$	$\times 10^{-4}$		-
$\gamma f_0(2020) \rightarrow \gamma \eta' \eta'$	$(2.63 \pm 0.32)$	$\times 10^{-4}$		-
$\gamma f_4(2050)$	$(2.7 \pm 0.7)$	$\times 10^{-3}$		891
$\gamma f_0(2100) \rightarrow \gamma \eta \eta$	$(1.13 \pm 0.60)$	$\times 10^{-4}$		-
$\gamma f_0(2100) \rightarrow \gamma \pi \pi$	$(6.2 \pm 1.0)$	$\times 10^{-4}$		-
$\gamma f_0(2200) \rightarrow \gamma K \bar{K}$	$(5.9 \pm 1.3)$	$\times 10^{-4}$		-
$\gamma f_0(2200) \rightarrow \gamma K_S^0 K_S^0$	$(2.72 \pm 0.19)$	$\times 10^{-4}$		-
$\gamma f_J(2220) \rightarrow \gamma \pi \pi$	$< 3.9$	$\times 10^{-5}$	CL=90%	-
$\gamma f_J(2220) \rightarrow \gamma K \bar{K}$	$< 4.1$	$\times 10^{-5}$	CL=90%	-
$\gamma f_J(2220) \rightarrow \gamma p \bar{p}$	$(1.5 \pm 0.8)$	$\times 10^{-5}$		-
$\gamma f_0(2330) \rightarrow \gamma K_S^0 K_S^0$	$(4.9 \pm 0.7)$	$\times 10^{-5}$		-
$\gamma f_0(2330) \rightarrow \gamma \eta' \eta'$	$(6.1 \pm 4.0)$	$\times 10^{-6}$		-
$\gamma f_2(2340) \rightarrow \gamma \eta \eta$	$(5.6 \pm 2.4)$	$\times 10^{-5}$		-
$\gamma f_2(2340) \rightarrow \gamma K_S^0 K_S^0$	$(5.5 \pm 4.0)$	$\times 10^{-5}$		-
$\gamma f_2(2340) \rightarrow \gamma \eta' \eta'$	$(8.7 \pm 0.9)$	$\times 10^{-6}$		-
$\gamma f_0(2470) \rightarrow \gamma \eta' \eta'$	$(8.2 \pm 4.0)$	$\times 10^{-7}$		-
$\gamma X(1835) \rightarrow \gamma \pi^+ \pi^- \eta'$	$(2.7 \pm 0.6)$	$\times 10^{-4}$	S=1.6	1006

$\gamma X(1835) \rightarrow \gamma p \bar{p}$	$(7.7 \pm_{-0.9}^{+1.5}) \times 10^{-5}$		—
$\gamma X(1835) \rightarrow \gamma K_S^0 K_S^0 \eta$	$(3.3 \pm_{-1.3}^{+2.0}) \times 10^{-5}$		—
$\gamma X(1835) \rightarrow \gamma \gamma \gamma$	$< 3.56$	$\times 10^{-6}$	CL=90% —
$\gamma X(1835) \rightarrow \gamma 3(\pi^+ \pi^-)$	$(2.4 \pm_{-0.8}^{+0.7}) \times 10^{-5}$		—
$\gamma X(2370) \rightarrow \gamma K^+ K^- \eta'$	$(1.8 \pm 0.7) \times 10^{-5}$		—
$\gamma X(2370) \rightarrow \gamma K_S^0 K_S^0 \eta'$	$(1.2 \pm 0.5) \times 10^{-5}$		—
$\gamma X(2370) \rightarrow \gamma \eta \eta \eta'$	$< 9.2$	$\times 10^{-6}$	CL=90% —
$\gamma p \bar{p}$	$(3.8 \pm 1.0) \times 10^{-4}$		1232
$\gamma p \bar{p} \pi^+ \pi^-$	$< 7.9$	$\times 10^{-4}$	CL=90% 1107
$\gamma \Lambda \bar{\Lambda}$	$< 1.3$	$\times 10^{-4}$	CL=90% 1074
$\gamma A^0 \rightarrow \gamma$ invisible	$[kka\bar{a}] < 1.7$	$\times 10^{-6}$	CL=90% —
$\gamma A^0 \rightarrow \gamma \mu^+ \mu^-$	$[l\bar{l}a\bar{a}] < 7.8$	$\times 10^{-7}$	CL=90% —

**Dalitz decays**

$\pi^0 e^+ e^-$	$(7.6 \pm 1.4) \times 10^{-7}$		1546
$\eta e^+ e^-$	$(1.42 \pm 0.08) \times 10^{-5}$		1500
$\eta'(958) e^+ e^-$	$(6.59 \pm 0.18) \times 10^{-5}$		1400
$X(1835) e^+ e^-, X \rightarrow \pi^+ \pi^- \eta'$	$(3.58 \pm 0.25) \times 10^{-6}$		—
$X(2120) e^+ e^-, X \rightarrow \pi^+ \pi^- \eta'$	$(8.2 \pm 1.3) \times 10^{-7}$		—
$X(2370) e^+ e^-, X \rightarrow \pi^+ \pi^- \eta'$	$(1.08 \pm 0.17) \times 10^{-6}$		—
$\eta U \rightarrow \eta e^+ e^-$	$[nna\bar{a}] < 9.11$	$\times 10^{-7}$	CL=90% —
$\eta'(958) U \rightarrow \eta'(958) e^+ e^-$	$[nna\bar{a}] < 2.0$	$\times 10^{-7}$	CL=90% —
$\phi e^+ e^-$	$< 1.2$	$\times 10^{-7}$	CL=90% 1381

**Weak decays**

$D^- e^+ \nu_e + c.c.$	$< 7.1$	$\times 10^{-8}$	CL=90% 984
$\bar{D}^0 e^+ e^- + c.c.$	$< 8.5$	$\times 10^{-8}$	CL=90% 987
$D_s^- e^+ \nu_e + c.c.$	$< 1.3$	$\times 10^{-6}$	CL=90% 923
$D_s^{*-} e^+ \nu_e + c.c.$	$< 1.8$	$\times 10^{-6}$	CL=90% 828
$D^- \pi^+ + c.c.$	$< 7.5$	$\times 10^{-5}$	CL=90% 977
$\bar{D}^0 \bar{K}^0 + c.c.$	$< 1.7$	$\times 10^{-4}$	CL=90% 898
$\bar{D}^0 \bar{K}^{*0} + c.c.$	$< 2.5$	$\times 10^{-6}$	CL=90% 670
$D_s^- \pi^+ + c.c.$	$< 1.3$	$\times 10^{-4}$	CL=90% 915
$D_s^- \rho^+ + c.c.$	$< 1.3$	$\times 10^{-5}$	CL=90% 663

**Charge conjugation (C), Parity (P),  
Lepton Family number (LF) violating modes**

$\gamma \gamma$	C	$< 2.7$	$\times 10^{-7}$	CL=90% 1548
$\gamma \phi$	C	$< 1.4$	$\times 10^{-6}$	CL=90% 1381
$e^\pm \mu^\mp$	LF	$< 1.6$	$\times 10^{-7}$	CL=90% 1547
$e^\pm \tau^\mp$	LF	$< 7.5$	$\times 10^{-8}$	CL=90% 1039
$\mu^\pm \tau^\mp$	LF	$< 2.0$	$\times 10^{-6}$	CL=90% 1035
$\Lambda_c^+ e^- + c.c.$		$< 6.9$	$\times 10^{-8}$	CL=90% 704

**Other decays**

invisible	$< 7$	$\times 10^{-4}$	CL=90% —
-----------	-------	------------------	----------

See Particle Listings for 13 decay modes that have been seen / not seen.

**$\chi_{c0}(1P)$**

$$J^G(J^{PC}) = 0^+(0^{++})$$

Mass  $m = 3414.71 \pm 0.30$  MeV

Full width  $\Gamma = 10.7 \pm 0.6$  MeV (S = 1.1)

$\chi_{c0}(1P)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
<b>Hadronic decays</b>			
$2(\pi^+\pi^-)$	$(2.3 \pm 0.4) \%$	S=2.0	1679
$\rho^0\pi^+\pi^-$	$(9.1 \pm 3.1) \times 10^{-3}$	S=1.1	1607
$f_0(980)f_0(980)$	$(6.7 \pm 2.1) \times 10^{-4}$		1391
$\pi^+\pi^-\pi^0\pi^0$	$(3.3 \pm 0.4) \%$		1680
$\rho^+\pi^-\pi^0 + c.c.$	$(2.9 \pm 0.4) \%$		1607
$4\pi^0$	$(3.3 \pm 0.4) \times 10^{-3}$		1681
$\pi^+\pi^-K^+K^-$	$(1.82 \pm 0.16) \%$	S=1.2	1580
$K_0^*(1430)^0\bar{K}_0^*(1430)^0 \rightarrow$ $\pi^+\pi^-K^+K^-$	$(9.9 \begin{smallmatrix} +4.0 \\ -2.8 \end{smallmatrix}) \times 10^{-4}$		—
$K_0^*(1430)^0\bar{K}_2^*(1430)^0 + c.c. \rightarrow$ $\pi^+\pi^-K^+K^-$	$(8.0 \begin{smallmatrix} +2.0 \\ -2.4 \end{smallmatrix}) \times 10^{-4}$		—
$K_1(1270)^+K^- + c.c. \rightarrow$ $\pi^+\pi^-K^+K^-$	$(6.3 \pm 1.9) \times 10^{-3}$		—
$K_1(1400)^+K^- + c.c. \rightarrow$ $\pi^+\pi^-K^+K^-$	$< 2.7 \times 10^{-3}$	CL=90%	—
$f_0(980)f_0(980)$	$(1.6 \begin{smallmatrix} +1.0 \\ -0.9 \end{smallmatrix}) \times 10^{-4}$		1391
$f_0(980)f_0(2200)$	$(7.9 \begin{smallmatrix} +2.0 \\ -2.5 \end{smallmatrix}) \times 10^{-4}$		586
$f_0(1370)f_0(1370)$	$< 2.7 \times 10^{-4}$	CL=90%	1019
$f_0(1370)f_0(1500)$	$< 1.7 \times 10^{-4}$	CL=90%	907
$f_0(1370)f_0(1710)$	$(6.7 \begin{smallmatrix} +3.5 \\ -2.3 \end{smallmatrix}) \times 10^{-4}$		709
$f_0(1500)f_0(1370)$	$< 1.3 \times 10^{-4}$	CL=90%	907
$f_0(1500)f_0(1500)$	$< 5 \times 10^{-5}$	CL=90%	774
$f_0(1500)f_0(1710)$	$< 7 \times 10^{-5}$	CL=90%	515
$K^+K^-\pi^+\pi^-\pi^0$	$(8.6 \pm 0.9) \times 10^{-3}$		1545
$K_S^0K^\pm\pi^\mp\pi^+\pi^-$	$(4.2 \pm 0.4) \times 10^{-3}$		1543
$K^+K^-\pi^0\pi^0$	$(5.6 \pm 0.9) \times 10^{-3}$		1582
$K^+\pi^-\bar{K}^0\pi^0 + c.c.$	$(2.49 \pm 0.33) \%$		1581
$\rho^+K^-K^0 + c.c.$	$(1.21 \pm 0.21) \%$		1458
$K^*(892)^-K^+\pi^0 \rightarrow$ $K^+\pi^-\bar{K}^0\pi^0 + c.c.$	$(4.6 \pm 1.2) \times 10^{-3}$		—
$K_S^0K_S^0\pi^+\pi^-$	$(5.7 \pm 1.1) \times 10^{-3}$		1579
$K^+K^-\eta\pi^0$	$(3.0 \pm 0.7) \times 10^{-3}$		1468
$3(\pi^+\pi^-)$	$(1.95 \pm 0.22) \%$	S=3.3	1633
$K^+\bar{K}^*(892)^0\pi^- + c.c.$	$(7.5 \pm 1.6) \times 10^{-3}$		1523
$K^*(892)^0\bar{K}^*(892)^0$	$(1.7 \pm 0.6) \times 10^{-3}$		1456
$\pi\pi$	$(8.5 \pm 0.4) \times 10^{-3}$	S=1.2	1702
$\pi^0\eta$	$< 1.8 \times 10^{-4}$		1661
$\pi^0\eta'$	$< 1.1 \times 10^{-3}$		1570
$\pi^0\eta_c$	$< 1.6 \times 10^{-3}$	CL=90%	383
$\eta\eta$	$(3.01 \pm 0.25) \times 10^{-3}$	S=1.3	1617
$\eta\eta'$	$(9.1 \pm 1.1) \times 10^{-5}$		1521
$\eta'\eta'$	$(2.17 \pm 0.12) \times 10^{-3}$		1413
$\omega\omega$	$(9.7 \pm 1.1) \times 10^{-4}$		1517
$\omega\phi$	$(1.42 \pm 0.13) \times 10^{-4}$		1447
$\omega K^+K^-$	$(1.94 \pm 0.21) \times 10^{-3}$		1457
$K^+K^-$	$(6.07 \pm 0.33) \times 10^{-3}$	S=1.1	1634
$K_S^0K_S^0$	$(3.17 \pm 0.19) \times 10^{-3}$	S=1.1	1633
$\pi^+\pi^-\eta$	$< 2.0 \times 10^{-4}$	CL=90%	1651
$\pi^+\pi^-\eta'$	$< 4 \times 10^{-4}$	CL=90%	1560

$\bar{K}^0 K^+ \pi^- + \text{c.c.}$	$< 9$	$\times 10^{-5}$	CL=90%	1610
$K^+ K^- \pi^0$	$< 6$	$\times 10^{-5}$	CL=90%	1611
$K^+ K^- \eta$	$< 2.3$	$\times 10^{-4}$	CL=90%	1512
$K^+ K^- K_S^0 K_S^0$	$(1.4 \pm 0.5)$	$\times 10^{-3}$		1331
$K_S^0 K_S^0 K_S^0 K_S^0$	$(5.8 \pm 0.5)$	$\times 10^{-4}$		1327
$K^+ K^- K^+ K^-$	$(2.8 \pm 0.4)$	$\times 10^{-3}$	S=1.5	1333
$K^+ K^- \phi$	$(9.7 \pm 2.5)$	$\times 10^{-4}$		1381
$\bar{K}^0 K^+ \pi^- \phi + \text{c.c.}$	$(3.7 \pm 0.6)$	$\times 10^{-3}$		1326
$K^+ K^- \pi^0 \phi$	$(1.90 \pm 0.35)$	$\times 10^{-3}$		1329
$\phi \pi^+ \pi^- \pi^0$	$(1.18 \pm 0.15)$	$\times 10^{-3}$		1525
$\phi \phi$	$(8.48 \pm 0.31)$	$\times 10^{-4}$		1370
$\phi \phi \eta$	$(8.4 \pm 1.0)$	$\times 10^{-4}$		1100
$\rho \bar{\rho}$	$(2.21 \pm 0.14)$	$\times 10^{-4}$	S=1.6	1426
$\rho \bar{\rho} \pi^0$	$(7.0 \pm 0.7)$	$\times 10^{-4}$	S=1.3	1379
$\rho \bar{\rho} \eta$	$(3.5 \pm 0.4)$	$\times 10^{-4}$		1187
$\rho \bar{\rho} \omega$	$(5.3 \pm 0.6)$	$\times 10^{-4}$		1043
$\rho \bar{\rho} \phi$	$(6.0 \pm 1.4)$	$\times 10^{-5}$		876
$\rho \bar{\rho} \pi^+ \pi^-$	$(2.1 \pm 0.7)$	$\times 10^{-3}$	S=1.4	1320
$\rho \bar{\rho} \pi^0 \pi^0$	$(1.04 \pm 0.28)$	$\times 10^{-3}$		1324
$\rho \bar{\rho} K^+ K^- (\text{non-resonant})$	$(1.22 \pm 0.26)$	$\times 10^{-4}$		890
$\rho \bar{\rho} K_S^0 K_S^0$	$< 8.8$	$\times 10^{-4}$	CL=90%	884
$\rho \bar{\eta} \pi^-$	$(1.27 \pm 0.11)$	$\times 10^{-3}$		1376
$\bar{\rho} \eta \pi^+$	$(1.37 \pm 0.12)$	$\times 10^{-3}$		1376
$\rho \bar{\eta} \pi^- \pi^0$	$(2.34 \pm 0.21)$	$\times 10^{-3}$		1321
$\bar{\rho} \eta \pi^+ \pi^0$	$(2.21 \pm 0.19)$	$\times 10^{-3}$		1321
$\Lambda \bar{\Lambda}$	$(3.60 \pm 0.17)$	$\times 10^{-4}$	S=1.1	1292
$\Lambda \bar{\Lambda} \pi^+ \pi^-$	$(1.18 \pm 0.13)$	$\times 10^{-3}$		1153
$\Lambda \bar{\Lambda} \pi^+ \pi^- (\text{non-resonant})$	$< 5$	$\times 10^{-4}$	CL=90%	1153
$\Sigma(1385)^+ \bar{\Lambda} \pi^- + \text{c.c.}$	$< 5$	$\times 10^{-4}$	CL=90%	1083
$\Sigma(1385)^- \bar{\Lambda} \pi^+ + \text{c.c.}$	$< 5$	$\times 10^{-4}$	CL=90%	1083
$\Lambda \bar{\Lambda} \eta$	$(2.3 \pm 0.4)$	$\times 10^{-4}$		979
$K^+ \bar{\rho} \Lambda + \text{c.c.}$	$(1.25 \pm 0.12)$	$\times 10^{-3}$	S=1.3	1132
$n K_S^0 \bar{\Lambda} + \text{c.c.}$	$(6.7 \pm 0.5)$	$\times 10^{-4}$		1129
$K^*(892)^+ \bar{\rho} \Lambda + \text{c.c.}$	$(4.8 \pm 0.9)$	$\times 10^{-4}$		845
$K^+ \bar{\rho} \Lambda(1520) + \text{c.c.}$	$(3.0 \pm 0.8)$	$\times 10^{-4}$		859
$\Lambda(1520) \bar{\Lambda}(1520)$	$(3.1 \pm 1.2)$	$\times 10^{-4}$		780
$\Sigma^0 \bar{\Sigma}^0$	$(4.69 \pm 0.32)$	$\times 10^{-4}$		1222
$\Sigma^+ \bar{\rho} K_S^0 + \text{c.c.}$	$(3.53 \pm 0.27)$	$\times 10^{-4}$		1089
$\Sigma^0 \bar{\rho} K^+ + \text{c.c.}$	$(3.04 \pm 0.20)$	$\times 10^{-4}$		1090
$\Sigma^+ \bar{\Sigma}^-$	$(4.7 \pm 0.8)$	$\times 10^{-4}$	S=2.6	1225
$\Sigma^- \bar{\Sigma}^+$	$(5.1 \pm 0.5)$	$\times 10^{-4}$		1217
$\Sigma(1385)^+ \bar{\Sigma}(1385)^-$	$(1.6 \pm 0.6)$	$\times 10^{-4}$		1001
$\Sigma(1385)^- \bar{\Sigma}(1385)^+$	$(2.3 \pm 0.7)$	$\times 10^{-4}$		1001
$K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$	$(1.95 \pm 0.35)$	$\times 10^{-4}$		873
$\Xi^0 \bar{\Xi}^0$	$(4.5 \pm 0.5)$	$\times 10^{-4}$	S=1.7	1089
$\Xi^- \bar{\Xi}^+$	$(4.47 \pm 0.20)$	$\times 10^{-4}$		1081
$\Omega^- \bar{\Omega}^+$	$(3.5 \pm 0.6)$	$\times 10^{-5}$		343
$\eta_c \pi^+ \pi^-$	$< 7$	$\times 10^{-4}$	CL=90%	307

## Radiative decays

$\gamma J/\psi(1S)$	$(1.41 \pm 0.09)$	%	S=1.7	303
$\gamma \rho^0$	$< 9$	$\times 10^{-6}$	CL=90%	1619
$\gamma \omega$	$< 8$	$\times 10^{-6}$	CL=90%	1618
$\gamma \phi$	$< 6$	$\times 10^{-6}$	CL=90%	1555
$\gamma \gamma$	$(2.04 \pm 0.10)$	$\times 10^{-4}$	S=1.1	1707

$e^+ e^- J/\psi(1S)$	$(1.34 \pm 0.30) \times 10^{-4}$	303
$\mu^+ \mu^- J/\psi(1S)$	$< 1.9 \times 10^{-5}$	CL=90% 226

 **$\chi_{c1}(1P)$** 

$$J^G(J^{PC}) = 0^+(1^{++})$$

Mass  $m = 3510.67 \pm 0.05$  MeV ( $S = 1.2$ )

Full width  $\Gamma = 0.84 \pm 0.04$  MeV ( $S = 1.1$ )

$\chi_{c1}(1P)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$e^+ e^-$	$(1.4 \pm_{-1.0}^{+1.5}) \times 10^{-7}$		1755
<b>Hadronic decays</b>			
$3(\pi^+ \pi^-)$	$(1.04 \pm 0.16) \%$	$S=4.6$	1683
$2(\pi^+ \pi^-)$	$(7.6 \pm 2.6) \times 10^{-3}$		1728
$\pi^+ \pi^- \pi^0 \pi^0$	$(1.19 \pm 0.15) \%$		1729
$\rho^+ \pi^- \pi^0 + c.c.$	$(1.45 \pm 0.24) \%$		1658
$\rho^0 \pi^+ \pi^-$	$(3.9 \pm 3.5) \times 10^{-3}$		1657
$4\pi^0$	$(5.4 \pm 0.8) \times 10^{-4}$		1729
$\pi^+ \pi^- K^+ K^-$	$(4.5 \pm 1.0) \times 10^{-3}$		1632
$K^+ K^- \pi^0 \pi^0$	$(1.12 \pm 0.27) \times 10^{-3}$		1634
$K^+ K^- \pi^+ \pi^- \pi^0$	$(1.15 \pm 0.13) \%$		1598
$K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$	$(7.5 \pm 0.8) \times 10^{-3}$		1596
$K^+ \pi^- \bar{K}^0 \pi^0 + c.c.$	$(8.6 \pm 1.4) \times 10^{-3}$		1632
$\rho^- K^+ \bar{K}^0 + c.c.$	$(5.0 \pm 1.2) \times 10^{-3}$		1514
$K^*(892)^0 \bar{K}^0 \pi^0 \rightarrow$ $K^+ \pi^- \bar{K}^0 \pi^0 + c.c.$	$(2.3 \pm 0.6) \times 10^{-3}$		-
$K^+ K^- \eta \pi^0$	$(1.12 \pm 0.34) \times 10^{-3}$		1523
$\pi^+ \pi^- K_S^0 K_S^0$	$(6.9 \pm 2.9) \times 10^{-4}$		1630
$K^+ K^- \eta$	$(3.2 \pm 1.0) \times 10^{-4}$		1566
$\bar{K}^0 K^+ \pi^- + c.c.$	$(7.0 \pm 0.6) \times 10^{-3}$	$S=1.1$	1661
$K^*(892)^0 \bar{K}^0 + c.c.$	$(1.03 \pm 0.15) \times 10^{-3}$		1602
$K^*(892)^+ K^- + c.c.$	$(1.21 \pm 0.23) \times 10^{-3}$		1602
$K_J^*(1430)^0 \bar{K}^0 + c.c. \rightarrow$ $K_S^0 K^+ \pi^- + c.c.$	$< 8 \times 10^{-4}$	CL=90%	-
$K_J^*(1430)^+ K^- + c.c. \rightarrow$ $K_S^0 K^+ \pi^- + c.c.$	$< 2.1 \times 10^{-3}$	CL=90%	-
$K^+ K^- \pi^0$	$(1.81 \pm 0.24) \times 10^{-3}$		1662
$\eta \pi^+ \pi^-$	$(4.62 \pm 0.24) \times 10^{-3}$		1701
$a_0(980)^+ \pi^- + c.c. \rightarrow \eta \pi^+ \pi^-$	$(3.2 \pm 0.4) \times 10^{-3}$	$S=2.1$	-
$a_2(1320)^+ \pi^- + c.c. \rightarrow \eta \pi^+ \pi^-$	$(1.76 \pm 0.24) \times 10^{-4}$		-
$a_2(1700)^+ \pi^- + c.c. \rightarrow \eta \pi^+ \pi^-$	$(4.6 \pm 0.7) \times 10^{-5}$		-
$f_2(1270) \eta \rightarrow \eta \pi^+ \pi^-$	$(3.5 \pm 0.6) \times 10^{-4}$		-
$f_4(2050) \eta \rightarrow \eta \pi^+ \pi^-$	$(2.5 \pm 0.9) \times 10^{-5}$		-
$\pi_1(1400)^+ \pi^- + c.c. \rightarrow \eta \pi^+ \pi^-$	$< 5 \times 10^{-5}$	CL=90%	-
$\pi_1(1600)^+ \pi^- + c.c. \rightarrow \eta \pi^+ \pi^-$	$< 1.5 \times 10^{-5}$	CL=90%	-
$\pi_1(2015)^+ \pi^- + c.c. \rightarrow \eta \pi^+ \pi^-$	$< 8 \times 10^{-6}$	CL=90%	-
$f_2(1270) \eta$	$(6.7 \pm 1.1) \times 10^{-4}$		1467
$\pi^+ \pi^- \eta'$	$(2.2 \pm 0.4) \times 10^{-3}$		1612
$K^+ K^- \eta'(958)$	$(8.8 \pm 0.9) \times 10^{-4}$		1461
$K_0^*(1430)^+ K^- + c.c.$	$(6.4 \pm_{-2.8}^{+2.2}) \times 10^{-4}$		-
$f_0(980) \eta'(958)$	$(1.6 \pm_{-0.7}^{+1.4}) \times 10^{-4}$		1460
$f_0(1710) \eta'(958)$	$(7 \pm_{-5}^{+7}) \times 10^{-5}$		1100

$f'_2(1525)\eta'(958)$	$(9 \pm 6) \times 10^{-5}$		1229
$K_2^*(1430)^+K^- + c.c.$	$(1.61 \pm 0.31) \times 10^{-3}$		1416
$K_2^*(1430)\bar{K}^0 + c.c.$	$(1.17 \pm 0.20) \times 10^{-3}$		1416
$\pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-$	$(3.5 \pm 0.9) \times 10^{-7}$		-
$K^+ \bar{K}^*(892)^0 \pi^- + c.c.$	$(3.2 \pm 2.1) \times 10^{-3}$		1577
$K^*(892)^0 \bar{K}^*(892)^0$	$(1.4 \pm 0.4) \times 10^{-3}$		1512
$K^+ K^- K_S^0 K_S^0$	$< 4 \times 10^{-4}$	CL=90%	1390
$K_S^0 K_S^0 K_S^0 K_S^0$	$(3.5 \pm 1.0) \times 10^{-5}$		1387
$K^+ K^- K^+ K^-$	$(5.4 \pm 1.1) \times 10^{-4}$		1393
$K^+ K^- \phi$	$(4.1 \pm 1.5) \times 10^{-4}$		1440
$\bar{K}^0 K^+ \pi^- \phi + c.c.$	$(3.3 \pm 0.5) \times 10^{-3}$		1387
$K^+ K^- \pi^0 \phi$	$(1.62 \pm 0.30) \times 10^{-3}$		1390
$\phi \pi^+ \pi^- \pi^0$	$(7.5 \pm 1.0) \times 10^{-4}$		1578
$\omega \omega$	$(5.7 \pm 0.7) \times 10^{-4}$		1571
$\omega K^+ K^-$	$(7.8 \pm 0.9) \times 10^{-4}$		1513
$\omega \phi$	$(2.7 \pm 0.4) \times 10^{-5}$		1503
$\phi \phi$	$(4.26 \pm 0.21) \times 10^{-4}$		1429
$\phi \phi \eta$	$(3.0 \pm 0.5) \times 10^{-4}$		1172
$\rho \bar{\rho}$	$(7.6 \pm 0.4) \times 10^{-5}$	S=1.2	1484
$\rho \bar{\rho} \pi^0$	$(1.55 \pm 0.18) \times 10^{-4}$		1438
$\rho \bar{\rho} \eta$	$(1.45 \pm 0.25) \times 10^{-4}$		1254
$\rho \bar{\rho} \omega$	$(2.12 \pm 0.31) \times 10^{-4}$		1117
$\rho \bar{\rho} \phi$	$< 1.7 \times 10^{-5}$	CL=90%	962
$\rho \bar{\rho} \pi^+ \pi^-$	$(5.0 \pm 1.9) \times 10^{-4}$		1381
$\rho \bar{\rho} \pi^0 \pi^0$	$< 5 \times 10^{-4}$	CL=90%	1385
$\rho \bar{\rho} K^+ K^-$ (non-resonant)	$(1.27 \pm 0.22) \times 10^{-4}$		974
$\rho \bar{\rho} K_S^0 K_S^0$	$< 4.5 \times 10^{-4}$	CL=90%	968
$\rho \bar{\rho} \pi^-$	$(3.8 \pm 0.5) \times 10^{-4}$		1435
$\bar{\rho} \eta \pi^+$	$(3.9 \pm 0.5) \times 10^{-4}$		1435
$\rho \bar{\rho} \pi^- \pi^0$	$(1.03 \pm 0.12) \times 10^{-3}$		1383
$\bar{\rho} \eta \pi^+ \pi^0$	$(1.01 \pm 0.12) \times 10^{-3}$		1383
$\Lambda \bar{\Lambda}$	$(1.27 \pm 0.09) \times 10^{-4}$	S=1.1	1355
$\Lambda \bar{\Lambda} \pi^+ \pi^-$	$(2.9 \pm 0.5) \times 10^{-4}$		1223
$\Lambda \bar{\Lambda} \pi^+ \pi^-$ (non-resonant)	$(2.5 \pm 0.6) \times 10^{-4}$		1223
$\Sigma(1385)^+ \bar{\Lambda} \pi^- + c.c.$	$< 1.3 \times 10^{-4}$	CL=90%	1157
$\Sigma(1385)^- \bar{\Lambda} \pi^+ + c.c.$	$< 1.3 \times 10^{-4}$	CL=90%	1157
$\Lambda \bar{\Lambda} \eta$	$(5.9 \pm 1.5) \times 10^{-5}$		1059
$K^+ \bar{\rho} \Lambda + c.c.$	$(4.2 \pm 0.4) \times 10^{-4}$	S=1.2	1203
$n K_S^0 \bar{\Lambda} + c.c.$	$(1.66 \pm 0.17) \times 10^{-4}$		1200
$K^*(892)^+ \bar{\rho} \Lambda + c.c.$	$(4.9 \pm 0.7) \times 10^{-4}$		935
$K^+ \bar{\rho} \Lambda(1520) + c.c.$	$(1.7 \pm 0.4) \times 10^{-4}$		951
$\Lambda(1520) \bar{\Lambda}(1520)$	$< 9 \times 10^{-5}$	CL=90%	880
$\Sigma^0 \bar{\Sigma}^0$	$(4.2 \pm 0.6) \times 10^{-5}$		1288
$\Sigma^+ \bar{\rho} K_S^0 + c.c.$	$(1.53 \pm 0.12) \times 10^{-4}$		1163
$\Sigma^0 \bar{\rho} K^+ + c.c.$	$(1.46 \pm 0.10) \times 10^{-4}$		1163
$\Sigma^+ \bar{\Sigma}^-$	$(3.6 \pm 0.7) \times 10^{-5}$		1291
$\Sigma^- \bar{\Sigma}^+$	$(5.7 \pm 1.5) \times 10^{-5}$		1283
$\Sigma(1385)^+ \bar{\Sigma}(1385)^-$	$< 9 \times 10^{-5}$	CL=90%	1081
$\Sigma(1385)^- \bar{\Sigma}(1385)^+$	$< 5 \times 10^{-5}$	CL=90%	1081
$K^- \Lambda \bar{\Xi}^+ + c.c.$	$(1.35 \pm 0.24) \times 10^{-4}$		963
$\Xi^0 \bar{\Xi}^0$	$(7.5 \pm 1.3) \times 10^{-5}$		1163
$\Xi^- \bar{\Xi}^+$	$(6.0 \pm 0.6) \times 10^{-5}$		1155
$\Omega^- \bar{\Omega}^+$	$(1.49 \pm 0.25) \times 10^{-5}$		533
$\pi^+ \pi^- + K^+ K^-$	$< 2.1 \times 10^{-3}$		-

$K_S^0 K_S^0$	< 6	$\times 10^{-5}$	CL=90%	1683
$\eta_c \pi^+ \pi^-$	< 3.2	$\times 10^{-3}$	CL=90%	413

**Radiative decays**

$\gamma J/\psi(1S)$	(34.3 $\pm$ 1.3 ) %	S=1.3	389
$\gamma \rho^0$	( 2.16 $\pm$ 0.17 ) $\times 10^{-4}$		1670
$\gamma \omega$	( 6.8 $\pm$ 0.8 ) $\times 10^{-5}$		1668
$\gamma \phi$	( 2.4 $\pm$ 0.5 ) $\times 10^{-5}$		1607
$\gamma \gamma$	< 6.3 $\times 10^{-6}$	CL=90%	1755
$e^+ e^- J/\psi(1S)$	( 3.46 $\pm$ 0.24 ) $\times 10^{-3}$		389
$\mu^+ \mu^- J/\psi(1S)$	( 2.33 $\pm$ 0.29 ) $\times 10^{-4}$		335

 **$h_c(1P)$** 

$$J^G(J^{PC}) = 0^-(1^{+-})$$

Mass  $m = 3525.37 \pm 0.14$  MeV (S = 1.2)

Full width  $\Gamma = 0.78 \pm 0.28$  MeV

<b><math>h_c(1P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$J/\psi(1S)\pi^0$	< 5 $\times 10^{-4}$	90%	382
$J/\psi(1S)\pi^+\pi^-$	< 2.7 $\times 10^{-3}$	90%	305
$\rho\bar{\rho}$	< 1.7 $\times 10^{-4}$	90%	1492
$\rho\bar{\rho}\pi^0$	< 8 $\times 10^{-4}$	90%	1447
$\rho\bar{\rho}\pi^+\pi^-$	( 3.3 $\pm$ 0.6 ) $\times 10^{-3}$		1390
$\rho\bar{\rho}\pi^0\pi^0$	< 6 $\times 10^{-4}$	90%	1394
$\rho\bar{\rho}\pi^+\pi^-\pi^0$	( 4.4 $\pm$ 1.3 ) $\times 10^{-3}$		1331
$\rho\bar{\rho}\eta$	( 7.4 $\pm$ 2.2 ) $\times 10^{-4}$		1264
$\pi^+\pi^-\pi^0$	( 1.9 $\pm$ 0.5 ) $\times 10^{-3}$		1749
$\pi^+\pi^-\pi^0\eta$	( 8.3 $\pm$ 2.4 ) $\times 10^{-3}$		1695
$2\pi^+2\pi^-\pi^0$	( 9.4 $\pm$ 1.7 ) $\times 10^{-3}$		1716
$3\pi^+3\pi^-\pi^0$	< 1.0 %	90%	1661
$K^+K^-\pi^+\pi^-$	< 7 $\times 10^{-4}$	90%	1640
$K^+K^-\pi^+\pi^-\pi^0$	( 3.8 $\pm$ 0.8 ) $\times 10^{-3}$		1606
$K^+K^-\pi^+\pi^-\eta$	< 2.7 $\times 10^{-3}$	90%	1480
$K^+K^-\pi^0$	< 6 $\times 10^{-4}$	90%	1670
$K^+K^-\pi^0\eta$	< 2.4 $\times 10^{-3}$	90%	1532
$K^+K^-\eta$	< 1.0 $\times 10^{-3}$	90%	1574
$2K^+2K^-\pi^0$	< 2.8 $\times 10^{-4}$	90%	1339
$K_S^0 K^\pm \pi^\mp$	< 6 $\times 10^{-4}$	90%	1668
$K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$	( 3.2 $\pm$ 1.0 ) $\times 10^{-3}$		1604

**Radiative decays**

$\gamma \eta$	( 4.7 $\pm$ 2.1 ) $\times 10^{-4}$	1720
$\gamma \eta'(958)$	( 1.5 $\pm$ 0.4 ) $\times 10^{-3}$	1633
$\gamma \eta_c(1S)$	( 60 $\pm$ 4 ) %	500

See Particle Listings for 1 decay modes that have been seen / not seen.

 **$\chi_{c2}(1P)$** 

$$J^G(J^{PC}) = 0^+(2^{++})$$

Mass  $m = 3556.17 \pm 0.07$  MeV

Full width  $\Gamma = 1.98 \pm 0.09$  MeV (S = 1.1)

$\chi_{c2}(1P)$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
<b>Hadronic decays</b>			
$2(\pi^+\pi^-)$	( 1.00±0.13 ) %	S=1.4	1751
$\pi^+\pi^-\pi^0\pi^0$	( 1.86±0.24 ) %		1752
$\rho^+\pi^-\pi^0 + \text{c.c.}$	( 2.22±0.35 ) %		1682
$4\pi^0$	( 1.13±0.15 ) × 10 <sup>-3</sup>		1752
$K^+K^-\pi^0\pi^0$	( 2.1 ±0.4 ) × 10 <sup>-3</sup>		1658
$K^+\pi^-\overline{K}^0\pi^0 + \text{c.c.}$	( 1.41±0.20 ) %		1657
$\rho^-K^+\overline{K}^0 + \text{c.c.}$	( 4.2 ±1.3 ) × 10 <sup>-3</sup>		1540
$K^*(892)^0K^-\pi^+ \rightarrow$ $K^-\pi^+K^0\pi^0 + \text{c.c.}$	( 3.0 ±0.8 ) × 10 <sup>-3</sup>		—
$K^*(892)^0\overline{K}^0\pi^0 \rightarrow$ $K^+\pi^-\overline{K}^0\pi^0 + \text{c.c.}$	( 3.9 ±0.9 ) × 10 <sup>-3</sup>		—
$K^*(892)^-K^+\pi^0 \rightarrow$ $K^+\pi^-\overline{K}^0\pi^0 + \text{c.c.}$	( 3.8 ±0.8 ) × 10 <sup>-3</sup>		—
$K^*(892)^+\overline{K}^0\pi^- \rightarrow$ $K^+\pi^-\overline{K}^0\pi^0 + \text{c.c.}$	( 3.0 ±0.8 ) × 10 <sup>-3</sup>		—
$K^+K^-\eta\pi^0$	( 1.3 ±0.4 ) × 10 <sup>-3</sup>		1549
$K^+K^-\pi^+\pi^-$	( 8.3 ±1.1 ) × 10 <sup>-3</sup>	S=1.2	1656
$K^+K^-\pi^+\pi^-\pi^0$	( 1.17±0.13 ) %		1623
$K_S^0K^\pm\pi^\mp\pi^+\pi^-$	( 7.3 ±0.8 ) × 10 <sup>-3</sup>		1621
$K^+\overline{K}^*(892)^0\pi^-\pi^+ + \text{c.c.}$	( 2.1 ±1.0 ) × 10 <sup>-3</sup>		1602
$K^*(892)^0\overline{K}^*(892)^0$	( 2.2 ±0.9 ) × 10 <sup>-3</sup>	S=2.3	1538
$3(\pi^+\pi^-)$	( 1.53±0.19 ) %	S=3.8	1707
$\phi\phi$	( 1.23±0.07 ) × 10 <sup>-3</sup>	S=1.9	1457
$\phi\phi\eta$	( 5.4 ±0.7 ) × 10 <sup>-4</sup>		1206
$\omega\omega$	( 8.6 ±1.0 ) × 10 <sup>-4</sup>		1597
$\omega K^+K^-$	( 7.3 ±0.9 ) × 10 <sup>-4</sup>		1540
$\omega\phi$	( 9.7 ±2.8 ) × 10 <sup>-6</sup>		1529
$\pi\pi$	( 2.27±0.10 ) × 10 <sup>-3</sup>		1773
$\rho^0\pi^+\pi^-$	( 3.6 ±1.5 ) × 10 <sup>-3</sup>		1682
$\pi^+\pi^-\pi^0$ (non-resonant)	( 2.0 ±0.4 ) × 10 <sup>-5</sup>		1765
$\rho(770)^\pm\pi^\mp$	( 6 ±4 ) × 10 <sup>-6</sup>		—
$\pi^+\pi^-\eta$	( 4.9 ±1.3 ) × 10 <sup>-4</sup>		1724
$\pi^+\pi^-\eta'$	( 5.1 ±1.9 ) × 10 <sup>-4</sup>		1636
$\eta\eta$	( 5.5 ±0.5 ) × 10 <sup>-4</sup>		1692
$K^+K^-$	( 1.02±0.15 ) × 10 <sup>-3</sup>	S=2.3	1708
$K_S^0K_S^0$	( 5.3 ±0.4 ) × 10 <sup>-4</sup>		1707
$K^*(892)^\pm K^\mp$	( 1.46±0.21 ) × 10 <sup>-4</sup>		1627
$K^*(892)^0\overline{K}^0 + \text{c.c.}$	( 1.27±0.27 ) × 10 <sup>-4</sup>		1627
$K_2^*(1430)^\pm K^\mp$	( 1.51±0.13 ) × 10 <sup>-3</sup>		—
$K_2^*(1430)^0\overline{K}^0 + \text{c.c.}$	( 1.27±0.17 ) × 10 <sup>-3</sup>		1443
$K_3^*(1780)^\pm K^\mp$	( 5.3 ±0.8 ) × 10 <sup>-4</sup>		—
$K_3^*(1780)^0\overline{K}^0 + \text{c.c.}$	( 5.7 ±2.1 ) × 10 <sup>-4</sup>		1274
$a_2(1320)^0\pi^0$	( 1.31±0.35 ) × 10 <sup>-3</sup>		—
$a_2(1320)^\pm\pi^\mp$	( 1.8 ±0.6 ) × 10 <sup>-3</sup>		1530
$\overline{K}^0K^+\pi^- + \text{c.c.}$	( 1.30±0.19 ) × 10 <sup>-3</sup>		1685
$K^+K^-\pi^0$	( 3.1 ±0.8 ) × 10 <sup>-4</sup>		1686
$K^+K^-\eta$	< 3.3 × 10 <sup>-4</sup>	CL=90%	1592
$K^+K^-\eta'(958)$	( 1.94±0.34 ) × 10 <sup>-4</sup>		1488
$\eta\eta'$	( 2.2 ±0.5 ) × 10 <sup>-5</sup>		1600
$\eta'\eta'$	( 4.6 ±0.6 ) × 10 <sup>-5</sup>		1498
$\pi^+\pi^-K_S^0K_S^0$	( 2.2 ±0.5 ) × 10 <sup>-3</sup>		1655



$K^+ K^- K_S^0 K_S^0$	$< 4 \times 10^{-4}$	CL=90%	1418
$K_S^0 K_S^0 K_S^0 K_S^0$	$(1.15 \pm 0.18) \times 10^{-4}$		1415
$K^+ K^- K^+ K^-$	$(1.67 \pm 0.22) \times 10^{-3}$	S=1.1	1421
$K^+ K^- \phi$	$(1.45 \pm 0.30) \times 10^{-3}$		1468
$\bar{K}^0 K^+ \pi^- \phi + \text{c.c.}$	$(4.8 \pm 0.7) \times 10^{-3}$		1416
$K^+ K^- \pi^0 \phi$	$(2.7 \pm 0.5) \times 10^{-3}$		1419
$\phi \pi^+ \pi^- \pi^0$	$(9.3 \pm 1.2) \times 10^{-4}$		1603
$\rho \bar{\rho}$	$(7.3 \pm 0.4) \times 10^{-5}$	S=1.1	1510
$\rho \bar{\rho} \pi^0$	$(4.7 \pm 0.4) \times 10^{-4}$		1465
$\rho \bar{\rho} \eta$	$(1.77 \pm 0.25) \times 10^{-4}$		1285
$\rho \bar{\rho} \omega$	$(3.7 \pm 0.4) \times 10^{-4}$		1152
$\rho \bar{\rho} \phi$	$(2.8 \pm 0.9) \times 10^{-5}$		1002
$\rho \bar{\rho} \pi^+ \pi^-$	$(1.32 \pm 0.34) \times 10^{-3}$		1410
$\rho \bar{\rho} \pi^0 \pi^0$	$(8.0 \pm 2.4) \times 10^{-4}$		1414
$\rho \bar{\rho} K^+ K^-$ (non-resonant)	$(1.94 \pm 0.33) \times 10^{-4}$		1013
$\rho \bar{\rho} K_S^0 K_S^0$	$< 7.9 \times 10^{-4}$	CL=90%	1007
$\rho \bar{\rho} \pi^-$	$(8.7 \pm 1.0) \times 10^{-4}$		1463
$\bar{\rho} n \pi^+$	$(9.1 \pm 0.8) \times 10^{-4}$		1463
$\rho \bar{\rho} \pi^- \pi^0$	$(2.21 \pm 0.18) \times 10^{-3}$		1411
$\bar{\rho} n \pi^+ \pi^0$	$(2.15 \pm 0.19) \times 10^{-3}$		1411
$\Lambda \bar{\Lambda}$	$(1.86 \pm 0.16) \times 10^{-4}$		1384
$\Lambda \bar{\Lambda} \pi^+ \pi^-$	$(1.28 \pm 0.16) \times 10^{-3}$		1255
$\Lambda \bar{\Lambda} \pi^+ \pi^-$ (non-resonant)	$(6.7 \pm 1.5) \times 10^{-4}$		1255
$\Sigma(1385)^+ \bar{\Lambda} \pi^- + \text{c.c.}$	$< 4 \times 10^{-4}$	CL=90%	1192
$\Sigma(1385)^- \bar{\Lambda} \pi^+ + \text{c.c.}$	$< 6 \times 10^{-4}$	CL=90%	1192
$\Lambda \bar{\Lambda} \eta$	$(1.07 \pm 0.26) \times 10^{-4}$		1096
$K^+ \bar{\rho} \Lambda + \text{c.c.}$	$(7.9 \pm 0.6) \times 10^{-4}$		1236
$n K_S^0 \bar{\Lambda} + \text{c.c.}$	$(3.64 \pm 0.29) \times 10^{-4}$		1233
$K^*(892)^+ \bar{\rho} \Lambda + \text{c.c.}$	$(8.3 \pm 1.2) \times 10^{-4}$		976
$K^+ \bar{\rho} \Lambda(1520) + \text{c.c.}$	$(2.9 \pm 0.7) \times 10^{-4}$		992
$\Lambda(1520) \bar{\Lambda}(1520)$	$(4.7 \pm 1.5) \times 10^{-4}$		924
$\Sigma^0 \bar{\Sigma}^0$	$(3.7 \pm 0.6) \times 10^{-5}$		1319
$\Sigma^+ \bar{\rho} K_S^0 + \text{c.c.}$	$(8.4 \pm 1.0) \times 10^{-5}$		1197
$\Sigma^0 \bar{\rho} K^+ + \text{c.c.}$	$(9.3 \pm 0.8) \times 10^{-5}$		1197
$\Sigma^+ \bar{\Sigma}^-$	$(3.4 \pm 0.7) \times 10^{-5}$		1322
$\Sigma^- \bar{\Sigma}^+$	$(4.5 \pm 1.8) \times 10^{-5}$		1314
$\Sigma(1385)^+ \bar{\Sigma}(1385)^-$	$< 1.6 \times 10^{-4}$	CL=90%	1118
$\Sigma(1385)^- \bar{\Sigma}(1385)^+$	$< 8 \times 10^{-5}$	CL=90%	1118
$K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$	$(1.80 \pm 0.32) \times 10^{-4}$		1004
$\Xi^0 \bar{\Xi}^0$	$(1.86 \pm 0.22) \times 10^{-4}$		1197
$\Xi^- \bar{\Xi}^+$	$(1.46 \pm 0.12) \times 10^{-4}$		1189
$\Omega^- \bar{\Omega}^+$	$(4.52 \pm 0.30) \times 10^{-5}$		604
$J/\psi(1S) \pi^+ \pi^- \pi^0$	$< 1.5 \%$	CL=90%	185
$\pi^0 \eta_c$	$< 3.2 \times 10^{-3}$	CL=90%	511
$\eta_c(1S) \pi^+ \pi^-$	$< 5.4 \times 10^{-3}$	CL=90%	459
<b>Radiative decays</b>			
$\gamma J/\psi(1S)$	$(19.5 \pm 0.8) \%$	S=1.5	430
$\gamma \rho^0$	$< 1.9 \times 10^{-5}$	CL=90%	1694
$\gamma \omega$	$< 6 \times 10^{-6}$	CL=90%	1692
$\gamma \phi$	$< 8 \times 10^{-6}$	CL=90%	1632
$\gamma \gamma$	$(2.92 \pm 0.12) \times 10^{-4}$	S=1.3	1778
$e^+ e^- J/\psi(1S)$	$(2.20 \pm 0.15) \times 10^{-3}$		430
$\mu^+ \mu^- J/\psi(1S)$	$(2.07 \pm 0.34) \times 10^{-4}$		381

**$\eta_c(2S)$**

$$I^G(J^{PC}) = 0^+(0^{-+})$$

Quantum numbers are quark model predictions.

Mass  $m = 3637.7 \pm 0.9$  MeV (S = 1.2)

Full width  $\Gamma = 11.8 \pm 1.6$  MeV

$\eta_c(2S)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$K\bar{K}\pi$	( 1.9±1.2 ) %		1729
$K\bar{K}\eta$	( 5 ± 4 ) × 10 <sup>-3</sup>		1637
$2\pi^+ 2\pi^-$	< 2.1 %	90%	1792
$\rho^0 \rho^0$	< 1.9 × 10 <sup>-3</sup>	90%	1645
$3\pi^+ 3\pi^-$	( 1.3±0.9 ) %		1749
$K^+ K^- \pi^+ \pi^-$	< 1.4 %	90%	1700
$K^{*0} \bar{K}^{*0}$	< 2.9 × 10 <sup>-3</sup>	90%	1585
$K^+ K^- \pi^+ \pi^- \pi^0$	( 1.4±1.0 ) %		1668
$K^+ K^- 2\pi^+ 2\pi^-$	< 1.4 %	90%	1627
$K_S^0 K^- 2\pi^+ \pi^- + c.c.$	( 1.0±0.8 ) %		1666
$2K^+ 2K^-$	< 1.3 × 10 <sup>-3</sup>	90%	1470
$\phi\phi$	< 1.1 × 10 <sup>-3</sup>	90%	1506
$\rho\bar{\rho}$	< 2.0 × 10 <sup>-3</sup>	90%	1558
$\gamma\gamma$	( 1.8±1.2 ) × 10 <sup>-4</sup>		1819
$\gamma J/\psi(1S)$	< 1.4 %	90%	501
$\pi^+ \pi^- \eta$	( 4.3±3.2 ) × 10 <sup>-3</sup>		1766
$\pi^+ \pi^- \eta'$	( 2.6±1.9 ) × 10 <sup>-3</sup>		1680
$\pi^+ \pi^- \eta_c(1S)$	< 25 %	90%	537

See Particle Listings for 8 decay modes that have been seen / not seen.

**$\psi(2S)$**

$$I^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 3686.097 \pm 0.011$  MeV (S = 1.1)

Full width  $\Gamma = 293 \pm 9$  keV (S = 1.2)

$\psi(2S)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
hadrons	(97.85 ± 0.13 ) %		—
virtual $\gamma \rightarrow$ hadrons	( 1.79 ± 0.04 ) %		—
$g g g$	(10.6 ± 1.6 ) %		—
$\gamma g g$	( 1.03 ± 0.29 ) %		—
light hadrons	(15.4 ± 1.5 ) %		—
$K_S^0$ anything	(16.0 ± 1.1 ) %		—
$e^+ e^-$	( 7.94 ± 0.22 ) × 10 <sup>-3</sup>	S=1.3	1843
$\mu^+ \mu^-$	( 8.0 ± 0.6 ) × 10 <sup>-3</sup>		1840
$\tau^+ \tau^-$	( 3.1 ± 0.4 ) × 10 <sup>-3</sup>		489
<b>Decays into <math>J/\psi(1S)</math> and anything</b>			
$J/\psi(1S)$ anything	(61.5 ± 0.7 ) %	S=1.3	—
$J/\psi(1S)$ neutrals	(25.4 ± 0.5 ) %	S=1.6	—
$J/\psi(1S) \pi^+ \pi^-$	(34.69 ± 0.34 ) %	S=1.1	477
$J/\psi(1S) \pi^0 \pi^0$	(18.2 ± 0.5 ) %	S=1.6	481
$J/\psi(1S) \eta$	( 3.37 ± 0.06 ) %	S=1.2	199
$J/\psi(1S) \pi^0$	( 1.268±0.032 ) × 10 <sup>-3</sup>		528
<b>Hadronic decays</b>			
$\pi^+ \pi^-$	( 7.8 ± 2.6 ) × 10 <sup>-6</sup>		1838
$\pi^+ \pi^- \pi^0$	( 2.01 ± 0.17 ) × 10 <sup>-4</sup>	S=1.7	1830

$\rho(770)\pi \rightarrow \pi^+\pi^-\pi^0$	( 3.2 $\pm$ 1.2 ) $\times 10^{-5}$	S=1.8	—
$\rho(2150)\pi \rightarrow \pi^+\pi^-\pi^0$	( 1.9 $\begin{smallmatrix} +1.2 \\ -0.4 \end{smallmatrix}$ ) $\times 10^{-4}$		—
$2(\pi^+\pi^-)$	( 2.4 $\pm$ 0.6 ) $\times 10^{-4}$	S=2.2	1817
$\rho^0\pi^+\pi^-$	( 2.2 $\pm$ 0.6 ) $\times 10^{-4}$	S=1.4	1750
$2(\pi^+\pi^-)\pi^0$	( 2.9 $\pm$ 1.0 ) $\times 10^{-3}$	S=4.7	1799
$\rho a_2(1320)$	( 2.6 $\pm$ 0.9 ) $\times 10^{-4}$		1500
$\pi^+\pi^-\pi^0\pi^0\pi^0$	( 5.3 $\pm$ 1.0 ) $\times 10^{-3}$		1800
$\rho^\pm\pi^\mp\pi^0\pi^0$	< 2.7 $\times 10^{-3}$	CL=90%	1737
$\pi^+\pi^-4\pi^0$	( 1.4 $\pm$ 1.0 ) $\times 10^{-3}$		1778
$3(\pi^+\pi^-)$	( 3.5 $\pm$ 2.0 ) $\times 10^{-4}$	S=2.8	1774
$2(\pi^+\pi^-\pi^0)$	( 4.8 $\pm$ 1.5 ) $\times 10^{-3}$		1776
$3(\pi^+\pi^-)\pi^0$	( 3.5 $\pm$ 1.6 ) $\times 10^{-3}$		1746
$2(\pi^+\pi^-)3\pi^0$	( 1.42 $\pm$ 0.31 ) %		1748
$\eta\pi^+\pi^-$	< 1.6 $\times 10^{-4}$	CL=90%	1791
$\eta\pi^+\pi^-\pi^0$	( 9.5 $\pm$ 1.7 ) $\times 10^{-4}$		1778
$\eta 2(\pi^+\pi^-)$	( 1.2 $\pm$ 0.6 ) $\times 10^{-3}$		1758
$\eta\pi^+\pi^-\pi^0\pi^0$	< 4 $\times 10^{-4}$	CL=90%	1760
$\eta\pi^+\pi^-3\pi^0$	< 2.1 $\times 10^{-3}$	CL=90%	1736
$\eta 2(\pi^+\pi^-\pi^0)$	< 2.1 $\times 10^{-3}$	CL=90%	1705
$\rho\eta$	( 2.2 $\pm$ 0.6 ) $\times 10^{-5}$	S=1.1	1717
$\eta'\pi^+\pi^-\pi^0$	( 4.5 $\pm$ 2.1 ) $\times 10^{-4}$		1692
$\eta'\rho$	( 1.9 $\begin{smallmatrix} +1.7 \\ -1.2 \end{smallmatrix}$ ) $\times 10^{-5}$		1625
$\omega\pi^0$	( 2.1 $\pm$ 0.6 ) $\times 10^{-5}$		1757
$\omega\pi^+\pi^-$	( 7.3 $\pm$ 1.2 ) $\times 10^{-4}$	S=2.1	1748
$\omega\pi^+\pi^-2\pi^0$	( 8.7 $\pm$ 2.4 ) $\times 10^{-3}$		1715
$b_1^\pm\pi^\mp$	( 4.0 $\pm$ 0.6 ) $\times 10^{-4}$	S=1.1	1635
$\omega f_2(1270)$	( 2.2 $\pm$ 0.4 ) $\times 10^{-4}$		1515
$\omega\pi^0\pi^0$	( 1.11 $\pm$ 0.35 ) $\times 10^{-3}$		1749
$\omega 3\pi^0$	< 8 $\times 10^{-4}$	CL=90%	1736
$b_1^0\pi^0$	( 2.4 $\pm$ 0.6 ) $\times 10^{-4}$		—
$\omega\eta$	< 1.1 $\times 10^{-5}$	CL=90%	1715
$\omega\eta'$	( 3.2 $\begin{smallmatrix} +2.5 \\ -2.1 \end{smallmatrix}$ ) $\times 10^{-5}$		1623
$\phi\pi^0$	< 4 $\times 10^{-7}$	CL=90%	1699
$\phi\pi^+\pi^-$	( 1.18 $\pm$ 0.26 ) $\times 10^{-4}$	S=1.5	1690
$\phi f_0(980) \rightarrow \pi^+\pi^-$	( 7.5 $\pm$ 3.3 ) $\times 10^{-5}$	S=1.6	—
$\phi\eta$	( 3.10 $\pm$ 0.31 ) $\times 10^{-5}$		1654
$\eta\phi(2170), \phi(2170) \rightarrow \phi f_0(980),$ $f_0 \rightarrow \pi^+\pi^-$	< 2.2 $\times 10^{-6}$	CL=90%	—
$\phi\eta'$	( 1.54 $\pm$ 0.20 ) $\times 10^{-5}$		1555
$\phi f_1(1285)$	( 3.0 $\pm$ 1.3 ) $\times 10^{-5}$		1436
$\phi\eta(1405) \rightarrow \phi\pi^+\pi^-\eta$	( 8.5 $\pm$ 1.7 ) $\times 10^{-6}$		—
$\phi f_2'(1525)$	( 4.4 $\pm$ 1.6 ) $\times 10^{-5}$		1325
$K^+K^-$	( 7.5 $\pm$ 0.5 ) $\times 10^{-5}$		1776
$K^+K^-\pi^+\pi^-$	( 7.3 $\pm$ 0.5 ) $\times 10^{-4}$		1726
$K^+K^-\pi^0$	( 4.07 $\pm$ 0.31 ) $\times 10^{-5}$		1754
$K_S^0 K_S^0$	< 4.6 $\times 10^{-6}$		1775
$K_S^0 K_L^0$	( 5.34 $\pm$ 0.33 ) $\times 10^{-5}$		1775
$K_S^0 K_L^0\pi^0$	< 3.0 $\times 10^{-4}$	CL=90%	1753
$K^+K^-\pi^0\pi^0$	( 2.6 $\pm$ 1.3 ) $\times 10^{-4}$		1728
$K^+K^-\pi^0\pi^0\pi^0$	( 6.6 $\pm$ 2.8 ) $\times 10^{-4}$		1696
$K_S^0 K^\pm\pi^\mp\pi^0\pi^0$	( 1.7 $\pm$ 0.6 ) $\times 10^{-3}$		1694
$K_S^0 K^\pm\pi^\mp\pi^+\pi^-$	( 2.2 $\pm$ 0.4 ) $\times 10^{-3}$		1692
$K^+K^-\pi^+\pi^-\pi^0$	( 1.26 $\pm$ 0.09 ) $\times 10^{-3}$		1694

$\omega f_0(1710) \rightarrow \omega K^+ K^-$	$(5.9 \pm 2.2) \times 10^{-5}$		—
$K^*(892)^0 K^- \pi^+ \pi^0 + \text{c.c.}$	$(8.6 \pm 2.2) \times 10^{-4}$		—
$K^*(892)^+ K^- \pi^+ \pi^- + \text{c.c.}$	$(9.6 \pm 2.8) \times 10^{-4}$		—
$K^*(892)^+ K^- \rho^0 + \text{c.c.}$	$(7.3 \pm 2.6) \times 10^{-4}$		—
$K^*(892)^0 K^- \rho^+ + \text{c.c.}$	$(6.1 \pm 1.8) \times 10^{-4}$		—
$K_S^0 K_S^0 \pi^+ \pi^-$	$(2.2 \pm 0.4) \times 10^{-4}$		1724
$K_S^0 K_L^0 \pi^0 \pi^0$	$(1.3 \pm 0.6) \times 10^{-3}$		1726
$K_S^0 K^*(892)^0 \pi^0 \pi^0$	$(3.0 \pm 1.3) \times 10^{-4}$		1645
$K_S^0 K^\pm \rho(770)^\mp \pi^0$	$< 7 \times 10^{-4}$	CL=90%	—
$K_S^0 K^\pm \pi^\mp \rho(770)^0$	$< 7 \times 10^{-4}$	CL=90%	—
$K^\mp K^*(892)^\pm \pi^0 \pi^0$	$(7.0 \pm 2.9) \times 10^{-4}$		1646
$K^*(892)^+ K^*(892)^- \pi^0$	$(3.6 \pm 1.8) \times 10^{-3}$		1573
$K_S^0 K_L^0 \eta$	$(1.3 \pm 0.5) \times 10^{-3}$		1661
$K^+ K^- \rho^0$	$(2.2 \pm 0.4) \times 10^{-4}$		1616
$K^*(892)^0 \overline{K}_2^*(1430)^0$	$(1.9 \pm 0.5) \times 10^{-4}$		1417
$K^+ K^- \pi^+ \pi^- \eta$	$(1.3 \pm 0.7) \times 10^{-3}$		1574
$K^+ K^- 2(\pi^+ \pi^-)$	$(1.9 \pm 0.9) \times 10^{-3}$		1654
$K^+ K^- 2(\pi^+ \pi^-) \pi^0$	$(1.00 \pm 0.31) \times 10^{-3}$		1611
$K^+ K^*(892)^- + \text{c.c.}$	$(2.9 \pm 0.4) \times 10^{-5}$	S=1.2	1698
$2(K^+ K^-)$	$(6.3 \pm 1.3) \times 10^{-5}$		1499
$2(K^+ K^-) \pi^0$	$(1.10 \pm 0.28) \times 10^{-4}$		1440
$K^+ K^- \phi$	$(7.0 \pm 1.6) \times 10^{-5}$		1546
$K_S^0 K_S^0 \phi$	$(3.53 \pm 0.29) \times 10^{-5}$		1543
$K_1(1270)^\pm K^\mp$	$(1.00 \pm 0.28) \times 10^{-3}$		1588
$K^+ \overline{K}^*(892)^0 \pi^- + \text{c.c.}$	$(6.7 \pm 2.5) \times 10^{-4}$		1674
$\eta K^+ K^-$ , no $\eta \phi$	$(3.49 \pm 0.17) \times 10^{-5}$		1664
$\eta K^+ K^-$	$< 2.6 \times 10^{-4}$	CL=90%	1664
$X(1750) \eta \rightarrow K^+ K^- \eta$	$(4.8 \pm 2.8) \times 10^{-6}$		—
$K_1(1400)^\pm K^\mp$	$< 3.1 \times 10^{-4}$	CL=90%	1532
$K_2^*(1430)^\pm K^\mp$	$(7.1 \pm 1.3 \pm 0.9) \times 10^{-5}$		—
$K^*(892)^0 \overline{K}^0 + \text{c.c.}$	$(1.09 \pm 0.20) \times 10^{-4}$		1697
$\omega K^+ K^-$	$(1.62 \pm 0.11) \times 10^{-4}$	S=1.1	1614
$\omega K_S^0 K_S^0$	$(7.0 \pm 0.5) \times 10^{-5}$		1612
$\omega K^*(892)^+ K^- + \text{c.c.}$	$(2.07 \pm 0.26) \times 10^{-4}$		1482
$\omega K_2^*(1430)^+ K^- + \text{c.c.}$	$(6.1 \pm 1.2) \times 10^{-5}$		1252
$\omega \overline{K}^*(892)^0 K^0$	$(1.68 \pm 0.30) \times 10^{-4}$		1481
$\omega \overline{K}_2^*(1430)^0 K^0$	$(5.8 \pm 2.2) \times 10^{-5}$		1250
$\omega X(1440) \rightarrow \omega K_S^0 K^- \pi^+ + \text{c.c.}$	$(1.6 \pm 0.4) \times 10^{-5}$		—
$\omega X(1440) \rightarrow \omega K^+ K^- \pi^0$	$(1.09 \pm 0.26) \times 10^{-5}$		—
$\omega f_1(1285) \rightarrow \omega K_S^0 K^- \pi^+ + \text{c.c.}$	$(3.0 \pm 1.0) \times 10^{-6}$		—
$\omega f_1(1285) \rightarrow \omega K^+ K^- \pi^0$	$(1.2 \pm 0.7) \times 10^{-6}$		—
$\rho \overline{\rho}$	$(2.94 \pm 0.09) \times 10^{-4}$	S=1.3	1586
$n \overline{n}$	$(3.06 \pm 0.15) \times 10^{-4}$		1586
$\rho \overline{\rho} \pi^0$	$(1.53 \pm 0.07) \times 10^{-4}$		1543
$N(940) \overline{\rho} + \text{c.c.} \rightarrow \rho \overline{\rho} \pi^0$	$(6.4 \pm 1.8 \pm 1.3) \times 10^{-5}$		—
$N(1440) \overline{\rho} + \text{c.c.} \rightarrow \rho \overline{\rho} \pi^0$	$(7.3 \pm 1.7 \pm 1.5) \times 10^{-5}$	S=2.5	—
$N(1520) \overline{\rho} + \text{c.c.} \rightarrow \rho \overline{\rho} \pi^0$	$(6.4 \pm 2.3 \pm 1.8) \times 10^{-6}$		—
$N(1535) \overline{\rho} + \text{c.c.} \rightarrow \rho \overline{\rho} \pi^0$	$(2.5 \pm 1.0) \times 10^{-5}$		—
$N(1650) \overline{\rho} + \text{c.c.} \rightarrow \rho \overline{\rho} \pi^0$	$(3.8 \pm 1.4 \pm 1.7) \times 10^{-5}$		—
$N(1720) \overline{\rho} + \text{c.c.} \rightarrow \rho \overline{\rho} \pi^0$	$(1.79 \pm 0.26 \pm 0.70) \times 10^{-5}$		—

$N(2300)\bar{p} + \text{c.c.} \rightarrow p\bar{p}\pi^0$	$(2.6 \begin{smallmatrix} +1.2 \\ -0.7 \end{smallmatrix}) \times 10^{-5}$		–
$N(2570)\bar{p} + \text{c.c.} \rightarrow p\bar{p}\pi^0$	$(2.13 \begin{smallmatrix} +0.40 \\ -0.31 \end{smallmatrix}) \times 10^{-5}$		–
$p\bar{p}\pi^+\pi^-$	$(6.0 \pm 0.4) \times 10^{-4}$		1491
$p\bar{p}K^+K^-$	$(2.7 \pm 0.7) \times 10^{-5}$		1118
$p\bar{p}\eta$	$(6.0 \pm 0.4) \times 10^{-5}$		1373
$N(1535)\bar{p} + \text{c.c.} \rightarrow p\bar{p}\eta$	$(4.5 \begin{smallmatrix} +0.7 \\ -0.6 \end{smallmatrix}) \times 10^{-5}$		–
$p\bar{p}\pi^+\pi^-\pi^0$	$(7.3 \pm 0.7) \times 10^{-4}$		1435
$p\bar{p}\rho^0$	$(5.0 \pm 2.2) \times 10^{-5}$		1252
$p\bar{p}\omega$	$(6.9 \pm 2.1) \times 10^{-5}$		1247
$p\bar{p}\eta'$	$(1.10 \pm 0.13) \times 10^{-5}$		1141
$p\bar{p}\phi$	$(6.1 \pm 0.6) \times 10^{-6}$		1109
$\phi X(1835) \rightarrow p\bar{p}\phi$	$< 1.82 \times 10^{-7}$	CL=90%	–
$p\bar{n}\pi^- \text{ or c.c.}$	$(2.48 \pm 0.17) \times 10^{-4}$		–
$p\bar{n}\pi^-\pi^0$	$(3.2 \pm 0.7) \times 10^{-4}$		1492
$\Lambda\bar{\Lambda}$	$(3.81 \pm 0.13) \times 10^{-4}$	S=1.4	1467
$\Lambda\bar{\Lambda}\pi^0$	$(1.4 \pm 0.7) \times 10^{-6}$		1412
$\Lambda\bar{\Lambda}\eta$	$(2.43 \pm 0.32) \times 10^{-5}$		1197
$\Lambda(1670)\bar{\Lambda} \rightarrow \Lambda\bar{\Lambda}\eta$	$(1.3 \pm 0.7) \times 10^{-5}$		–
$\Lambda\bar{\Lambda}\eta'$	$(7.3 \pm 1.0) \times 10^{-6}$		892
$\Lambda\bar{\Lambda}\omega(782)$	$(3.3 \pm 0.4) \times 10^{-5}$		1037
$\Lambda\bar{\Lambda}\pi^+\pi^-$	$(2.8 \pm 0.6) \times 10^{-4}$		1346
$\Lambda\bar{p}K^+$	$(1.00 \pm 0.14) \times 10^{-4}$		1327
$\Lambda\bar{p}K^*(892)^+ + \text{c.c.}$	$(6.3 \pm 0.7) \times 10^{-5}$		1087
$\Lambda\bar{p}K^+\pi^+\pi^-$	$(1.8 \pm 0.4) \times 10^{-4}$		1167
$\bar{\Lambda}n K_S^0 + \text{c.c.}$	$(8.1 \pm 1.8) \times 10^{-5}$		1324
$\Delta^{++}\bar{\Delta}^{--}$	$(1.28 \pm 0.35) \times 10^{-4}$		1371
$\Lambda\bar{\Sigma}^+\pi^- + \text{c.c.}$	$(1.40 \pm 0.13) \times 10^{-4}$		1376
$\Lambda\bar{\Sigma}^-\pi^+ + \text{c.c.}$	$(1.54 \pm 0.14) \times 10^{-4}$		1379
$\Lambda\bar{\Sigma}^0 + \text{c.c.}$	$(1.6 \pm 0.7) \times 10^{-6}$		1437
$\Sigma^0\bar{p}K^+ + \text{c.c.}$	$(1.67 \pm 0.18) \times 10^{-5}$		1291
$\Sigma^+\bar{\Sigma}^-$	$(2.43 \pm 0.10) \times 10^{-4}$	S=1.4	1408
$\Sigma^0\bar{\Sigma}^0$	$(2.35 \pm 0.09) \times 10^{-4}$	S=1.1	1405
$\Sigma^-\bar{\Sigma}^+$	$(2.82 \pm 0.09) \times 10^{-4}$		1401
$\Sigma^+\bar{\Sigma}^-\eta$	$(9.6 \pm 2.4) \times 10^{-6}$		1108
$\Sigma^+\bar{\Sigma}^-\omega$	$(1.89 \pm 0.28) \times 10^{-5}$		926
$\Sigma^+\bar{\Sigma}^-\phi$	$(3.0 \pm 0.7) \times 10^{-6}$		686
$\Sigma(1385)^+\bar{\Sigma}(1385)^-$	$(8.5 \pm 0.7) \times 10^{-5}$		1218
$\Sigma(1385)^-\bar{\Sigma}(1385)^+$	$(8.5 \pm 0.8) \times 10^{-5}$		1218
$\Sigma(1385)^0\bar{\Sigma}(1385)^0$	$(6.9 \pm 0.7) \times 10^{-5}$		1218
$\Xi^-\bar{\Xi}^+$	$(2.87 \pm 0.11) \times 10^{-4}$	S=1.1	1284
$\Xi^0\bar{\Xi}^0$	$(2.3 \pm 0.4) \times 10^{-4}$	S=4.2	1291
$\Xi(1530)^0\bar{\Xi}(1530)^0$	$(6.8 \pm 0.4) \times 10^{-5}$		1025
$\Lambda\bar{\Xi}^+K^- + \text{c.c.}$	$(3.9 \pm 0.4) \times 10^{-5}$		1114
$\Xi(1690)^-\bar{\Xi}^+ \rightarrow K^-\Lambda\bar{\Xi}^+ + \text{c.c.}$	$(5.2 \pm 1.6) \times 10^{-6}$		–
$\Xi(1820)^-\bar{\Xi}^+ \rightarrow K^-\Lambda\bar{\Xi}^+ + \text{c.c.}$	$(1.20 \pm 0.32) \times 10^{-5}$		–
$\Xi(1530)^-\bar{\Xi}(1530)^+$	$(1.15 \pm 0.07) \times 10^{-4}$		1025
$\Xi(1530)^-\bar{\Xi}^+$	$(7.0 \pm 1.2) \times 10^{-6}$		1165
$\Xi(1530)^0\bar{\Xi}^0$	$(5.3 \pm 0.5) \times 10^{-6}$		1169
$\Sigma^0\bar{\Xi}^+K^- + \text{c.c.}$	$(3.7 \pm 0.4) \times 10^{-5}$		1060
$\Omega^-\bar{\Omega}^+$	$(5.66 \pm 0.30) \times 10^{-5}$	S=1.3	774
$\eta_c\pi^+\pi^-\pi^0$	$< 1.0 \times 10^{-3}$	CL=90%	512
$h_c(1P)\pi^0$	$(7.4 \pm 0.5) \times 10^{-4}$		85

$\Lambda_c^+ \bar{p} e^+ e^- + \text{c.c.}$	$< 1.7$	$\times 10^{-6}$	CL=90%	830
$\Theta(1540) \bar{\Theta}(1540) \rightarrow$ $K_S^0 p K^- \bar{n} + \text{c.c.}$	[ <i>iiaa</i> ] $< 8.8$	$\times 10^{-6}$	CL=90%	—
$\Theta(1540) K^- \bar{n} \rightarrow K_S^0 p K^- \bar{n}$	[ <i>iiaa</i> ] $< 1.0$	$\times 10^{-5}$	CL=90%	—
$\Theta(1540) K_S^0 \bar{p} \rightarrow K_S^0 \bar{p} K^+ n$	[ <i>iiaa</i> ] $< 7.0$	$\times 10^{-6}$	CL=90%	—
$\bar{\Theta}(1540) K^+ n \rightarrow K_S^0 \bar{p} K^+ n$	[ <i>iiaa</i> ] $< 2.6$	$\times 10^{-5}$	CL=90%	—
$\bar{\Theta}(1540) K_S^0 p \rightarrow K_S^0 p K^- \bar{n}$	[ <i>iiaa</i> ] $< 6.0$	$\times 10^{-6}$	CL=90%	—

**Radiative decays**

$\gamma \chi_{c0}(1P)$	( 9.77 $\pm$ 0.23 ) %		S=1.1	261
$\gamma \chi_{c1}(1P)$	( 9.75 $\pm$ 0.27 ) %		S=1.1	171
$\gamma \chi_{c2}(1P)$	( 9.36 $\pm$ 0.23 ) %		S=1.2	128
$\gamma \eta_c(1S)$	( 3.6 $\pm$ 0.5 ) $\times 10^{-3}$		S=1.3	635
$\gamma \eta_c(2S)$	( 7 $\pm$ 5 ) $\times 10^{-4}$			48
$\gamma \pi^0$	( 1.04 $\pm$ 0.22 ) $\times 10^{-6}$		S=1.4	1841
$\gamma 2(\pi^+ \pi^-)$	( 4.0 $\pm$ 0.6 ) $\times 10^{-4}$			1817
$\gamma 3(\pi^+ \pi^-)$	$< 1.7$	$\times 10^{-4}$	CL=90%	1774
$\gamma \eta'(958)$	( 1.24 $\pm$ 0.04 ) $\times 10^{-4}$			1719
$\gamma f_2(1270)$	( 2.73 $^{+0.29}_{-0.25}$ ) $\times 10^{-4}$		S=1.8	1622
$\gamma f_0(1370) \rightarrow \gamma K \bar{K}$	( 3.1 $\pm$ 1.7 ) $\times 10^{-5}$			1588
$\gamma f_0(1500)$	( 9.3 $\pm$ 1.9 ) $\times 10^{-5}$			1529
$\gamma f'_2(1525)$	( 3.3 $\pm$ 0.8 ) $\times 10^{-5}$			1531
$\gamma f_0(1710) \rightarrow \gamma \pi \pi$	( 3.5 $\pm$ 0.6 ) $\times 10^{-5}$			—
$\gamma f_0(1710) \rightarrow \gamma K \bar{K}$	( 6.6 $\pm$ 0.7 ) $\times 10^{-5}$			—
$\gamma f_0(2100) \rightarrow \gamma \pi \pi$	( 4.8 $\pm$ 1.0 ) $\times 10^{-6}$			1244
$\gamma f_0(2200) \rightarrow \gamma K \bar{K}$	( 3.2 $\pm$ 1.0 ) $\times 10^{-6}$			1193
$\gamma f_J(2220) \rightarrow \gamma \pi \pi$	$< 5.8$	$\times 10^{-6}$	CL=90%	1168
$\gamma f_J(2220) \rightarrow \gamma K \bar{K}$	$< 9.5$	$\times 10^{-6}$	CL=90%	1168
$\gamma \eta$	( 9.2 $\pm$ 1.8 ) $\times 10^{-7}$			1802
$\gamma \eta \pi^+ \pi^-$	( 8.7 $\pm$ 2.1 ) $\times 10^{-4}$			1791
$\gamma \eta(1405) \rightarrow \gamma K \bar{K} \pi$	$< 9$	$\times 10^{-5}$	CL=90%	1569
$\gamma \eta(1405) \rightarrow \gamma \eta \pi^+ \pi^-$	( 3.6 $\pm$ 2.5 ) $\times 10^{-5}$			—
$\gamma \eta(1405) \rightarrow \gamma f_0(980) \pi^0 \rightarrow$ $\gamma \pi^+ \pi^- \pi^0$	$< 5.0$	$\times 10^{-7}$	CL=90%	—
$\gamma \eta(1475) \rightarrow \gamma K \bar{K} \pi$	$< 1.4$	$\times 10^{-4}$	CL=90%	—
$\gamma \eta(1475) \rightarrow \gamma \eta \pi^+ \pi^-$	$< 8.8$	$\times 10^{-5}$	CL=90%	—
$\gamma K^{*0} K^+ \pi^- + \text{c.c.}$	( 3.7 $\pm$ 0.9 ) $\times 10^{-4}$			1674
$\gamma K^{*0} \bar{K}^{*0}$	( 2.4 $\pm$ 0.7 ) $\times 10^{-4}$			1613
$\gamma K_S^0 K^+ \pi^- + \text{c.c.}$	( 2.6 $\pm$ 0.5 ) $\times 10^{-4}$			1753
$\gamma K^+ K^- \pi^+ \pi^-$	( 1.9 $\pm$ 0.5 ) $\times 10^{-4}$			1726
$\gamma K^+ K^- 2(\pi^+ \pi^-)$	$< 2.2$	$\times 10^{-4}$	CL=90%	1654
$\gamma 2(K^+ K^-)$	$< 4$	$\times 10^{-5}$	CL=90%	1499
$\gamma \rho \bar{\rho}$	( 3.9 $\pm$ 0.5 ) $\times 10^{-5}$		S=2.0	1586
$\gamma f_2(1950) \rightarrow \gamma \rho \bar{\rho}$	( 1.20 $\pm$ 0.22 ) $\times 10^{-5}$			—
$\gamma f_2(2150) \rightarrow \gamma \rho \bar{\rho}$	( 7.2 $\pm$ 1.8 ) $\times 10^{-6}$			—
$\gamma X(1835) \rightarrow \gamma \rho \bar{\rho}$	( 4.6 $^{+1.8}_{-4.0}$ ) $\times 10^{-6}$			—
$\gamma X \rightarrow \gamma \rho \bar{\rho}$	[ <i>ooaa</i> ] $< 2$	$\times 10^{-6}$	CL=90%	—
$\gamma \rho \bar{\rho} \pi^+ \pi^-$	( 2.8 $\pm$ 1.4 ) $\times 10^{-5}$			1491
$\gamma \gamma$	$< 1.5$	$\times 10^{-4}$	CL=90%	1843
$\gamma \gamma J/\psi$	( 3.1 $^{+1.0}_{-1.2}$ ) $\times 10^{-4}$			542
$e^+ e^- \eta'$	( 1.90 $\pm$ 0.26 ) $\times 10^{-6}$			1719
$e^+ e^- \eta_c(1S)$	( 3.8 $\pm$ 0.4 ) $\times 10^{-5}$			635
$e^+ e^- \chi_{c0}(1P)$	( 1.06 $\pm$ 0.25 ) $\times 10^{-3}$			261

$e^+ e^- \chi_{c1}(1P)$	$( 8.5 \pm 0.7 ) \times 10^{-4}$	171
$e^+ e^- \chi_{c2}(1P)$	$( 6.8 \pm 0.8 ) \times 10^{-4}$	128

**Weak decays**

$D^0 e^+ e^- + \text{c.c.}$	$< 1.4$	$\times 10^{-7}$	CL=90%	1371
$\Lambda_c^+ \bar{\Sigma}^- + \text{c.c.}$	$< 1.4$	$\times 10^{-5}$	CL=90%	586

**Other decays**

invisible	$< 1.6$	%	CL=90%	—
-----------	---------	---	--------	---

See Particle Listings for 3 decay modes that have been seen / not seen.

 **$\psi(3770)$** 

$$J^{PC} = 0^-(1^--)$$

Mass  $m = 3773.7 \pm 0.7$  MeV ( $S = 2.3$ )Full width  $\Gamma = 27.2 \pm 1.0$  MeV

$\psi(3770)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$D\bar{D}$	$(93 \frac{+8}{-9})\%$	S=2.0	287
$D^0\bar{D}^0$	$(52 \frac{+4}{-5})\%$	S=2.0	287
$D^+ D^-$	$(41 \pm 4)\%$	S=2.0	254
$J/\psi X$	$( 5.0 \pm 2.2 ) \times 10^{-3}$		—
$J/\psi \pi^+ \pi^-$	$( 1.93 \pm 0.28 ) \times 10^{-3}$		561
$J/\psi \pi^0 \pi^0$	$( 8.0 \pm 3.0 ) \times 10^{-4}$		565
$J/\psi \eta$	$( 8.7 \pm 1.2 ) \times 10^{-4}$		361
$J/\psi \pi^0$	$< 2.8$	$\times 10^{-4}$	CL=90% 604
$e^+ e^-$	$( 9.6 \pm 0.7 ) \times 10^{-6}$	S=1.3	1887

**Decays to light hadrons**

$b_1(1235)\pi$	$< 1.4$	$\times 10^{-5}$	CL=90%	1684
$\phi\eta'$	$< 2.3$	$\times 10^{-5}$	CL=90%	1607
$\omega\eta'$	$< 4$	$\times 10^{-4}$	CL=90%	1672
$\rho^0\eta'$	$< 6$	$\times 10^{-4}$	CL=90%	1674
$\phi\eta$	$( 3.1 \pm 0.7 ) \times 10^{-4}$			1703
$\omega\eta$	$< 1.4$	$\times 10^{-5}$	CL=90%	1762
$\rho^0\eta$	$< 5$	$\times 10^{-4}$	CL=90%	1764
$\phi\pi^0$	$< 3$	$\times 10^{-5}$	CL=90%	1746
$\omega\pi^0$	$< 6$	$\times 10^{-4}$	CL=90%	1803
$\pi^+ \pi^- \pi^0$	$< 5$	$\times 10^{-6}$	CL=90%	1874
$\rho\pi$	$< 5$	$\times 10^{-6}$	CL=90%	1805
$K^*(892)^+ K^- + \text{c.c.}$	$< 1.4$	$\times 10^{-5}$	CL=90%	1745
$K^*(892)^0 \bar{K}^0 + \text{c.c.}$	$< 1.2$	$\times 10^{-3}$	CL=90%	1745
$K_S^0 K_L^0$	$< 1.2$	$\times 10^{-5}$	CL=90%	1820
$2(\pi^+ \pi^-)$	$< 1.12$	$\times 10^{-3}$	CL=90%	1861
$2(\pi^+ \pi^-)\pi^0$	$< 1.06$	$\times 10^{-3}$	CL=90%	1844
$2(\pi^+ \pi^- \pi^0)$	$< 5.85$	%	CL=90%	1821
$\omega\pi^+ \pi^-$	$< 6.0$	$\times 10^{-4}$	CL=90%	1794
$3(\pi^+ \pi^-)$	$< 9.1$	$\times 10^{-3}$	CL=90%	1820
$3(\pi^+ \pi^-)\pi^0$	$< 1.37$	%	CL=90%	1792
$3(\pi^+ \pi^-)2\pi^0$	$< 11.74$	%	CL=90%	1760
$\eta\pi^+ \pi^-$	$< 1.24$	$\times 10^{-3}$	CL=90%	1836
$\pi^+ \pi^- 2\pi^0$	$< 8.9$	$\times 10^{-3}$	CL=90%	1862
$\rho^0\pi^+ \pi^-$	$< 6.9$	$\times 10^{-3}$	CL=90%	1796
$\eta 3\pi$	$< 1.34$	$\times 10^{-3}$	CL=90%	1824
$\eta 2(\pi^+ \pi^-)$	$< 2.43$	%	CL=90%	1804

$\eta\rho^0\pi^+\pi^-$	< 1.45	%	CL=90%	1708
$\eta'3\pi$	< 2.44	$\times 10^{-3}$	CL=90%	1741
$K^+K^-\pi^+\pi^-$	< 9.0	$\times 10^{-4}$	CL=90%	1773
$\phi\pi^+\pi^-$	< 4.1	$\times 10^{-4}$	CL=90%	1737
$K^+K^-2\pi^0$	< 4.2	$\times 10^{-3}$	CL=90%	1774
$4(\pi^+\pi^-)$	< 1.67	%	CL=90%	1757
$4(\pi^+\pi^-)\pi^0$	< 3.06	%	CL=90%	1720
$\phi f_0(980)$	< 4.5	$\times 10^{-4}$	CL=90%	1597
$K^+K^-\pi^+\pi^-\pi^0$	< 2.36	$\times 10^{-3}$	CL=90%	1741
$K^+K^-\rho^0\pi^0$	< 8	$\times 10^{-4}$	CL=90%	1624
$K^+K^-\rho^+\pi^-$	< 1.46	%	CL=90%	1623
$\omega K^+K^-$	< 3.4	$\times 10^{-4}$	CL=90%	1664
$\phi\pi^+\pi^-\pi^0$	< 3.8	$\times 10^{-3}$	CL=90%	1723
$K^{*0}K^-\pi^+\pi^0 + \text{c.c.}$	< 1.62	%	CL=90%	1694
$K^{*+}K^-\pi^+\pi^- + \text{c.c.}$	< 3.23	%	CL=90%	1693
$K^+K^-\pi^+\pi^-2\pi^0$	< 2.67	%	CL=90%	1705
$K^+K^-2(\pi^+\pi^-)$	< 1.03	%	CL=90%	1702
$K^+K^-2(\pi^+\pi^-)\pi^0$	< 3.60	%	CL=90%	1661
$\eta K^+K^-$	< 4.1	$\times 10^{-4}$	CL=90%	1712
$\eta K^+K^-\pi^+\pi^-$	< 1.24	%	CL=90%	1624
$\rho^0 K^+K^-$	< 5.0	$\times 10^{-3}$	CL=90%	1666
$2(K^+K^-)$	< 6.0	$\times 10^{-4}$	CL=90%	1552
$\phi K^+K^-$	< 7.5	$\times 10^{-4}$	CL=90%	1598
$2(K^+K^-)\pi^0$	< 2.9	$\times 10^{-4}$	CL=90%	1494
$2(K^+K^-)\pi^+\pi^-$	< 3.2	$\times 10^{-3}$	CL=90%	1426
$K_S^0 K^-\pi^+$	< 3.2	$\times 10^{-3}$	CL=90%	1799
$K_S^0 K^-\pi^+\pi^0$	< 1.33	%	CL=90%	1773
$K_S^0 K^-\rho^+$	< 6.6	$\times 10^{-3}$	CL=90%	1665
$K_S^0 K^-2\pi^+\pi^-$	< 8.7	$\times 10^{-3}$	CL=90%	1740
$K_S^0 K^-\pi^+\rho^0$	< 1.6	%	CL=90%	1621
$K_S^0 K^-\pi^+\eta$	< 1.3	%	CL=90%	1670
$K_S^0 K^-2\pi^+\pi^-\pi^0$	< 4.18	%	CL=90%	1703
$K_S^0 K^-2\pi^+\pi^-\eta$	< 4.8	%	CL=90%	1570
$K_S^0 K^-\pi^+2(\pi^+\pi^-)$	< 1.22	%	CL=90%	1658
$K_S^0 K^-\pi^+2\pi^0$	< 2.65	%	CL=90%	1742
$K_S^0 K^-K^+K^-\pi^+$	< 4.9	$\times 10^{-3}$	CL=90%	1491
$K_S^0 K^-K^+K^-\pi^+\pi^0$	< 3.0	%	CL=90%	1427
$K_S^0 K^-K^+K^-\pi^+\eta$	< 2.2	%	CL=90%	1214
$K^{*0}K^-\pi^+ + \text{c.c.}$	< 9.7	$\times 10^{-3}$	CL=90%	1722
$\rho\bar{\rho}\pi^0$	< 4	$\times 10^{-5}$	CL=90%	1595
$\rho\bar{\rho}\pi^+\pi^-$	< 5.8	$\times 10^{-4}$	CL=90%	1544
$\Lambda\bar{\Lambda}$	< 1.2	$\times 10^{-4}$	CL=90%	1522
$\rho\bar{\rho}\pi^+\pi^-\pi^0$	< 1.85	$\times 10^{-3}$	CL=90%	1490
$\omega\rho\bar{\rho}$	< 2.9	$\times 10^{-4}$	CL=90%	1310
$\Lambda\bar{\Lambda}\pi^0$	< 7	$\times 10^{-5}$	CL=90%	1469
$\rho\bar{\rho}2(\pi^+\pi^-)$	< 2.6	$\times 10^{-3}$	CL=90%	1426
$\eta\rho\bar{\rho}$	< 5.4	$\times 10^{-4}$	CL=90%	1431
$\eta\rho\bar{\rho}\pi^+\pi^-$	< 3.3	$\times 10^{-3}$	CL=90%	1284
$\rho^0\rho\bar{\rho}$	< 1.7	$\times 10^{-3}$	CL=90%	1314
$\rho\bar{\rho}K^+K^-$	< 3.2	$\times 10^{-4}$	CL=90%	1186
$\eta\rho\bar{\rho}K^+K^-$	< 6.9	$\times 10^{-3}$	CL=90%	737
$\pi^0\rho\bar{\rho}K^+K^-$	< 1.2	$\times 10^{-3}$	CL=90%	1094
$\phi\rho\bar{\rho}$	< 1.3	$\times 10^{-4}$	CL=90%	1178
$\Lambda\bar{\Lambda}\pi^+\pi^-$	< 2.5	$\times 10^{-4}$	CL=90%	1405



$\Lambda\bar{p}K^+$	< 2.8	$\times 10^{-4}$	CL=90%	1387
$\Lambda\bar{p}K^+\pi^+\pi^-$	< 6.3	$\times 10^{-4}$	CL=90%	1234
$\Lambda\bar{\Lambda}\eta$	< 1.9	$\times 10^{-4}$	CL=90%	1263
$\Sigma^+\bar{\Sigma}^-$	< 1.0	$\times 10^{-4}$	CL=90%	1465
$\Sigma^0\bar{\Sigma}^0$	< 4	$\times 10^{-5}$	CL=90%	1462
$\Xi^+\bar{\Xi}^-$	< 1.5	$\times 10^{-4}$	CL=90%	1347
$\Xi^0\bar{\Xi}^0$	< 1.4	$\times 10^{-4}$	CL=90%	1353
$\Xi^-\bar{\Xi}^+$	( 1.4 $\pm$ 0.4 )	$\times 10^{-4}$		1347

**Radiative decays**

$\gamma\chi_{c2}$	< 6.4	$\times 10^{-4}$	CL=90%	211
$\gamma\chi_{c1}$	( 2.49 $\pm$ 0.23 )	$\times 10^{-3}$		254
$\gamma\chi_{c0}$	( 6.9 $\pm$ 0.6 )	$\times 10^{-3}$		342
$\gamma\eta_c$	< 7	$\times 10^{-4}$	CL=90%	707
$\gamma\eta_c(2S)$	< 9	$\times 10^{-4}$	CL=90%	133
$\gamma\eta'$	< 1.8	$\times 10^{-4}$	CL=90%	1765
$\gamma\eta$	< 1.5	$\times 10^{-4}$	CL=90%	1847
$\gamma\pi^0$	< 2	$\times 10^{-4}$	CL=90%	1884

See Particle Listings for 2 decay modes that have been seen / not seen.

 **$\psi_2(3823)$** 

$$I^G(J^{PC}) = 0^-(2^{--})$$

$I, J, P$  need confirmation.

was  $\psi(3823), X(3823)$

Mass  $m = 3823.51 \pm 0.34$  MeV

Full width  $\Gamma < 2.9$  MeV, CL = 90%

Branching fractions are given relative to the one **DEFINED AS 1**.

<b><math>\psi_2(3823)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$J/\psi(1S)\pi^+\pi^-$	<0.06	90%	607
$J/\psi(1S)\pi^0\pi^0$	<0.11	90%	610
$J/\psi(1S)\pi^0$	<0.030	90%	646
$J/\psi(1S)\eta$	<0.14	90%	431
$\chi_{c0}\gamma$	<0.24	90%	387
$\chi_{c1}\gamma$	<b>DEFINED AS 1</b>		300
$\chi_{c2}\gamma$	0.28 $\begin{smallmatrix} +0.14 \\ -0.11 \end{smallmatrix}$		258

 **$\psi_3(3842)$** 

$$I^G(J^{PC}) = 0^-(3^{--})$$

$J, P$  need confirmation.

Seen by a single experiment only.

Mass  $m = 3842.71 \pm 0.20$  MeV

Full width  $\Gamma = 2.8 \pm 0.6$  MeV

 **$\chi_{c1}(3872)$** 

$$I^G(J^{PC}) = 0^+(1^{++})$$

also known as  $X(3872)$

Mass  $m = 3871.64 \pm 0.06$  MeV

$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$  MeV

Full width  $\Gamma = 1.19 \pm 0.21$  MeV ( $S = 1.1$ )

<b><math>\chi_{c1}(3872)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$e^+e^-$	< 2.7	$\times 10^{-7}$	90%

$\pi^+ \pi^- \pi^0$	$< 8 \times 10^{-3}$	90%	1924
$\pi^+ \pi^- J/\psi(1S)$	$(3.5 \pm 0.9) \%$		650
$\omega \eta_c(1S)$	$< 30 \%$	90%	368
$\rho(770)^0 J/\psi(1S)$	$(2.8 \pm 0.7) \%$		—
$\omega J/\psi(1S)$	$(4.1 \pm 1.4) \%$		†
$D^0 \bar{D}^0 \pi^0$	$(45 \pm 21) \%$		116
$\bar{D}^{*0} D^0$	$(34 \pm 12) \%$		†
$\gamma \gamma$	$< 10 \%$	90%	1936
$D^0 \bar{D}^0$	$< 26 \%$	90%	519
$D^+ D^-$	$< 17 \%$	90%	502
$\pi^0 \chi_{c2}$	$< 4 \%$	90%	273
$\pi^0 \chi_{c1}$	$(3.1^+_{-1.3}) \%$		319
$\pi^0 \chi_{c0}$	$< 13 \%$	90%	411
$\pi^+ \pi^- \eta_c(1S)$	$< 13 \%$	90%	745
$\pi^0 \pi^0 \chi_{c0}$	$< 6 \%$	90%	347
$\pi^+ \pi^- \chi_{c0}$	$< 2.0 \%$	90%	340
$\pi^+ \pi^- \chi_{c1}$	$< 7 \times 10^{-3}$	90%	218
$\rho \bar{p}$	$< 2.2 \times 10^{-5}$	95%	1693

**Radiative decays**

$\gamma D^+ D^-$	$< 3.5 \%$	90%	502
$\gamma \bar{D}^0 D^0$	$< 6 \%$	90%	519
$\gamma J/\psi$	$(7.8 \pm 2.9) \times 10^{-3}$		697
$\gamma \chi_{c1}$	$< 8 \times 10^{-3}$	90%	344
$\gamma \chi_{c2}$	$< 2.9 \%$	90%	303

**C-violating decays**

$\eta J/\psi$	$< 1.7 \%$	90%	491
---------------	------------	-----	-----

See Particle Listings for 3 decay modes that have been seen / not seen.

**$\chi_{c0}(3915)$**

$$I^G(J^{PC}) = 0^+(0^{++})$$

was X(3915)

$$\text{Mass } m = 3922.1 \pm 1.8 \text{ MeV } (S = 1.5)$$

$$\text{Full width } \Gamma = 20 \pm 4 \text{ MeV } (S = 1.1)$$

**$\chi_{c2}(3930)$**

$$I^G(J^{PC}) = 0^+(2^{++})$$

$$\text{Mass } m = 3922.5 \pm 1.0 \text{ MeV } (S = 1.7)$$

$$\text{Full width } \Gamma = 35.2 \pm 2.2 \text{ MeV } (S = 1.2)$$

**$\psi(4040)$  [ppa $\bar{a}$ ]**

$$I^G(J^{PC}) = 0^-(1^{--})$$

$$\text{Mass } m = 4040 \pm 4 \text{ MeV}$$

$$\text{Full width } \Gamma = 84 \pm 12 \text{ MeV}$$

Due to the complexity of the  $c\bar{c}$  threshold region, in this listing, “seen” (“not seen”) means that a cross section for the mode in question has been measured at effective  $\sqrt{s}$  near this particle’s central mass value, more (less) than  $2\sigma$  above zero, without regard to any peaking behavior in  $\sqrt{s}$  or absence thereof. See mode listing(s) for details and references.

<b><math>\psi(4040)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$e^+ e^-$	$(1.02 \pm 0.17) \times 10^{-5}$		2020

$J/\psi \pi^+ \pi^-$	< 4	$\times 10^{-3}$	90%	795
$J/\psi \pi^0 \pi^0$	< 2	$\times 10^{-3}$	90%	797
$J/\psi \eta$	$(5.2 \pm 0.7)$	$\times 10^{-3}$		676
$J/\psi \pi^0$	< 2.8	$\times 10^{-4}$	90%	824
$J/\psi \pi^+ \pi^- \pi^0$	< 2	$\times 10^{-3}$	90%	747
$\chi_{c1} \gamma$	< 3.4	$\times 10^{-3}$	90%	494
$\chi_{c2} \gamma$	< 5	$\times 10^{-3}$	90%	455
$\chi_{c1} \pi^+ \pi^- \pi^0$	< 1.1	%	90%	307
$\chi_{c2} \pi^+ \pi^- \pi^0$	< 3.2	%	90%	234
$h_c(1P) \pi^+ \pi^-$	< 3	$\times 10^{-3}$	90%	404
$\phi \pi^+ \pi^-$	< 3	$\times 10^{-3}$	90%	1880
$\Lambda \bar{\Lambda} \pi^+ \pi^-$	< 2.9	$\times 10^{-4}$	90%	1579
$\Lambda \bar{\Lambda} \pi^0$	< 9	$\times 10^{-5}$	90%	1636
$\Lambda \bar{\Lambda} \eta$	< 3.0	$\times 10^{-4}$	90%	1452
$\Lambda \bar{\Lambda}$	< 6	$\times 10^{-6}$	90%	1684
$\Sigma^+ \bar{\Sigma}^-$	< 1.3	$\times 10^{-4}$	90%	1632
$\Sigma^0 \bar{\Sigma}^0$	< 7	$\times 10^{-5}$	90%	1630
$\Xi^+ \bar{\Xi}^-$	< 1.6	$\times 10^{-4}$	90%	1527
$\Xi^0 \bar{\Xi}^0$	< 1.8	$\times 10^{-4}$	90%	1533
$\Xi^- \bar{\Xi}^+$	< 6	$\times 10^{-5}$	90%	1527
$\mu^+ \mu^-$	$(9 \pm 6)$	$\times 10^{-6}$		2017

See Particle Listings for 16 decay modes that have been seen / not seen.

**$\chi_{c1}(4140)$**

$$I^G(J^{PC}) = 0^+(1^{++})$$

was  $X(4140)$

$$\text{Mass } m = 4146.5 \pm 3.0 \text{ MeV} \quad (S = 1.3)$$

$$\text{Full width } \Gamma = 19^{+7}_{-5} \text{ MeV}$$

**$\psi(4160)$**  [ $ppaa$ ]

$$I^G(J^{PC}) = 0^-(1^{--})$$

$$\text{Mass } m = 4191 \pm 5 \text{ MeV}$$

$$\text{Full width } \Gamma = 69 \pm 10 \text{ MeV}$$

Due to the complexity of the  $c\bar{c}$  threshold region, in this listing, “seen” (“not seen”) means that a cross section for the mode in question has been measured at effective  $\sqrt{s}$  near this particle’s central mass value, more (less) than  $2\sigma$  above zero, without regard to any peaking behavior in  $\sqrt{s}$  or absence thereof. See mode listing(s) for details and references.

<b><math>\psi(4160)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$e^+ e^-$	$(6.9 \pm 3.3) \times 10^{-6}$		2096
$J/\psi \pi^+ \pi^-$	< 3	$\times 10^{-3}$	919
$J/\psi \pi^0 \pi^0$	< 3	$\times 10^{-3}$	921
$J/\psi K^+ K^-$	< 2	$\times 10^{-3}$	407
$J/\psi \eta$	< 8	$\times 10^{-3}$	821
$J/\psi \pi^0$	< 1	$\times 10^{-3}$	944
$J/\psi \eta'$	< 5	$\times 10^{-3}$	456
$J/\psi \pi^+ \pi^- \pi^0$	< 1	$\times 10^{-3}$	879
$\psi(2S) \pi^+ \pi^-$	< 4	$\times 10^{-3}$	395
$\chi_{c1} \gamma$	< 5	$\times 10^{-3}$	625
$\chi_{c2} \gamma$	< 1.3	%	587
$\chi_{c1} \pi^+ \pi^- \pi^0$	< 2	$\times 10^{-3}$	496
$\chi_{c2} \pi^+ \pi^- \pi^0$	< 8	$\times 10^{-3}$	444

$h_c(1P)\pi^+\pi^-$	< 5	$\times 10^{-3}$	90%	556
$h_c(1P)\pi^0\pi^0$	< 2	$\times 10^{-3}$	90%	560
$h_c(1P)\eta$	< 2	$\times 10^{-3}$	90%	348
$h_c(1P)\pi^0$	< 4	$\times 10^{-4}$	90%	600
$\phi\pi^+\pi^-$	< 2	$\times 10^{-3}$	90%	1961
$\gamma\chi_{c1}(3872)$	< 1.9	$\times 10^{-3}$	90%	307
$\gamma\chi_{c0}(3915) \rightarrow \gamma J/\psi\pi^+\pi^-$	< 1.36	$\times 10^{-4}$	90%	—
$\gamma X(3930) \rightarrow \gamma J/\psi\pi^+\pi^-$	< 1.18	$\times 10^{-4}$	90%	—
$\gamma X(3940) \rightarrow \gamma J/\psi\pi^+\pi^-$	< 1.47	$\times 10^{-4}$	90%	—
$\gamma\chi_{c0}(3915) \rightarrow \gamma\gamma J/\psi$	< 1.26	$\times 10^{-4}$	90%	—
$\gamma X(3930) \rightarrow \gamma\gamma J/\psi$	< 8.8	$\times 10^{-5}$	90%	—
$\gamma X(3940) \rightarrow \gamma\gamma J/\psi$	< 1.79	$\times 10^{-4}$	90%	—
$\Lambda\bar{\Lambda}$	< 1.5	$\times 10^{-6}$	90%	1774
$\Xi^-\Xi^+$	< 8	$\times 10^{-5}$	90%	1626
$pK^-\bar{\Lambda} + c.c.$	< 6	$\times 10^{-6}$	90%	1659

See Particle Listings for 21 decay modes that have been seen / not seen.

<b><math>\psi(4230)</math></b>	$I^G(J^{PC}) = 0^-(1^{--})$	
also known as $Y(4230)$ ; was $\psi(4260)$		
Mass $m = 4222.1 \pm 2.3$ MeV (S = 1.7)		
Full width $\Gamma = 49 \pm 7$ MeV (S = 3.4)		
<b><math>\psi(4230)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$\mu^+\mu^-$	$(3.1 \pm 2.8) \times 10^{-5}$	2107
See Particle Listings for 72 decay modes that have been seen / not seen.		

<b><math>\chi_{c1}(4274)</math></b>	$I^G(J^{PC}) = 0^+(1^{++})$
was $X(4274)$	
Mass $m = 4286^{+8}_{-9}$ MeV (S = 1.7)	
Full width $\Gamma = 51 \pm 7$ MeV	

<b><math>\psi(4360)</math></b>	$I^G(J^{PC}) = 0^-(1^{--})$
also known as $Y(4360)$ ; was $X(4360)$	
Mass $m = 4374 \pm 7$ MeV (S = 2.4)	
Full width $\Gamma = 118 \pm 12$ MeV (S = 2.1)	

<b><math>\psi(4415)</math> [<math>\rho\rho a\bar{a}</math>]</b>	$I^G(J^{PC}) = 0^-(1^{--})$
Mass $m = 4415 \pm 5$ MeV	
Full width $\Gamma = 110 \pm 22$ MeV (S = 2.3)	
Due to the complexity of the $c\bar{c}$ threshold region, in this listing, “seen” (“not seen”) means that a cross section for the mode in question has been measured at effective $\sqrt{s}$ near this particle’s central mass value, more (less) than $2\sigma$ above zero, without regard to any peaking behavior in $\sqrt{s}$ or absence thereof. See mode listing(s) for details and references.	

<b><math>\psi(4415)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$D^0 D^- \pi^+$ (excl. $D^*(2010)^+ D^-$ ) +c.c.	< 2.3 %	90%	—

$D\bar{D}_2^*(2460) \rightarrow D^0 D^- \pi^+ + \text{c.c.}$	$(10 \pm 4) \%$		—
$D^0 D^{*-} \pi^+ + \text{c.c.}$	$< 19 \%$		90% 918
$J/\psi \eta$	$< 6 \times 10^{-3}$		90% 1017
$\chi_{c1} \gamma$	$< 8 \times 10^{-4}$		90% 812
$\chi_{c2} \gamma$	$< 4 \times 10^{-3}$		90% 775
$\Lambda \bar{\Lambda}$	$< 3.1 \times 10^{-6}$		90% 1905
$\Xi^- \bar{\Xi}^+$	$< 4 \times 10^{-5}$		90% 1768
$pK^- \bar{\Lambda} + \text{c.c.}$	$< 6 \times 10^{-6}$		90% 1798
$e^+ e^-$	$(5.3 \pm 1.2) \times 10^{-6}$		2207
$\mu^+ \mu^-$	$(1.1 \pm 0.5) \times 10^{-5}$		2205

See Particle Listings for 18 decay modes that have been seen / not seen.

**$\psi(4660)$**

$$J^G(J^{PC}) = 0^-(1^{--})$$

also known as  $Y(4660)$ ; was  $X(4660)$

$$\text{Mass } m = 4641 \pm 10 \text{ MeV} \quad (S = 2.7)$$

$$\text{Full width } \Gamma = 73_{-11}^{+13} \text{ MeV} \quad (S = 1.7)$$

## $b\bar{b}$ MESONS (including possibly non- $q\bar{q}$ states)

**$\eta_b(1S)$**

$$J^G(J^{PC}) = 0^+(0^{-+})$$

$$\text{Mass } m = 9398.7 \pm 2.0 \text{ MeV} \quad (S = 1.5)$$

$$\text{Full width } \Gamma = 10_{-4}^{+5} \text{ MeV}$$

$\eta_b(1S)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\mu^+ \mu^-$	$< 9 \times 10^{-3}$	90%	4698
$\tau^+ \tau^-$	$< 8 \%$	90%	4350

See Particle Listings for 5 decay modes that have been seen / not seen.

**$\Upsilon(1S)$**

$$J^G(J^{PC}) = 0^-(1^{--})$$

$$\text{Mass } m = 9460.40 \pm 0.10 \text{ MeV}$$

$$\text{Full width } \Gamma = 54.02 \pm 1.25 \text{ keV}$$

$\Upsilon(1S)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$\tau^+ \tau^-$	$(2.60 \pm 0.10) \%$		4384
$e^+ e^-$	$(2.39 \pm 0.08) \%$		4730
$\mu^+ \mu^-$	$(2.48 \pm 0.04) \%$		4729

### Hadronic decays

$g g g$	$(81.7 \pm 0.7) \%$		—
$\gamma g g$	$(2.2 \pm 0.6) \%$		—
$\eta'(958)$ anything	$(2.94 \pm 0.24) \%$		—
$J/\psi(1S)$ anything	$(5.4 \pm 0.4) \times 10^{-4}$	$S=1.4$	4223
$J/\psi(1S) \eta_c$	$< 2.2 \times 10^{-6}$	CL=90%	3623
$J/\psi(1S) \chi_{c0}$	$< 3.4 \times 10^{-6}$	CL=90%	3429
$J/\psi(1S) \chi_{c1}$	$(3.9 \pm 1.2) \times 10^{-6}$		3382

$J/\psi(1S)\chi_{c2}$	< 1.4	$\times 10^{-6}$	CL=90%	3359
$J/\psi(1S)\eta_c(2S)$	< 2.2	$\times 10^{-6}$	CL=90%	3317
$J/\psi(1S)X(3940)$	< 5.4	$\times 10^{-6}$	CL=90%	3148
$J/\psi(1S)X(4160)$	< 5.4	$\times 10^{-6}$	CL=90%	3020
$X(4350)$ anything, $X \rightarrow J/\psi(1S)\phi$	< 8.1	$\times 10^{-6}$	CL=90%	-
$T_{c\bar{c}1}(3900)^\pm$ anything, $T_{c\bar{c}1} \rightarrow J/\psi(1S)\pi^\pm$	< 1.3	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(4200)^\pm$ anything, $Z_c \rightarrow J/\psi(1S)\pi^\pm$	< 6.0	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(4430)^\pm$ anything, $T_{c\bar{c}1} \rightarrow J/\psi(1S)\pi^\pm$	< 4.9	$\times 10^{-5}$	CL=90%	-
$X_{cs}^\pm$ anything, $X \rightarrow J/\psi K^\pm$	< 5.7	$\times 10^{-6}$	CL=90%	-
$\psi(4230)$ anything, $\psi \rightarrow J/\psi(1S)\pi^+\pi^-$	< 3.8	$\times 10^{-5}$	CL=90%	-
$\psi(4230)$ anything, $\psi \rightarrow J/\psi(1S)K^+K^-$	< 7.5	$\times 10^{-6}$	CL=90%	-
$\chi_{c1}(4140)$ anything, $\chi_{c1} \rightarrow J/\psi(1S)\phi$	< 5.2	$\times 10^{-6}$	CL=90%	-
$\chi_{c0}$ anything	< 4	$\times 10^{-3}$	CL=90%	-
$\chi_{c1}$ anything	$(1.90 \pm 0.35) \times 10^{-4}$			-
$\chi_{c1}(1P)X_{tetra}$	< 3.78	$\times 10^{-5}$	CL=90%	-
$\chi_{c2}$ anything	$(2.8 \pm 0.8) \times 10^{-4}$			-
$\psi(2S)$ anything	$(1.23 \pm 0.20) \times 10^{-4}$			-
$\psi(2S)\eta_c$	< 3.6	$\times 10^{-6}$	CL=90%	3345
$\psi(2S)\chi_{c0}$	< 6.5	$\times 10^{-6}$	CL=90%	3124
$\psi(2S)\chi_{c1}$	< 4.5	$\times 10^{-6}$	CL=90%	3070
$\psi(2S)\chi_{c2}$	< 2.1	$\times 10^{-6}$	CL=90%	3043
$\psi(2S)\eta_c(2S)$	< 3.2	$\times 10^{-6}$	CL=90%	2994
$\psi(2S)X(3940)$	< 2.9	$\times 10^{-6}$	CL=90%	2797
$\psi(2S)X(4160)$	< 2.9	$\times 10^{-6}$	CL=90%	2645
$\psi(4230)$ anything, $\psi \rightarrow \psi(2S)\pi^+\pi^-$	< 7.9	$\times 10^{-5}$	CL=90%	-
$\psi(4360)$ anything, $\psi \rightarrow \psi(2S)\pi^+\pi^-$	< 5.2	$\times 10^{-5}$	CL=90%	-
$\psi(4660)$ anything, $\psi \rightarrow \psi(2S)\pi^+\pi^-$	< 2.2	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4050)^\pm$ anything, $X \rightarrow \psi(2S)\pi^\pm$	< 8.8	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(4430)^\pm$ anything, $T_{c\bar{c}1} \rightarrow \psi(2S)\pi^\pm$	< 6.7	$\times 10^{-5}$	CL=90%	-
$\chi_{c1}(3872)$ anything	< 2.7	$\times 10^{-4}$	CL=90%	-
$T_{c\bar{c}1}(4200)^+ T_{c\bar{c}1}(4200)^-$	< 2.23	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(3900)^\pm T_{c\bar{c}1}(4200)^\mp$	< 8.1	$\times 10^{-6}$	CL=90%	-
$T_{c\bar{c}1}(3900)^+ T_{c\bar{c}1}(3900)^-$	< 1.8	$\times 10^{-6}$	CL=90%	-
$T_{c\bar{c}}(4050)^+ T_{c\bar{c}}(4050)^-$	< 1.58	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4250)^+ T_{c\bar{c}}(4250)^-$	< 2.66	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4050)^\pm T_{c\bar{c}}(4250)^\mp$	< 4.42	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}1}(4430)^+ T_{c\bar{c}1}(4430)^-$	< 2.03	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4055)^\pm T_{c\bar{c}}(4055)^\mp$	< 2.33	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4055)^\pm T_{c\bar{c}1}(4430)^\mp$	< 4.55	$\times 10^{-5}$	CL=90%	-
$\rho\pi$	< 3.68	$\times 10^{-6}$	CL=90%	4697
$\omega\pi^0$	< 3.90	$\times 10^{-6}$	CL=90%	4697
$\pi^+\pi^-$	< 5	$\times 10^{-4}$	CL=90%	4728
$K^+K^-$	< 5	$\times 10^{-4}$	CL=90%	4704

$\rho\bar{\rho}$	< 5	$\times 10^{-4}$	CL=90%	4636
$\pi^+\pi^-\pi^0$	( 2.1 $\pm$ 0.8 )	$\times 10^{-6}$		4725
$\phi K^+K^-$	( 2.4 $\pm$ 0.5 )	$\times 10^{-6}$		4623
$\omega\pi^+\pi^-$	( 4.5 $\pm$ 1.0 )	$\times 10^{-6}$		4694
$K^*(892)^0 K^-\pi^+ + \text{c.c.}$	( 4.4 $\pm$ 0.8 )	$\times 10^{-6}$		4667
$\phi f_2'(1525)$	< 1.63	$\times 10^{-6}$	CL=90%	4551
$\omega f_2(1270)$	< 1.79	$\times 10^{-6}$	CL=90%	4611
$\rho(770) a_2(1320)$	< 2.24	$\times 10^{-6}$	CL=90%	4605
$K^*(892)^0 K_2^*(1430)^0 + \text{c.c.}$	( 3.0 $\pm$ 0.8 )	$\times 10^{-6}$		4579
$K_1(1270)^\pm K^\mp$	< 2.41	$\times 10^{-6}$	CL=90%	4634
$K_1(1400)^\pm K^\mp$	( 1.0 $\pm$ 0.4 )	$\times 10^{-6}$		4613
$b_1(1235)^\pm \pi^\mp$	< 1.25	$\times 10^{-6}$	CL=90%	4649
$\pi^+\pi^-\pi^0\pi^0$	( 1.28 $\pm$ 0.30 )	$\times 10^{-5}$		4720
$K_S^0 K^+\pi^- + \text{c.c.}$	( 1.6 $\pm$ 0.4 )	$\times 10^{-6}$		4696
$K^*(892)^0 \bar{K}^0 + \text{c.c.}$	( 2.9 $\pm$ 0.9 )	$\times 10^{-6}$		4675
$K^*(892)^- K^+ + \text{c.c.}$	< 1.11	$\times 10^{-6}$	CL=90%	4675
$f_1(1285)$ anything	( 4.6 $\pm$ 3.1 )	$\times 10^{-3}$		-
$D^*(2010)^\pm$ anything	( 2.52 $\pm$ 0.20 )	%		-
$\underline{f}_1(1285) X_{tetra}$	< 6.24	$\times 10^{-5}$	CL=90%	-
${}^2H$ anything	( 2.85 $\pm$ 0.25 )	$\times 10^{-5}$		-
Sum of 100 exclusive modes	( 1.200 $\pm$ 0.017 )	%		-

## Radiative decays

$\gamma\pi^+\pi^-$	( 6.3 $\pm$ 1.8 )	$\times 10^{-5}$		4728
$\gamma\pi^0\pi^0$	( 1.7 $\pm$ 0.7 )	$\times 10^{-5}$		4728
$\gamma\pi\pi$ (S-wave)	( 4.6 $\pm$ 0.7 )	$\times 10^{-5}$		4728
$\gamma\pi^0\eta$	< 2.4	$\times 10^{-6}$	CL=90%	4713
$\gamma K^+K^-$	[ <i>qqaa</i> ] ( 1.14 $\pm$ 0.13 )	$\times 10^{-5}$		4704
$\gamma\rho\bar{\rho}$	[ <i>rraa</i> ] < 6	$\times 10^{-6}$	CL=90%	4636
$\gamma 2h^+2h^-$	( 7.0 $\pm$ 1.5 )	$\times 10^{-4}$		4720
$\gamma 3h^+3h^-$	( 5.4 $\pm$ 2.0 )	$\times 10^{-4}$		4703
$\gamma 4h^+4h^-$	( 7.4 $\pm$ 3.5 )	$\times 10^{-4}$		4679
$\gamma\pi^+\pi^-K^+K^-$	( 2.9 $\pm$ 0.9 )	$\times 10^{-4}$		4686
$\gamma 2\pi^+2\pi^-$	( 2.5 $\pm$ 0.9 )	$\times 10^{-4}$		4720
$\gamma 3\pi^+3\pi^-$	( 2.5 $\pm$ 1.2 )	$\times 10^{-4}$		4703
$\gamma 2\pi^+2\pi^-K^+K^-$	( 2.4 $\pm$ 1.2 )	$\times 10^{-4}$		4659
$\gamma\pi^+\pi^-\rho\bar{\rho}$	( 1.5 $\pm$ 0.6 )	$\times 10^{-4}$		4604
$\gamma 2\pi^+2\pi^-\rho\bar{\rho}$	( 4 $\pm$ 6 )	$\times 10^{-5}$		4563
$\gamma 2K^+2K^-$	( 2.0 $\pm$ 2.0 )	$\times 10^{-5}$		4601
$\gamma\eta'(958)$	< 1.9	$\times 10^{-6}$	CL=90%	4682
$\gamma\eta$	< 1.0	$\times 10^{-6}$	CL=90%	4714
$\gamma f_0(980)$	< 3	$\times 10^{-5}$	CL=90%	4678
$\gamma f_2'(1525)$	( 2.9 $\pm$ 0.6 )	$\times 10^{-5}$		4609
$\gamma f_2(1270)$	( 1.01 $\pm$ 0.06 )	$\times 10^{-4}$		4644
$\gamma\eta(1405)$	< 8.2	$\times 10^{-5}$	CL=90%	4625
$\gamma f_0(1500)$	< 1.5	$\times 10^{-5}$	CL=90%	4608
$\gamma f_0(1500) \rightarrow \gamma K^+K^-$	( 1.0 $\pm$ 0.4 )	$\times 10^{-5}$		-
$\gamma f_0(1710)$	< 2.6	$\times 10^{-4}$	CL=90%	4571
$\gamma f_0(1710) \rightarrow \gamma K^+K^-$	( 1.01 $\pm$ 0.32 )	$\times 10^{-5}$		-
$\gamma f_0(1710) \rightarrow \gamma\pi^+\pi^-$	( 5.3 $\pm$ 2.0 )	$\times 10^{-6}$		-
$\gamma f_0(1710) \rightarrow \gamma\pi^0\pi^0$	< 1.4	$\times 10^{-6}$	CL=90%	-
$\gamma f_0(1710) \rightarrow \gamma\eta\eta$	< 1.8	$\times 10^{-6}$	CL=90%	-
$\gamma f_4(2050)$	< 5.3	$\times 10^{-5}$	CL=90%	4515
$\gamma f_0(2200) \rightarrow \gamma K^+K^-$	< 2	$\times 10^{-4}$	CL=90%	4475
$\gamma f_J(2220) \rightarrow \gamma K^+K^-$	< 8	$\times 10^{-7}$	CL=90%	4469

$\gamma f_J(2220) \rightarrow \gamma \pi^+ \pi^-$	< 6	$\times 10^{-7}$	CL=90%	—
$\gamma f_J(2220) \rightarrow \gamma p \bar{p}$	< 1.1	$\times 10^{-6}$	CL=90%	—
$\gamma \eta(2225) \rightarrow \gamma \phi \phi$	< 3	$\times 10^{-3}$	CL=90%	4469
$\gamma \eta_c(1S)$	< 2.9	$\times 10^{-5}$	CL=90%	4260
$\gamma \eta_c(2S)$	< 4	$\times 10^{-4}$	CL=90%	4031
$\gamma \chi_{c0}$	< 6.6	$\times 10^{-5}$	CL=90%	4114
$\gamma \chi_{c1}$	( 4.7 $\begin{smallmatrix} +2.4 \\ -1.9 \end{smallmatrix}$ )	$\times 10^{-5}$		4079
$\gamma \chi_{c2}$	< 7.6	$\times 10^{-6}$	CL=90%	4062
$\gamma \chi_{c1}(3872)$	< 5	$\times 10^{-5}$	CL=90%	3938
$\gamma \chi_{c1}(3872), \chi_{c1} \rightarrow \pi^+ \pi^- \pi^0 J/\psi$	< 2.8	$\times 10^{-6}$	CL=90%	—
$\gamma \chi_{c0}(3915) \rightarrow \omega J/\psi$	< 3.0	$\times 10^{-6}$	CL=90%	—
$\gamma \chi_{c1}(4140) \rightarrow \phi J/\psi$	< 2.2	$\times 10^{-6}$	CL=90%	—
$\gamma X \bar{X} (m_X < 3.1 \text{ GeV})$	[ssaa] < 1	$\times 10^{-3}$	CL=90%	—
$\gamma X \bar{X} (m_X < 4.5 \text{ GeV})$	[ttaa] < 2.4	$\times 10^{-4}$	CL=90%	—
$\gamma X \rightarrow \gamma + \geq 4 \text{ prongs}$	[uuaa] < 1.78	$\times 10^{-4}$	CL=95%	—
$\gamma A^0 \rightarrow \gamma \mu^+ \mu^-$	[vvaa] < 9	$\times 10^{-6}$	CL=90%	—
$\gamma A^0 \rightarrow \gamma \tau^+ \tau^-$	[qqaa] < 1.30	$\times 10^{-4}$	CL=90%	—
$\gamma A^0 \rightarrow \gamma g g$	[xxaa] < 1	%	CL=90%	—
$\gamma A^0 \rightarrow \gamma S \bar{S}$	[xxaa] < 1	$\times 10^{-3}$	CL=90%	—

### Lepton Family number (LF) violating modes

$e^\pm \mu^\mp$	LF	< 3.9	$\times 10^{-7}$	CL=90%	4730
$\mu^\pm \tau^\mp$	LF	< 2.7	$\times 10^{-6}$	CL=90%	4563
$e^\pm \tau^\mp$	LF	< 2.7	$\times 10^{-6}$	CL=90%	4563
$\gamma e^\pm \mu^\mp$	LF	< 4.2	$\times 10^{-7}$	CL=90%	4730
$\gamma \mu^\pm \tau^\mp$	LF	< 6.1	$\times 10^{-6}$	CL=90%	4563
$\gamma e^\pm \tau^\mp$	LF	< 6.5	$\times 10^{-6}$	CL=90%	4563

### Other decays

invisible	< 3.0	$\times 10^{-4}$	CL=90%	—
hadrons	(96 $\pm 4$ ) %			—

**$\chi_{b0}(1P)$  [yyaa]**

$$I^G(J^{PC}) = 0^+(0^{++})$$

$J$  needs confirmation.

$$\text{Mass } m = 9859.44 \pm 0.42 \pm 0.31 \text{ MeV}$$

$\chi_{b0}(1P)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\gamma \Upsilon(1S)$	( 1.94 $\pm 0.27$ ) %		391
$D^0 X$	< 10.4	%	90%
$\pi^+ \pi^- K^+ K^- \pi^0$	< 1.6	$\times 10^{-4}$	90%
$2\pi^+ \pi^- K^- K_S^0$	< 5	$\times 10^{-5}$	90%
$2\pi^+ \pi^- K^- K_S^0 2\pi^0$	< 5	$\times 10^{-4}$	90%
$2\pi^+ 2\pi^- 2\pi^0$	< 2.1	$\times 10^{-4}$	90%
$2\pi^+ 2\pi^- K^+ K^-$	( 1.1 $\pm 0.6$ )	$\times 10^{-4}$	
$2\pi^+ 2\pi^- K^+ K^- \pi^0$	< 2.7	$\times 10^{-4}$	90%
$2\pi^+ 2\pi^- K^+ K^- 2\pi^0$	< 5	$\times 10^{-4}$	90%
$3\pi^+ 2\pi^- K^- K_S^0 \pi^0$	< 1.6	$\times 10^{-4}$	90%
$3\pi^+ 3\pi^-$	< 8	$\times 10^{-5}$	90%
$3\pi^+ 3\pi^- 2\pi^0$	< 6	$\times 10^{-4}$	90%
$3\pi^+ 3\pi^- K^+ K^-$	( 2.4 $\pm 1.2$ )	$\times 10^{-4}$	
$3\pi^+ 3\pi^- K^+ K^- \pi^0$	< 1.0	$\times 10^{-3}$	90%
$4\pi^+ 4\pi^-$	< 8	$\times 10^{-5}$	90%



$4\pi^+ 4\pi^- 2\pi^0$	< 2.1	$\times 10^{-3}$	90%	4850
$J/\psi J/\psi$	< 7	$\times 10^{-5}$	90%	3836
$J/\psi \psi(2S)$	< 1.2	$\times 10^{-4}$	90%	3571
$\psi(2S)\psi(2S)$	< 3.1	$\times 10^{-5}$	90%	3273
$J/\psi(1S)$ anything	< 2.3	$\times 10^{-3}$	90%	—

 **$\chi_{b1}(1P)$**  [yyaa]

$$J^G(J^{PC}) = 0^+(1^{++})$$

 $J$  needs confirmation.

Mass  $m = 9892.78 \pm 0.26 \pm 0.31$  MeV

<b><math>\chi_{b1}(1P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\gamma \Upsilon(1S)$	(35.2 $\pm$ 2.0) %		423
$D^0 X$	(12.6 $\pm$ 2.2) %		—
$\pi^+ \pi^- K^+ K^- \pi^0$	( 2.0 $\pm$ 0.6) $\times 10^{-4}$		4892
$2\pi^+ \pi^- K^- K_S^0$	( 1.3 $\pm$ 0.5) $\times 10^{-4}$		4892
$2\pi^+ \pi^- K^- K_S^0 2\pi^0$	< 6 $\times 10^{-4}$	90%	4863
$2\pi^+ 2\pi^- 2\pi^0$	( 8.0 $\pm$ 2.5) $\times 10^{-4}$		4921
$2\pi^+ 2\pi^- K^+ K^-$	( 1.5 $\pm$ 0.5) $\times 10^{-4}$		4878
$2\pi^+ 2\pi^- K^+ K^- \pi^0$	( 3.5 $\pm$ 1.2) $\times 10^{-4}$		4863
$2\pi^+ 2\pi^- K^+ K^- 2\pi^0$	( 8.6 $\pm$ 3.2) $\times 10^{-4}$		4845
$3\pi^+ 2\pi^- K^- K_S^0 \pi^0$	( 9.3 $\pm$ 3.3) $\times 10^{-4}$		4844
$3\pi^+ 3\pi^-$	( 1.9 $\pm$ 0.6) $\times 10^{-4}$		4921
$3\pi^+ 3\pi^- 2\pi^0$	( 1.7 $\pm$ 0.5) $\times 10^{-3}$		4898
$3\pi^+ 3\pi^- K^+ K^-$	( 2.6 $\pm$ 0.8) $\times 10^{-4}$		4844
$3\pi^+ 3\pi^- K^+ K^- \pi^0$	( 7.5 $\pm$ 2.6) $\times 10^{-4}$		4825
$4\pi^+ 4\pi^-$	( 2.6 $\pm$ 0.9) $\times 10^{-4}$		4897
$4\pi^+ 4\pi^- 2\pi^0$	( 1.4 $\pm$ 0.6) $\times 10^{-3}$		4867
$\omega$ anything	( 4.9 $\pm$ 1.4) %		—
$\omega X_{tetra}$	< 4.44 $\times 10^{-4}$	90%	—
$J/\psi J/\psi$	< 2.7 $\times 10^{-5}$	90%	3857
$J/\psi \psi(2S)$	< 1.7 $\times 10^{-5}$	90%	3594
$\psi(2S)\psi(2S)$	< 6 $\times 10^{-5}$	90%	3298
$J/\psi(1S)$ anything	< 1.1 $\times 10^{-3}$	90%	—
$J/\psi(1S) X_{tetra}$	< 2.27 $\times 10^{-4}$	90%	—

 **$h_b(1P)$** 

$$J^G(J^{PC}) = 0^-(1^{+-})$$

Mass  $m = 9899.3 \pm 0.8$  MeV

<b><math>h_b(1P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$\eta_b(1S)\gamma$	(52 $^{+6}_{-5}$ ) %	488

 **$\chi_{b2}(1P)$**  [yyaa]

$$J^G(J^{PC}) = 0^+(2^{++})$$

 $J$  needs confirmation.

Mass  $m = 9912.21 \pm 0.26 \pm 0.31$  MeV

<b><math>\chi_{b2}(1P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\gamma \Upsilon(1S)$	(18.0 $\pm$ 1.0) %		442
$D^0 X$	< 7.9 %	90%	—

$\pi^+ \pi^- K^+ K^- \pi^0$	$( 8 \pm 5 ) \times 10^{-5}$		4902
$2\pi^+ \pi^- K^- K_S^0$	$< 1.0 \times 10^{-4}$	90%	4901
$2\pi^+ \pi^- K^- K_S^0 2\pi^0$	$( 5.3 \pm 2.4 ) \times 10^{-4}$		4873
$2\pi^+ 2\pi^- 2\pi^0$	$( 3.5 \pm 1.4 ) \times 10^{-4}$		4931
$2\pi^+ 2\pi^- K^+ K^-$	$( 1.1 \pm 0.4 ) \times 10^{-4}$		4888
$2\pi^+ 2\pi^- K^+ K^- \pi^0$	$( 2.1 \pm 0.9 ) \times 10^{-4}$		4872
$2\pi^+ 2\pi^- K^+ K^- 2\pi^0$	$( 3.9 \pm 1.8 ) \times 10^{-4}$		4855
$3\pi^+ 2\pi^- K^- K_S^0 \pi^0$	$< 5 \times 10^{-4}$	90%	4854
$3\pi^+ 3\pi^-$	$( 7.0 \pm 3.1 ) \times 10^{-5}$		4931
$3\pi^+ 3\pi^- 2\pi^0$	$( 1.0 \pm 0.4 ) \times 10^{-3}$		4908
$3\pi^+ 3\pi^- K^+ K^-$	$< 8 \times 10^{-5}$	90%	4854
$3\pi^+ 3\pi^- K^+ K^- \pi^0$	$( 3.6 \pm 1.5 ) \times 10^{-4}$		4835
$4\pi^+ 4\pi^-$	$( 8 \pm 4 ) \times 10^{-5}$		4907
$4\pi^+ 4\pi^- 2\pi^0$	$( 1.8 \pm 0.7 ) \times 10^{-3}$		4877
$J/\psi J/\psi$	$< 4 \times 10^{-5}$	90%	3869
$J/\psi \psi(2S)$	$< 5 \times 10^{-5}$	90%	3608
$\psi(2S) \psi(2S)$	$< 1.6 \times 10^{-5}$	90%	3313
$J/\psi(1S)$ anything	$( 1.5 \pm 0.4 ) \times 10^{-3}$		—

**$\Upsilon(2S)$**

$$I^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 10023.4 \pm 0.5$  MeV

$m_{\Upsilon(3S)} - m_{\Upsilon(2S)} = 331.50 \pm 0.13$  MeV

Full width  $\Gamma = 31.98 \pm 2.63$  keV

<b><math>\Upsilon(2S)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$\Upsilon(1S) \pi^+ \pi^-$	$(17.85 \pm 0.26) \%$		475
$\Upsilon(1S) \pi^0 \pi^0$	$( 8.6 \pm 0.4 ) \%$		480
$\tau^+ \tau^-$	$( 2.00 \pm 0.21 ) \%$		4686
$\mu^+ \mu^-$	$( 1.93 \pm 0.17 ) \%$	S=2.2	5011
$e^+ e^-$	$( 1.91 \pm 0.16 ) \%$		5012
$\Upsilon(1S) \pi^0$	$< 4 \times 10^{-5}$	CL=90%	531
$\Upsilon(1S) \eta$	$( 2.9 \pm 0.4 ) \times 10^{-4}$	S=2.0	126
$J/\psi(1S)$ anything	$< 6 \times 10^{-3}$	CL=90%	4533
$J/\psi(1S) \eta_c$	$< 5.4 \times 10^{-6}$	CL=90%	3984
$J/\psi(1S) \chi_{c0}$	$< 3.4 \times 10^{-6}$	CL=90%	3808
$J/\psi(1S) \chi_{c1}$	$< 1.2 \times 10^{-6}$	CL=90%	3765
$J/\psi(1S) \chi_{c2}$	$< 2.0 \times 10^{-6}$	CL=90%	3745
$J/\psi(1S) \eta_c(2S)$	$< 2.5 \times 10^{-6}$	CL=90%	3707
$J/\psi(1S) X(3940)$	$< 2.0 \times 10^{-6}$	CL=90%	3555
$J/\psi(1S) X(4160)$	$< 2.0 \times 10^{-6}$	CL=90%	3442
$\chi_{c1}$ anything	$( 2.2 \pm 0.5 ) \times 10^{-4}$		—
$\chi_{c1}(1P)^0 X_{tetra}$	$< 3.67 \times 10^{-5}$	CL=90%	—
$\chi_{c2}$ anything	$( 2.3 \pm 0.8 ) \times 10^{-4}$		—
$\psi(2S) \eta_c$	$< 5.1 \times 10^{-6}$	CL=90%	3732
$\psi(2S) \chi_{c0}$	$< 4.7 \times 10^{-6}$	CL=90%	3536
$\psi(2S) \chi_{c1}$	$< 2.5 \times 10^{-6}$	CL=90%	3488
$\psi(2S) \chi_{c2}$	$< 1.9 \times 10^{-6}$	CL=90%	3464
$\psi(2S) \eta_c(2S)$	$< 3.3 \times 10^{-6}$	CL=90%	3422
$\psi(2S) X(3940)$	$< 3.9 \times 10^{-6}$	CL=90%	3250
$\psi(2S) X(4160)$	$< 3.9 \times 10^{-6}$	CL=90%	3120
$T_{c\bar{c}1}(3900)^+ T_{c\bar{c}1}(3900)^-$	$< 1.0 \times 10^{-6}$	CL=90%	—
$T_{c\bar{c}1}(4200)^+ T_{c\bar{c}1}(4200)^-$	$< 1.67 \times 10^{-5}$	CL=90%	—
$T_{c\bar{c}1}(3900)^\pm T_{c\bar{c}1}(4200)^\mp$	$< 7.3 \times 10^{-6}$	CL=90%	—

$T_{c\bar{c}}(4050)^+ T_{c\bar{c}}(4050)^-$	$< 1.35$	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4250)^+ T_{c\bar{c}}(4250)^-$	$< 2.67$	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4050)^\pm T_{c\bar{c}}(4250)^\mp$	$< 2.72$	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}\tau_1}(4430)^+ T_{c\bar{c}\tau_1}(4430)^-$	$< 2.03$	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4055)^\pm T_{c\bar{c}}(4055)^\mp$	$< 1.11$	$\times 10^{-5}$	CL=90%	-
$T_{c\bar{c}}(4055)^\pm T_{c\bar{c}\tau_1}(4430)^\mp$	$< 2.11$	$\times 10^{-5}$	CL=90%	-
${}^2\bar{H}$ anything	$(2.78^+_{-0.26})$	$\times 10^{-5}$	S=1.2	-
hadrons	$(94 \pm 11)$	%		-
$g g g$	$(58.8 \pm 1.2)$	%		-
$\gamma g g$	$(1.87 \pm 0.28)$	%		-
$\phi K^+ K^-$	$(1.6 \pm 0.4)$	$\times 10^{-6}$		4910
$\omega \pi^+ \pi^-$	$< 2.58$	$\times 10^{-6}$	CL=90%	4977
$K^*(892)^0 K^- \pi^+ + \text{c.c.}$	$(2.3 \pm 0.7)$	$\times 10^{-6}$		4952
$\phi f'_2(1525)$	$< 1.33$	$\times 10^{-6}$	CL=90%	4843
$\omega f_2(1270)$	$< 5.7$	$\times 10^{-7}$	CL=90%	4899
$\rho(770) a_2(1320)$	$< 8.8$	$\times 10^{-7}$	CL=90%	4894
$K^*(892)^0 K_2^*(1430)^0 + \text{c.c.}$	$(1.5 \pm 0.6)$	$\times 10^{-6}$		4869
$K_1(1270)^\pm K^\mp$	$< 3.22$	$\times 10^{-6}$	CL=90%	4921
$K_1(1400)^\pm K^\mp$	$< 8.3$	$\times 10^{-7}$	CL=90%	4901
$b_1(1235)^\pm \pi^\mp$	$< 4.0$	$\times 10^{-7}$	CL=90%	4935
$\rho \pi$	$< 1.16$	$\times 10^{-6}$	CL=90%	4981
$\pi^+ \pi^- \pi^0$	$< 8.0$	$\times 10^{-7}$	CL=90%	5007
$\omega \pi^0$	$< 1.63$	$\times 10^{-6}$	CL=90%	4980
$\pi^+ \pi^- \pi^0 \pi^0$	$(1.30 \pm 0.28)$	$\times 10^{-5}$		5002
$K_S^0 K^+ \pi^- + \text{c.c.}$	$(1.14 \pm 0.33)$	$\times 10^{-6}$		4979
$K^*(892)^0 \bar{K}^0 + \text{c.c.}$	$< 4.22$	$\times 10^{-6}$	CL=90%	4959
$K^*(892)^- K^+ + \text{c.c.}$	$< 1.45$	$\times 10^{-6}$	CL=90%	4960
$f_1(1285)$ anything	$(2.2 \pm 1.6)$	$\times 10^{-3}$		-
$f_1(1285) X_{tetra}$	$< 6.47$	$\times 10^{-5}$	CL=90%	-
$D_s^+ D_{s1}(2536)^-, D_{s1}^- \rightarrow$ $K^- D^*(2007)^0$	$(1.6 \pm 0.4)$	$\times 10^{-5}$		-
$D_s^+ D_{s1}(2536)^-, D_{s1}^- \rightarrow$ $K_S^0 D^*(2010)^-$	$(8.4 \pm 2.3)$	$\times 10^{-6}$		-
$D_s^{*+} D_{s1}(2536)^-, D_{s1}^- \rightarrow$ $K^- D^*(2007)^0$	$(1.4 \pm 0.4)$	$\times 10^{-5}$		-
$D_s^{*+} D_{s1}(2536)^-, D_{s1}^- \rightarrow$ $K_S^0 D^*(2010)^-$	$(8.2 \pm 3.1)$	$\times 10^{-6}$		-
$D_s^+ D_{s2}^*(2573)^-, D_{s2}^{*-} \rightarrow$ $K^- D^0$	$(1.4 \pm 0.4)$	$\times 10^{-5}$		-
$D_s^+ D_{s2}^*(2573)^-, D_{s2}^{*-} \rightarrow$ $K_S^0 D^-$	$(6.9 \pm 3.0)$	$\times 10^{-6}$		-
$D_s^{*+} D_{s2}^*(2573)^-, D_{s2}^{*-} \rightarrow$ $K^- D^0$	$(9 \pm 5)$	$\times 10^{-6}$		-
$D_s^{*+} D_{s2}^*(2573)^-, D_{s2}^{*-} \rightarrow$ $K_S^0 D^-$	$(5 \pm 6)$	$\times 10^{-6}$		-
Sum of 100 exclusive modes	$(2.90 \pm 0.30)$	$\times 10^{-3}$		-
<b>Radiative decays</b>				
$\gamma \chi_{b1}(1P)$	$(6.9 \pm 0.4)$	%		130
$\gamma \chi_{b2}(1P)$	$(7.15 \pm 0.35)$	%		111
$\gamma \chi_{b0}(1P)$	$(3.8 \pm 0.4)$	%		163
$\gamma f_0(1710)$	$< 5.9$	$\times 10^{-4}$	CL=90%	4862
$\gamma f'_2(1525)$	$< 5.3$	$\times 10^{-4}$	CL=90%	4897

$\gamma f_2(1270)$	< 2.41	$\times 10^{-4}$	CL=90%	4931
$\gamma \eta_c(1S)$	< 2.7	$\times 10^{-5}$	CL=90%	4568
$\gamma \chi_{c0}$	< 1.0	$\times 10^{-4}$	CL=90%	4430
$\gamma \chi_{c1}$	< 3.6	$\times 10^{-6}$	CL=90%	4397
$\gamma \chi_{c2}$	< 1.5	$\times 10^{-5}$	CL=90%	4381
$\gamma \chi_{c1}(3872)$	< 2.3	$\times 10^{-5}$	CL=90%	4264
$\gamma \chi_{c1}(3872), \chi_{c1} \rightarrow \pi^+ \pi^- \pi^0 J/\psi$	< 2.4	$\times 10^{-6}$	CL=90%	—
$\gamma \chi_{c0}(3915) \rightarrow \omega J/\psi$	< 2.8	$\times 10^{-6}$	CL=90%	—
$\gamma \chi_{c1}(4140) \rightarrow \phi J/\psi$	< 1.2	$\times 10^{-6}$	CL=90%	—
$\gamma X(4350) \rightarrow \phi J/\psi$	< 1.3	$\times 10^{-6}$	CL=90%	—
$\gamma \eta_b(1S)$	$(5.5 \pm_{-0.9}^{+1.1}) \times 10^{-4}$		S=1.2	605
$\gamma \eta_b(1S) \rightarrow \gamma$ Sum of 26 exclusive modes	< 3.7	$\times 10^{-6}$	CL=90%	—
$\gamma X_{b\bar{D}} \rightarrow \gamma$ Sum of 26 exclusive modes	< 4.9	$\times 10^{-6}$	CL=90%	—
$\gamma X \rightarrow \gamma + \geq 4$ prongs	[zzaa] < 1.95	$\times 10^{-4}$	CL=95%	—
$\gamma A^0 \rightarrow \gamma$ hadrons	< 8	$\times 10^{-5}$	CL=90%	—
$\gamma A^0 \rightarrow \gamma \mu^+ \mu^-$	< 8.3	$\times 10^{-6}$	CL=90%	—
<b>Lepton Family number (LF) violating modes</b>				
$e^\pm \tau^\mp$	LF	< 3.2	$\times 10^{-6}$	CL=90% 4854
$\mu^\pm \tau^\mp$	LF	< 3.3	$\times 10^{-6}$	CL=90% 4854

**$\Upsilon_2(1D)$**

$$I^{G(J^{PC})} = 0^-(2^{--})$$

was  $\Upsilon(1D)$ 

$$\text{Mass } m = 10163.7 \pm 1.4 \text{ MeV} \quad (S = 1.7)$$

 **$\Upsilon_2(1D)$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ ) $\rho$  (MeV/c)

$\pi^+ \pi^- \Upsilon(1S)$	$(6.6 \pm 1.6) \times 10^{-3}$	623
----------------------------	--------------------------------	-----

See Particle Listings for 3 decay modes that have been seen / not seen.

**$\chi_{b0}(2P)$**  [yyaa]

$$I^{G(J^{PC})} = 0^+(0^{++})$$

 $J$  needs confirmation.

$$\text{Mass } m = 10232.5 \pm 0.4 \pm 0.5 \text{ MeV}$$

 **$\chi_{b0}(2P)$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ )

Confidence level

 $\rho$  (MeV/c)

$\gamma \Upsilon(2S)$	$(1.38 \pm 0.30) \%$		207
$\gamma \Upsilon(1S)$	$(3.8 \pm 1.7) \times 10^{-3}$		743
$D^0 X$	< 8.2	%	90% —
$\pi^+ \pi^- K^+ K^- \pi^0$	< 3.4	$\times 10^{-5}$	90% 5064
$2\pi^+ \pi^- K^- K_S^0$	< 5	$\times 10^{-5}$	90% 5063
$2\pi^+ \pi^- K^- K_S^0 2\pi^0$	< 2.2	$\times 10^{-4}$	90% 5036
$2\pi^+ 2\pi^- 2\pi^0$	< 2.4	$\times 10^{-4}$	90% 5092
$2\pi^+ 2\pi^- K^+ K^-$	< 1.5	$\times 10^{-4}$	90% 5050
$2\pi^+ 2\pi^- K^+ K^- \pi^0$	< 2.2	$\times 10^{-4}$	90% 5035
$2\pi^+ 2\pi^- K^+ K^- 2\pi^0$	< 1.1	$\times 10^{-3}$	90% 5019
$3\pi^+ 2\pi^- K^- K_S^0 \pi^0$	< 7	$\times 10^{-4}$	90% 5018
$3\pi^+ 3\pi^-$	< 7	$\times 10^{-5}$	90% 5091
$3\pi^+ 3\pi^- 2\pi^0$	< 1.2	$\times 10^{-3}$	90% 5070

$3\pi^+ 3\pi^- K^+ K^-$	< 1.5	$\times 10^{-4}$	90%	5017
$3\pi^+ 3\pi^- K^+ K^- \pi^0$	< 7	$\times 10^{-4}$	90%	4999
$4\pi^+ 4\pi^-$	< 1.7	$\times 10^{-4}$	90%	5069
$4\pi^+ 4\pi^- 2\pi^0$	< 6	$\times 10^{-4}$	90%	5039

 **$\chi_{b1}(2P)$**  [yyaa]

$$I^G(J^{PC}) = 0^+(1^{++})$$

 $J$  needs confirmation.

Mass  $m = 10255.46 \pm 0.22 \pm 0.50$  MeV

$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)} = 23.5 \pm 1.0$  MeV

<b><math>\chi_{b1}(2P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$\omega \Upsilon(1S)$	( 1.63 <sup>+0.40</sup> <sub>-0.34</sub> ) %	134
$\gamma \Upsilon(2S)$	(18.1 $\pm$ 1.9 ) %	229
$\gamma \Upsilon(1S)$	( 9.9 $\pm$ 1.0 ) %	764
$\pi\pi\chi_{b1}(1P)$	( 9.1 $\pm$ 1.3 ) $\times 10^{-3}$	238
$D^0 X$	( 8.8 $\pm$ 1.7 ) %	—
$\pi^+ \pi^- K^+ K^- \pi^0$	( 3.1 $\pm$ 1.0 ) $\times 10^{-4}$	5075
$2\pi^+ \pi^- K^- K_S^0$	( 1.1 $\pm$ 0.5 ) $\times 10^{-4}$	5075
$2\pi^+ \pi^- K^- K_S^0 2\pi^0$	( 7.7 $\pm$ 3.2 ) $\times 10^{-4}$	5047
$2\pi^+ 2\pi^- 2\pi^0$	( 5.9 $\pm$ 2.0 ) $\times 10^{-4}$	5104
$2\pi^+ 2\pi^- K^+ K^-$	(10 $\pm$ 4 ) $\times 10^{-5}$	5062
$2\pi^+ 2\pi^- K^+ K^- \pi^0$	( 5.5 $\pm$ 1.8 ) $\times 10^{-4}$	5047
$2\pi^+ 2\pi^- K^+ K^- 2\pi^0$	(10 $\pm$ 4 ) $\times 10^{-4}$	5030
$3\pi^+ 2\pi^- K^- K_S^0 \pi^0$	( 6.7 $\pm$ 2.6 ) $\times 10^{-4}$	5029
$3\pi^+ 3\pi^-$	( 1.2 $\pm$ 0.4 ) $\times 10^{-4}$	5103
$3\pi^+ 3\pi^- 2\pi^0$	( 1.2 $\pm$ 0.4 ) $\times 10^{-3}$	5081
$3\pi^+ 3\pi^- K^+ K^-$	( 2.0 $\pm$ 0.8 ) $\times 10^{-4}$	5029
$3\pi^+ 3\pi^- K^+ K^- \pi^0$	( 6.1 $\pm$ 2.2 ) $\times 10^{-4}$	5011
$4\pi^+ 4\pi^-$	( 1.7 $\pm$ 0.6 ) $\times 10^{-4}$	5080
$4\pi^+ 4\pi^- 2\pi^0$	( 1.9 $\pm$ 0.7 ) $\times 10^{-3}$	5051

 **$h_b(2P)$** 

$$I^G(J^{PC}) = 0^-(1^{+-})$$

Mass  $m = 10259.8 \pm 1.2$  MeV

<b><math>h_b(2P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$\eta_b(1S)\gamma$	(22 $\pm$ 5) %	825
$\eta_b(2S)\gamma$	(48 $\pm$ 13) %	257

See Particle Listings for 1 decay modes that have been seen / not seen.

 **$\chi_{b2}(2P)$**  [yyaa]

$$I^G(J^{PC}) = 0^+(2^{++})$$

 $J$  needs confirmation.

Mass  $m = 10268.65 \pm 0.22 \pm 0.50$  MeV

$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} = 13.10 \pm 0.24$  MeV

<b><math>\chi_{b2}(2P)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\omega \Upsilon(1S)$	(1.10 <sup>+0.34</sup> <sub>-0.30</sub> ) %		194
$\gamma \Upsilon(2S)$	(8.9 $\pm$ 1.2 ) %		242
$\gamma \Upsilon(1S)$	(6.6 $\pm$ 0.8 ) %		776

$\pi\pi\chi_{b2}(1P)$	$(5.1 \pm 0.9) \times 10^{-3}$		229
$D^0 X$	$< 2.4$	%	90% -
$\pi^+\pi^-K^+K^-\pi^0$	$< 1.1$	$\times 10^{-4}$	90% 5082
$2\pi^+\pi^-K^-K_S^0$	$< 9$	$\times 10^{-5}$	90% 5082
$2\pi^+\pi^-K^-K_S^0 2\pi^0$	$< 7$	$\times 10^{-4}$	90% 5054
$2\pi^+ 2\pi^- 2\pi^0$	$(3.9 \pm 1.6) \times 10^{-4}$		5110
$2\pi^+ 2\pi^- K^+ K^-$	$(9 \pm 4) \times 10^{-5}$		5068
$2\pi^+ 2\pi^- K^+ K^- \pi^0$	$(2.4 \pm 1.1) \times 10^{-4}$		5054
$2\pi^+ 2\pi^- K^+ K^- 2\pi^0$	$(4.7 \pm 2.3) \times 10^{-4}$		5037
$3\pi^+ 2\pi^- K^- K_S^0 \pi^0$	$< 4$	$\times 10^{-4}$	90% 5036
$3\pi^+ 3\pi^-$	$(9 \pm 4) \times 10^{-5}$		5110
$3\pi^+ 3\pi^- 2\pi^0$	$(1.2 \pm 0.4) \times 10^{-3}$		5088
$3\pi^+ 3\pi^- K^+ K^-$	$(1.4 \pm 0.7) \times 10^{-4}$		5036
$3\pi^+ 3\pi^- K^+ K^- \pi^0$	$(4.2 \pm 1.7) \times 10^{-4}$		5017
$4\pi^+ 4\pi^-$	$(9 \pm 5) \times 10^{-5}$		5087
$4\pi^+ 4\pi^- 2\pi^0$	$(1.3 \pm 0.5) \times 10^{-3}$		5058

**$\Upsilon(3S)$**

$$J^{PC} = 0^-(1^{--})$$

Mass  $m = 10355.1 \pm 0.5$  MeV

$m_{\Upsilon(3S)} - m_{\Upsilon(2S)} = 331.50 \pm 0.13$  MeV

Full width  $\Gamma = 20.32 \pm 1.85$  keV

<b><math>\Upsilon(3S)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$\Upsilon(2S)$ anything	$(10.6 \pm 0.8) \%$		296
$\Upsilon(2S)\pi^+\pi^-$	$(2.82 \pm 0.18) \%$	S=1.6	176
$\Upsilon(2S)\pi^0\pi^0$	$(1.85 \pm 0.14) \%$		190
$\Upsilon(2S)\gamma\gamma$	$(5.0 \pm 0.7) \%$		326
$\Upsilon(2S)\pi^0$	$< 5.1$	$\times 10^{-4}$ CL=90%	298
$\Upsilon(1S)\pi^+\pi^-$	$(4.37 \pm 0.08) \%$		813
$\Upsilon(1S)\pi^0\pi^0$	$(2.20 \pm 0.13) \%$		816
$\Upsilon(1S)\eta$	$< 1$	$\times 10^{-4}$ CL=90%	677
$\Upsilon(1S)\pi^0$	$< 7$	$\times 10^{-5}$ CL=90%	846
$h_b(1P)\pi^0$	$< 1.2$	$\times 10^{-3}$ CL=90%	426
$h_b(1P)\pi^0 \rightarrow \gamma\eta_b(1S)\pi^0$	$(4.3 \pm 1.4) \times 10^{-4}$		-
$h_b(1P)\pi^+\pi^-$	$< 1.2$	$\times 10^{-4}$ CL=90%	352
$\tau^+\tau^-$	$(2.29 \pm 0.30) \%$		4863
$\mu^+\mu^-$	$(2.18 \pm 0.21) \%$	S=2.1	5176
$e^+e^-$	$(2.18 \pm 0.20) \%$		5178
hadrons	$(93 \pm 12) \%$		-
$ggg$	$(35.7 \pm 2.6) \%$		-
$\gamma gg$	$(9.7 \pm 1.8) \times 10^{-3}$		-
$^2H$ anything	$(2.33 \pm 0.33) \times 10^{-5}$		-

**Radiative decays**

$\gamma\chi_{b2}(2P)$	$(13.1 \pm 1.6) \%$	S=3.4	86
$\gamma\chi_{b1}(2P)$	$(12.6 \pm 1.2) \%$	S=2.4	99
$\gamma\chi_{b0}(2P)$	$(5.9 \pm 0.6) \%$	S=1.4	122
$\gamma\chi_{b2}(1P)$	$(10.0 \pm 1.0) \times 10^{-3}$	S=1.7	433
$\gamma\chi_{b1}(1P)$	$(9 \pm 5) \times 10^{-4}$	S=1.8	452
$\gamma\chi_{b0}(1P)$	$(2.7 \pm 0.4) \times 10^{-3}$		484
$\gamma\eta_b(2S)$	$< 6.2$	$\times 10^{-4}$ CL=90%	350
$\gamma\eta_b(1S)$	$(5.1 \pm 0.7) \times 10^{-4}$		912
$\gamma A^0 \rightarrow \gamma$ hadrons	$< 8$	$\times 10^{-5}$ CL=90%	-

$\gamma X \rightarrow \gamma + \geq 4$ prongs	$[aabb] < 2.2$	$\times 10^{-4}$	CL=95%	—
$\gamma A^0 \rightarrow \gamma \mu^+ \mu^-$	$< 5.5$	$\times 10^{-6}$	CL=90%	—
$\gamma A^0 \rightarrow \gamma \tau^+ \tau^-$	$[bbbb] < 1.6$	$\times 10^{-4}$	CL=90%	—

**Lepton Family number (LF) violating modes**

$e^\pm \tau^\mp$	LF	$< 4.2$	$\times 10^{-6}$	CL=90%	5025
$e^\pm \mu^\mp$	LF	$< 3.6$	$\times 10^{-7}$	CL=90%	5177
$\mu^\pm \tau^\mp$	LF	$< 3.1$	$\times 10^{-6}$	CL=90%	5025

 **$\chi_{b1}(3P)$**  [yyaa]

$$J^G(J^{PC}) = 0^+(1^{++})$$

*J* needs confirmation.

Mass  $m = 10513.4 \pm 0.7$  MeV

 **$\chi_{b2}(3P)$**  [yyaa]

$$J^G(J^{PC}) = 0^+(2^{++})$$

*J* needs confirmation.

Mass  $m = 10524.0 \pm 0.8$  MeV

 **$\Upsilon(4S)$** 

$$J^G(J^{PC}) = 0^-(1^{--})$$

also known as  $\Upsilon(10580)$ 

Mass  $m = 10579.4 \pm 1.2$  MeV

Full width  $\Gamma = 20.5 \pm 2.5$  MeV

<b><math>\Upsilon(4S)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$B\bar{B}$	$> 96$ %	95%	326
$B^+ B^-$	$(51.4 \pm 0.6)$ %		331
$D^+$ anything + c.c.	$(17.8 \pm 2.6)$ %		—
$B^0 \bar{B}^0$	$(48.6 \pm 0.6)$ %		326
$J/\psi K_S^0 + (J/\psi, \eta_c) K_S^0$	$< 4$ $\times 10^{-7}$	90%	—
non- $B\bar{B}$	$< 4$ %	95%	—
$e^+ e^-$	$(1.57 \pm 0.08) \times 10^{-5}$		5290
$\rho^+ \rho^-$	$< 5.7$ $\times 10^{-6}$	90%	5233
$K^*(892)^0 \bar{K}^0$	$< 2.0$ $\times 10^{-6}$	90%	5240
$J/\psi(1S)$ anything	$< 1.9$ $\times 10^{-4}$	95%	—
$D^{*+}$ anything + c.c.	$< 7.4$ %	90%	5099
$\phi$ anything	$(7.1 \pm 0.6)$ %		5240
$\phi \eta$	$< 1.8$ $\times 10^{-6}$	90%	5226
$\phi \eta'$	$< 4.3$ $\times 10^{-6}$	90%	5196
$\rho \eta$	$< 1.3$ $\times 10^{-6}$	90%	5247
$\rho \eta'$	$< 2.5$ $\times 10^{-6}$	90%	5217
$\Upsilon(1S)$ anything	$< 4$ $\times 10^{-3}$	90%	1053
$\Upsilon(1S) \pi^+ \pi^-$	$(8.2 \pm 0.4) \times 10^{-5}$		1026
$\Upsilon(1S) \eta$	$(1.81 \pm 0.18) \times 10^{-4}$		924
$\Upsilon(1S) \eta'$	$(3.4 \pm 0.9) \times 10^{-5}$		—
$\Upsilon(2S) \pi^+ \pi^-$	$(8.2 \pm 0.8) \times 10^{-5}$		468
$h_b(1P) \eta$	$(2.18 \pm 0.21) \times 10^{-3}$		390
$\eta_b(1S) \omega$	$< 1.8$ $\times 10^{-4}$	90%	—
${}^2H$ anything	$< 1.3$ $\times 10^{-5}$	90%	—

Double Radiative Decays

$\gamma\gamma \Upsilon(D) \rightarrow \gamma\gamma\eta \Upsilon(1S)$  < 2.3  $\times 10^{-5}$  90% -  
 See Particle Listings for 1 decay modes that have been seen / not seen.

**$\Upsilon(10860)$**

$$J^{PC} = 0^{-}(1^{-}-)$$

Mass  $m = 10885.2^{+2.6}_{-1.6}$  MeV

Full width  $\Gamma = 37 \pm 4$  MeV

<b><math>\Upsilon(10860)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$B\bar{B}X$	( 76.2 $^{+2.7}_{-4.0}$ ) %		-
$B\bar{B}$	( 5.5 $\pm 1.0$ ) %		1322
$B\bar{B}^* + c.c.$	( 13.7 $\pm 1.6$ ) %		-
$B^*\bar{B}^*$	( 38.1 $\pm 3.4$ ) %		1127
$B\bar{B}^{(*)}\pi$	< 19.7 %	90%	1015
$B\bar{B}\pi$	( 0.0 $\pm 1.2$ ) %		1015
$B^*\bar{B}\pi + B\bar{B}^*\pi$	( 7.3 $\pm 2.3$ ) %		-
$B^*\bar{B}^*\pi$	( 1.0 $\pm 1.4$ ) %		739
$B\bar{B}\pi\pi$	< 8.9 %	90%	550
$B_s^{(*)}\bar{B}_s^{(*)}$	( 20.1 $\pm 3.1$ ) %		904
$B_s\bar{B}_s$	( 5 $\pm 5$ ) $\times 10^{-3}$		904
$B_s\bar{B}_s^* + c.c.$	( 1.35 $\pm 0.32$ ) %		-
$B_s^*\bar{B}_s^*$	( 17.6 $\pm 2.7$ ) %		543
no open-bottom	( 3.8 $^{+5.0}_{-0.5}$ ) %		-
$e^+e^-$	( 8.3 $\pm 2.1$ ) $\times 10^{-6}$		5443
$K^*(892)^0\bar{K}^0$	< 1.0 $\times 10^{-5}$	90%	5395
$\Upsilon(1S)\pi^+\pi^-$	( 5.3 $\pm 0.6$ ) $\times 10^{-3}$		1306
$\Upsilon(1S)\eta$	( 8.5 $\pm 1.7$ ) $\times 10^{-4}$		1229
$\Upsilon(1S)\eta'$	< 6.9 $\times 10^{-5}$	90%	985
$\Upsilon(2S)\pi^+\pi^-$	( 7.8 $\pm 1.3$ ) $\times 10^{-3}$		783
$\Upsilon(2S)\eta$	( 4.1 $\pm 0.6$ ) $\times 10^{-3}$		639
$\Upsilon(3S)\pi^+\pi^-$	( 4.8 $^{+1.9}_{-1.7}$ ) $\times 10^{-3}$		440
$\Upsilon(1S)K^+K^-$	( 6.1 $\pm 1.8$ ) $\times 10^{-4}$		959
$\eta \Upsilon_J(1D)$	( 4.8 $\pm 1.1$ ) $\times 10^{-3}$		-
$h_b(1P)\pi^+\pi^-$	( 3.5 $^{+1.0}_{-1.3}$ ) $\times 10^{-3}$		903
$h_b(2P)\pi^+\pi^-$	( 5.7 $^{+1.7}_{-2.1}$ ) $\times 10^{-3}$		544
$\chi_{bJ}(1P)\pi^+\pi^-\pi^0$	( 2.5 $\pm 2.3$ ) $\times 10^{-3}$		894
$\chi_{b0}(1P)\pi^+\pi^-\pi^0$	< 6.3 $\times 10^{-3}$	90%	894
$\chi_{b0}(1P)\omega$	< 3.9 $\times 10^{-3}$	90%	631
$\chi_{b0}(1P)(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	< 4.8 $\times 10^{-3}$	90%	-
$\chi_{b1}(1P)\pi^+\pi^-\pi^0$	( 1.85 $\pm 0.33$ ) $\times 10^{-3}$		861
$\chi_{b1}(1P)\omega$	( 1.57 $\pm 0.30$ ) $\times 10^{-3}$		582
$\chi_{b1}(1P)(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	( 5.2 $\pm 1.9$ ) $\times 10^{-4}$		-
$\chi_{b2}(1P)\pi^+\pi^-\pi^0$	( 1.17 $\pm 0.30$ ) $\times 10^{-3}$		841
$\chi_{b2}(1P)\omega$	( 6.0 $\pm 2.7$ ) $\times 10^{-4}$		552
$\chi_{b2}(1P)(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	( 6 $\pm 4$ ) $\times 10^{-4}$		-
$\gamma X_b \rightarrow \gamma \Upsilon(1S)\omega$	< 3.8 $\times 10^{-5}$	90%	-
$\eta_b(1S)\omega$	< 1.3 $\times 10^{-3}$	90%	1177
$\eta_b(2S)\omega$	< 5.6 $\times 10^{-3}$	90%	399



## Inclusive Decays.

These decay modes are submodes of one or more of the decay modes above.

$\phi$ anything	( 13.8 $^{+2.4}_{-1.7}$ ) %	—
$D^0$ anything + c.c.	(112 $\pm 6$ ) %	—
$D_S$ anything + c.c.	( 44.7 $\pm 2.6$ ) %	—
$J/\psi$ anything	( 2.06 $\pm 0.21$ ) %	—
$B^0$ anything + c.c.	( 77 $\pm 8$ ) %	—
$B^+$ anything + c.c.	( 72 $\pm 6$ ) %	—

 **$\Upsilon(11020)$** 

$$I^G(J^{PC}) = 0^-(1^{--})$$

Mass  $m = 11000 \pm 4$  MeV

Full width  $\Gamma = 24^{+8}_{-6}$  MeV

 **$\Upsilon(11020)$  DECAY MODES**

Fraction ( $\Gamma_i/\Gamma$ )

$p$  (MeV/c)

$e^+ e^-$	(5.4 $^{+1.9}_{-2.1}$ ) $\times 10^{-6}$	5500
$\chi_{bJ}(1P)\pi^+\pi^-\pi^0$	(9 $^{+9}_{-8}$ ) $\times 10^{-3}$	1007

See Particle Listings for 2 decay modes that have been seen / not seen.

**OTHER MESONS** **$T_{c\bar{c}1}(3900)$** 

$$I^G(J^{PC}) = 1^+(1^{+-})$$

was  $Z_c(3900)$ ,  $X(3900)$

Mass  $m = 3887.1 \pm 2.6$  MeV ( $S = 1.7$ )

Full width  $\Gamma = 28.4 \pm 2.6$  MeV

 **$T_{c\bar{c}1}(4020)$** 

$$I^G(J^{PC}) = 1^+(?^{? -})$$

was  $X(4020)$

Mass  $m = 4024.1 \pm 1.9$  MeV

Full width  $\Gamma = 13 \pm 5$  MeV ( $S = 1.7$ )

 **$T_{c\bar{c}1}(4430)^{\pm}$** 

$$I^G(J^{PC}) = 1^+(1^{+-})$$

$G, C$  need confirmation.

was  $Z_c(4430)$ ,  $X(4430)^{\pm}$

Quantum numbers not established.

Mass  $m = 4478^{+15}_{-18}$  MeV

Full width  $\Gamma = 181 \pm 31$  MeV

 **$T_{b\bar{b}1}(10610)$** 

$$I^G(J^{PC}) = 1^+(1^{+-})$$

was  $Z_b(10610)$ ,  $X(10610)$

Mass  $m = 10607.2 \pm 2.0$  MeV

Mass  $m = 10609 \pm 6$  MeV

Full width  $\Gamma = 18.4 \pm 2.4$  MeV

$T_{b\bar{b}1}(10610)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$\gamma(1S)\pi^+$	$(5.4^{+1.9}_{-1.5}) \times 10^{-3}$	1077
$\gamma(2S)\pi^+$	$(3.6^{+1.1}_{-0.8})\%$	551
$\gamma(3S)\pi^+$	$(2.1^{+0.8}_{-0.6})\%$	207
$h_b(1P)\pi^+$	$(3.5^{+1.2}_{-0.9})\%$	671
$h_b(2P)\pi^+$	$(4.7^{+1.7}_{-1.3})\%$	313
$B^+\bar{B}^{*0} + B^{*+}\bar{B}^0$	$(85.6^{+2.1}_{-2.9})\%$	—

See Particle Listings for 4 decay modes that have been seen / not seen.

 **$T_{b\bar{b}1}(10650)^+$** 

$$I^G(J^{PC}) = 1^+(1^+ -)$$

$I, G, C$  need confirmation.

was  $Z_b(10650), X(10650)^\pm$

$$\text{Mass } m = 10652.2 \pm 1.5 \text{ MeV}$$

$$\text{Full width } \Gamma = 11.5 \pm 2.2 \text{ MeV}$$

$T_{b\bar{b}1}(10650)^-$  decay modes are charge conjugates of the modes below.

$T_{b\bar{b}1}(10650)^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$\gamma(1S)\pi^+$	$(1.7^{+0.8}_{-0.6}) \times 10^{-3}$	1117
$\gamma(2S)\pi^+$	$(1.4^{+0.6}_{-0.4})\%$	595
$\gamma(3S)\pi^+$	$(1.6^{+0.7}_{-0.5})\%$	259
$h_b(1P)\pi^+$	$(8.4^{+2.9}_{-2.4})\%$	714
$h_b(2P)\pi^+$	$(15 \pm 4)\%$	360
$B^{*+}\bar{B}^{*0}$	$(74 \pm 4)\%$	120

See Particle Listings for 2 decay modes that have been seen / not seen.

## NOTES

In this Summary Table:

When a quantity has “(S = ...)” to its right, the error on the quantity has been enlarged by the “scale factor” S, defined as  $S = \sqrt{\chi^2/(N-1)}$ , where N is the number of measurements used in calculating the quantity.

A decay momentum  $p$  is given for each decay mode. For a 2-body decay,  $p$  is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay,  $p$  is the largest momentum any of the products can have in this frame.

- [a] See the review on “Form Factors for Radiative Pion and Kaon Decays” for definitions and details.
- [b] Measurements of  $\Gamma(e^+ \nu_e)/\Gamma(\mu^+ \nu_\mu)$  always include decays with  $\gamma$ 's, and measurements of  $\Gamma(e^+ \nu_e \gamma)$  and  $\Gamma(\mu^+ \nu_\mu \gamma)$  never include low-energy  $\gamma$ 's. Therefore, since no clean separation is possible, we consider the modes with  $\gamma$ 's to be subreactions of the modes without them, and let  $[\Gamma(e^+ \nu_e) + \Gamma(\mu^+ \nu_\mu)]/\Gamma_{\text{total}} = 100\%$ .
- [c] See the  $\pi^\pm$  Particle Listings in the Full *Review of Particle Physics* for the energy limits used in this measurement; low-energy  $\gamma$ 's are not included.
- [d] Derived from an analysis of neutrino-oscillation experiments.
- [e] Forbidden by angular momentum conservation.
- [f] C parity forbids this to occur as a single-photon process.
- [g] As measured in  $e^+ e^- \rightarrow \rho^0$ .
- [h] The  $\omega\rho$  interference is then due to  $\omega\rho$  mixing only, and is expected to be small. If  $e\mu$  universality holds,  $\Gamma(\rho^0 \rightarrow \mu^+ \mu^-) = \Gamma(\rho^0 \rightarrow e^+ e^-) \times 0.99785$ .
- [i] Our estimate. See the Particle Listings for details.
- [j] See the “Note on  $a_1(1260)$ ” in the  $a_1(1260)$  Particle Listings in PDG 06, *Journal of Physics* **G33** 1 (2006).
- [k] See also the  $\omega(1650)$ .
- [l] See also the  $\omega(1420)$ .
- [n] See the note in the  $K^\pm$  Particle Listings in the Full *Review of Particle Physics*.
- [o] Neglecting photon channels. See, e.g., A. Pais and S.B. Treiman, *Phys. Rev.* **D12**, 2744 (1975).
- [p] The definition of the slope parameters of the  $K \rightarrow 3\pi$  Dalitz plot is as follows (see also “Note on Dalitz Plot Parameters for  $K \rightarrow 3\pi$  Decays” in the  $K^\pm$  Particle Listings in the Full *Review of Particle Physics*):
 
$$|M|^2 = 1 + g(s_3 - s_0)/m_{\pi^+}^2 + \dots$$
- [q] For more details and definitions of parameters see Particle Listings in the Full *Review of Particle Physics*.
- [r] See the  $K^\pm$  Particle Listings in the Full *Review of Particle Physics* for the energy limits used in this measurement.
- [s] Most of this radiative mode, the low-momentum  $\gamma$  part, is also included in the parent mode listed without  $\gamma$ 's.
- [t] Structure-dependent part.
- [u] Direct-emission branching fraction.
- [v] Violates angular-momentum conservation.

[x] Derived from measured values of  $\phi_{+-}$ ,  $\phi_{00}$ ,  $|\eta|$ ,  $|m_{K_L^0} - m_{K_S^0}|$ , and  $\tau_{K_S^0}$ , as described in the introduction to “Tests of Conservation Laws.”

[y] The  $CP$ -violation parameters are defined as follows (see also “Note on  $CP$  Violation in  $K_S \rightarrow 3\pi$ ” and “Note on  $CP$  Violation in  $K_L^0$  Decay” in the Particle Listings in the Full *Review of Particle Physics*):

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} = \frac{A(K_L^0 \rightarrow \pi^+\pi^-)}{A(K_S^0 \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = |\eta_{00}|e^{i\phi_{00}} = \frac{A(K_L^0 \rightarrow \pi^0\pi^0)}{A(K_S^0 \rightarrow \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

$$\delta = \frac{\Gamma(K_L^0 \rightarrow \pi^-\ell^+\nu) - \Gamma(K_L^0 \rightarrow \pi^+\ell^-\nu)}{\Gamma(K_L^0 \rightarrow \pi^-\ell^+\nu) + \Gamma(K_L^0 \rightarrow \pi^+\ell^-\nu)},$$

$$\text{Im}(\eta_{+-0})^2 = \frac{\Gamma(K_S^0 \rightarrow \pi^+\pi^-\pi^0)^{CP \text{ viol.}}}{\Gamma(K_L^0 \rightarrow \pi^+\pi^-\pi^0)},$$

$$\text{Im}(\eta_{000})^2 = \frac{\Gamma(K_S^0 \rightarrow \pi^0\pi^0\pi^0)}{\Gamma(K_L^0 \rightarrow \pi^0\pi^0\pi^0)}.$$

where for the last two relations  $CPT$  is assumed valid, *i.e.*,  $\text{Re}(\eta_{+-0}) \simeq 0$  and  $\text{Re}(\eta_{000}) \simeq 0$ .

[z] See the  $K_S^0$  Particle Listings in the Full *Review of Particle Physics* for the energy limits used in this measurement.

[aa] The value is for the sum of the charge states or particle/antiparticle states indicated.

[bb]  $\text{Re}(\epsilon'/\epsilon) = \epsilon'/\epsilon$  to a very good approximation provided the phases satisfy  $CPT$  invariance.

[cc] This mode includes gammas from inner bremsstrahlung but not the direct emission mode  $K_L^0 \rightarrow \pi^+\pi^-\gamma(\text{DE})$ .

[dd] See the  $K_L^0$  Particle Listings in the Full *Review of Particle Physics* for the energy limits used in this measurement.

[ee] Allowed by higher-order electroweak interactions.

[ff] Violates  $CP$  in leading order. Test of direct  $CP$  violation since the indirect  $CP$ -violating and  $CP$ -conserving contributions are expected to be suppressed.

[gg] See our minireview under the  $K_2(1770)$  in the 2004 edition of this *Review*.

[hh] This result applies to  $Z^0 \rightarrow c\bar{c}$  decays only. Here  $\ell^+$  is an average (not a sum) of  $e^+$  and  $\mu^+$  decays.

[ii] See the Particle Listings for the (complicated) definition of this quantity.

[jj] The branching fraction for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers in the Particle Listings in the Full *Review of Particle Physics*.

[kk] These subfractions of the  $K^-2\pi^+$  mode are uncertain: see the Particle Listings.

[ll] See the listings under “ $D \rightarrow K\pi\pi\pi$  partial wave analyses” and our 2008 Review (Physics Letters **B667** 1 (2008)) for measurements of submodes of this mode.

[nn] The unseen decay modes of the resonances are included.

- [oo] This is *not* a test for the  $\Delta C=1$  weak neutral current, but leads to the  $\pi^+ \ell^+ \ell^-$  final state.
- [pp] This mode is not a useful test for a  $\Delta C=1$  weak neutral current because both quarks must change flavor in this decay.
- [qq] In the 2010 *Review*, the values for these quantities were given using a measure of the asymmetry that was inconsistent with the usual definition.
- [rr] This value is obtained by subtracting the branching fractions for 2-, 4- and 6-prongs from unity.
- [ss] This is the sum of our  $K^- 2\pi^+ \pi^-$ ,  $K^- 2\pi^+ \pi^- \pi^0$ ,  $\bar{K}^0 2\pi^+ 2\pi^-$ ,  $K^+ 2K^- \pi^+$ ,  $2\pi^+ 2\pi^-$ ,  $2\pi^+ 2\pi^- \pi^0$ ,  $K^+ K^- \pi^+ \pi^-$ , and  $K^+ K^- \pi^+ \pi^- \pi^0$ , branching fractions.
- [tt] This is the sum of our  $K^- 3\pi^+ 2\pi^-$  and  $3\pi^+ 3\pi^-$  branching fractions.
- [uu] The branching fractions for the  $K^- e^+ \nu_e$ ,  $K^*(892)^- e^+ \nu_e$ ,  $\pi^- e^+ \nu_e$ , and  $\rho^- e^+ \nu_e$  modes add up to  $6.17 \pm 0.17$  %.
- [vv] This is a doubly Cabibbo-suppressed mode.
- [xx] Submodes of the  $D^0 \rightarrow K_S^0 \pi^+ \pi^- \pi^0$  mode with a  $K^*$  and/or  $\rho$  were studied by COFFMAN 92B, but with only 140 events. With nothing new for 18 years, we refer to our 2008 edition, Physics Letters **B667** 1 (2008), for those results.
- [yy] This branching fraction includes all the decay modes of the resonance in the final state.
- [zz] This limit assumes the average of  $B(D^0 \rightarrow K^- e^+ \nu_e)$  and  $B(D^0 \rightarrow K^- \mu^+ \nu_\mu)$  for the  $B(D^0 \rightarrow K^- \ell^+ \nu_\ell)$  value.
- [aaa] This is the purely  $e^+$  semileptonic branching fraction: the  $e^+$  fraction from  $\tau^+$  decays has been subtracted off. The sum of our (non- $\tau$ )  $e^+$  exclusive fractions — an  $e^+ \nu_e$  with an  $\eta$ ,  $\eta'$ ,  $\phi$ ,  $K^0$ , or  $K^{*0}$  — is  $5.99 \pm 0.31$  %.
- [bbb] This fraction includes  $\eta$  from  $\eta'$  decays.
- [ccc] The sum of our exclusive  $\eta'$  fractions —  $\eta' e^+ \nu_e$ ,  $\eta' \mu^+ \nu_\mu$ ,  $\eta' \pi^+$ ,  $\eta' \rho^+$ , and  $\eta' K^+$  — is  $11.8 \pm 1.6$  %.
- [ddd] This branching fraction includes all the decay modes of the final-state resonance.
- [eee] A test for  $u\bar{u}$  or  $d\bar{d}$  content in the  $D_S^+$ . Neither Cabibbo-favored nor Cabibbo-suppressed decays can contribute, and  $\omega - \phi$  mixing is an unlikely explanation for any fraction above about  $2 \times 10^{-4}$ .
- [fff] We decouple the  $D_S^+ \rightarrow \phi \pi^+$  branching fraction obtained from mass projections (and used to get some of the other branching fractions) from the  $D_S^+ \rightarrow \phi \pi^+$ ,  $\phi \rightarrow K^+ K^-$  branching fraction obtained from the Dalitz-plot analysis of  $D_S^+ \rightarrow K^+ K^- \pi^+$ . That is, the ratio of these two branching fractions is not exactly the  $\phi \rightarrow K^+ K^-$  branching fraction 0.491.
- [ggg] This is the average of a model-independent and a  $K$ -matrix parametrization of the  $\pi^+ \pi^- S$ -wave and is a sum over several  $f_0$  mesons.
- [hhh] An  $\ell$  indicates an  $e$  or a  $\mu$  mode, not a sum over these modes.
- [iii] An  $CP(\pm 1)$  indicates the  $CP=+1$  and  $CP=-1$  eigenstates of the  $D^0$ - $\bar{D}^0$  system.
- [jjj]  $D$  denotes  $D^0$  or  $\bar{D}^0$ .
- [kkk]  $D_{CP+}^{*0}$  decays into  $D^0 \pi^0$  with the  $D^0$  reconstructed in  $CP$ -even eigenstates  $K^+ K^-$  and  $\pi^+ \pi^-$ .

- [lll]  $\overline{D}^{**}$  represents an excited state with mass  $2.2 < M < 2.8 \text{ GeV}/c^2$ .
- [nnn]  $\chi_{c1}(3872)^+$  is a hypothetical charged partner of the  $\chi_{c1}(3872)$ .
- [ooo]  $\Theta(1710)^{++}$  is a possible narrow pentaquark state and  $G(2220)$  is a possible glueball resonance.
- [ppp]  $(\overline{\Lambda}_c^- \rho)_s$  denotes a low-mass enhancement near  $3.35 \text{ GeV}/c^2$ .
- [qqq] Stands for the possible candidates of  $K^*(1410)$ ,  $K_0^*(1430)$  and  $K_2^*(1430)$ .
- [rrr]  $B^0$  and  $B_S^0$  contributions not separated. Limit is on weighted average of the two decay rates.
- [sss] This decay refers to the coherent sum of resonant and nonresonant  $J^P = 0^+ K\pi$  components with  $1.60 < m_{K\pi} < 2.15 \text{ GeV}/c^2$ .
- [ttt]  $X(214)$  is a hypothetical particle of mass  $214 \text{ MeV}/c^2$  reported by the HyperCP experiment, Physical Review Letters **94** 021801 (2005)
- [uuu]  $\Theta(1540)^+$  denotes a possible narrow pentaquark state.
- [vvv]  $\psi_{DS}$  is a GeV-scale dark sector antibaryon (mass range  $1\text{--}4 \text{ GeV}/c^2$ ).
- [xxx] Here  $S$  and  $P$  are the hypothetical scalar and pseudoscalar particles with masses of  $2.5 \text{ GeV}/c^2$  and  $214.3 \text{ MeV}/c^2$ , respectively.
- [yyy] These values are model dependent.
- [zzz] Here “anything” means at least one particle observed.
- [aaaa] This is a  $B(B^0 \rightarrow D^{*-} \ell^+ \nu_\ell)$  value.
- [bbaa]  $D^{**}$  stands for the sum of the  $D(1^1P_1)$ ,  $D(1^3P_0)$ ,  $D(1^3P_1)$ ,  $D(1^3P_2)$ ,  $D(2^1S_0)$ , and  $D(2^1S_1)$  resonances.
- [ccaa]  $D^{(*)}\overline{D}^{(*)}$  stands for the sum of  $D^*\overline{D}^*$ ,  $D^*\overline{D}$ ,  $D\overline{D}^*$ , and  $D\overline{D}$ .
- [ddaa]  $X(3915)$  denotes a near-threshold enhancement in the  $\omega J/\psi$  mass spectrum.
- [eeaa] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.
- [ffaa]  $D_j$  represents an unresolved mixture of pseudoscalar and tensor  $D^{**}$  ( $P$ -wave) states.
- [ggaa] Not a pure measurement. See note at head of  $B_S^0$  Decay Modes.
- [hhaa] For  $E_\gamma > 100 \text{ MeV}$ .
- [iiaa]  $\Theta(1540)$  is a hypothetical pentaquark state of  $1.54 \text{ GeV}/c^2$  mass and a width of less than  $25 \text{ MeV}/c^2$ .
- [jja] Includes  $\rho\overline{p}\pi^+\pi^-\gamma$  and excludes  $\rho\overline{p}\eta$ ,  $\rho\overline{p}\omega$ ,  $\rho\overline{p}\eta'$ .
- [kkaa] For a narrow state  $A$  with mass less than  $960 \text{ MeV}$ .
- [llaa] For a narrow scalar or pseudoscalar  $A^0$  with mass  $0.21\text{--}3.0 \text{ GeV}$ .
- [nnaa] For a dark photon  $U$  with mass between  $100$  and  $2100 \text{ MeV}$ .
- [ooaa] For a narrow resonance in the range  $2.2 < M(X) < 2.8 \text{ GeV}$ .
- [ppaa]  $J^{PC}$  known by production in  $e^+e^-$  via single photon annihilation.  $I^G$  is not known; interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.
- [qqaa]  $2m_\tau < M(\tau^+\tau^-) < 9.2 \text{ GeV}$
- [rraa]  $2 \text{ GeV} < m_{K^+K^-} < 3 \text{ GeV}$
- [ssaa]  $X\overline{X} =$  vectors with  $m < 3.1 \text{ GeV}$
- [ttaa]  $X$  and  $\overline{X} =$  zero spin with  $m < 4.5 \text{ GeV}$
- [uuaa]  $1.5 \text{ GeV} < m_X < 5.0 \text{ GeV}$

[*vvaa*]  $201 \text{ MeV} < M(\mu^+ \mu^-) < 3565 \text{ MeV}$

[*xxaa*]  $0.5 \text{ GeV} < m_X < 9.0 \text{ GeV}$ , where  $m_X$  is the invariant mass of the hadronic final state.

[*yyaa*] Spectroscopic labeling for these states is theoretical, pending experimental information.

[*zzaa*]  $1.5 \text{ GeV} < m_X < 5.0 \text{ GeV}$

[*aabb*]  $1.5 \text{ GeV} < m_X < 5.0 \text{ GeV}$

[*bbbb*] For  $m_{\tau^+ \tau^-}$  in the ranges 4.03–9.52 and 9.61–10.10 GeV.

# N BARYONS

## ( $S = 0, I = 1/2$ )

$$p, N^+ = uud; \quad n, N^0 = udd$$

**p**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass  $m = 1.007276466621 \pm 0.000000000053$  u

Mass  $m = 938.27208816 \pm 0.00000029$  MeV <sup>[a]</sup>

$$|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}, \text{ CL} = 90\% \text{ [b]}$$

$$|\frac{q_{\bar{p}}}{m_{\bar{p}}}|/(\frac{q_p}{m_p}) = 1.000000000003 \pm 0.000000000016$$

$$|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}, \text{ CL} = 90\% \text{ [b]}$$

$$|q_p + q_e|/e < 1 \times 10^{-21} \text{ [c]}$$

Magnetic moment  $\mu = 2.7928473446 \pm 0.0000000008 \mu_N$

$$(\mu_p + \mu_{\bar{p}}) / \mu_p = (0.002 \pm 0.004) \times 10^{-6}$$

Electric dipole moment  $d < 0.021 \times 10^{-23}$  e cm

Electric polarizability  $\alpha = (11.2 \pm 0.4) \times 10^{-4}$  fm<sup>3</sup>

Magnetic polarizability  $\beta = (2.5 \pm 0.4) \times 10^{-4}$  fm<sup>3</sup> ( $S = 1.2$ )

Charge radius,  $\mu p$  Lamb shift =  $0.84087 \pm 0.00039$  fm <sup>[d]</sup>

Charge radius =  $0.8409 \pm 0.0004$  fm <sup>[d]</sup>

Magnetic radius =  $0.851 \pm 0.026$  fm <sup>[e]</sup>

Mean life  $\tau > 9 \times 10^{29}$  years, CL = 90% ( $p \rightarrow$  invisible mode)

See the "Note on Nucleon Decay" in our 1994 edition (Phys. Rev. **D50**, 1173) for a short review.

The "partial mean life" limits tabulated here are the limits on  $\tau/B_j$ , where  $\tau$  is the total mean life and  $B_j$  is the branching fraction for the mode in question. For  $N$  decays,  $p$  and  $n$  indicate proton and neutron partial lifetimes.

<b>p DECAY MODES</b>	Partial mean life ( $10^{30}$ years)	Confidence level	$p$ (MeV/c)
<b>Antilepton + meson</b>			
$N \rightarrow e^+ \pi$	$> 5300$ ( $n$ ), $> 24000$ ( $p$ )	90%	459
$N \rightarrow \mu^+ \pi$	$> 3500$ ( $n$ ), $> 16000$ ( $p$ )	90%	453
$N \rightarrow \nu \pi$	$> 1100$ ( $n$ ), $> 390$ ( $p$ )	90%	459
$p \rightarrow e^+ \eta$	$> 10000$	90%	309
$p \rightarrow \mu^+ \eta$	$> 4700$	90%	297
$n \rightarrow \nu \eta$	$> 158$	90%	310
$N \rightarrow e^+ \rho$	$> 217$ ( $n$ ), $> 720$ ( $p$ )	90%	149
$N \rightarrow \mu^+ \rho$	$> 228$ ( $n$ ), $> 570$ ( $p$ )	90%	113
$N \rightarrow \nu \rho$	$> 19$ ( $n$ ), $> 162$ ( $p$ )	90%	149
$p \rightarrow e^+ \omega$	$> 1600$	90%	143
$p \rightarrow \mu^+ \omega$	$> 2800$	90%	105
$n \rightarrow \nu \omega$	$> 108$	90%	144
$N \rightarrow e^+ K$	$> 17$ ( $n$ ), $> 1000$ ( $p$ )	90%	339
$N \rightarrow \mu^+ K$	$> 26$ ( $n$ ), $> 4500$ ( $p$ )	90%	329
$N \rightarrow \nu K$	$> 86$ ( $n$ ), $> 5900$ ( $p$ )	90%	339
$n \rightarrow \nu K_S^0$	$> 260$	90%	338
$p \rightarrow e^+ K^*(892)^0$	$> 84$	90%	45
$N \rightarrow \nu K^*(892)$	$> 78$ ( $n$ ), $> 51$ ( $p$ )	90%	45
<b>Antilepton + mesons</b>			
$p \rightarrow e^+ \pi^+ \pi^-$	$> 82$	90%	448



$p \rightarrow e^+ \pi^0 \pi^0$	> 147	90%	449
$n \rightarrow e^+ \pi^- \pi^0$	> 52	90%	449
$p \rightarrow \mu^+ \pi^+ \pi^-$	> 133	90%	425
$p \rightarrow \mu^+ \pi^0 \pi^0$	> 101	90%	427
$n \rightarrow \mu^+ \pi^- \pi^0$	> 74	90%	427
$n \rightarrow e^+ K^0 \pi^-$	> 18	90%	319

**Lepton + meson**

$n \rightarrow e^- \pi^+$	> 65	90%	459
$n \rightarrow \mu^- \pi^+$	> 49	90%	453
$n \rightarrow e^- \rho^+$	> 62	90%	150
$n \rightarrow \mu^- \rho^+$	> 7	90%	115
$n \rightarrow e^- K^+$	> 32	90%	340
$n \rightarrow \mu^- K^+$	> 57	90%	330

**Lepton + mesons**

$p \rightarrow e^- \pi^+ \pi^+$	> 30	90%	448
$n \rightarrow e^- \pi^+ \pi^0$	> 29	90%	449
$p \rightarrow \mu^- \pi^+ \pi^+$	> 17	90%	425
$n \rightarrow \mu^- \pi^+ \pi^0$	> 34	90%	427
$p \rightarrow e^- \pi^+ K^+$	> 75	90%	320
$p \rightarrow \mu^- \pi^+ K^+$	> 245	90%	279

**Antilepton + photon(s)**

$p \rightarrow e^+ \gamma$	> 670	90%	469
$p \rightarrow \mu^+ \gamma$	> 478	90%	463
$n \rightarrow \nu \gamma$	> 550	90%	470
$p \rightarrow e^+ \gamma \gamma$	> 100	90%	469
$n \rightarrow \nu \gamma \gamma$	> 219	90%	470

**Antilepton + single massless**

$p \rightarrow e^+ X$	> 790	90%	—
$p \rightarrow \mu^+ X$	> 410	90%	—

**Three (or more) leptons**

$p \rightarrow e^+ e^+ e^-$	> 34000	90%	469
$p \rightarrow e^+ \mu^+ \mu^-$	> 9200	90%	457
$p \rightarrow e^+ \nu \nu$	> 170	90%	469
$n \rightarrow e^+ e^- \nu$	> 257	90%	470
$n \rightarrow \mu^+ e^- \nu$	> 83	90%	464
$n \rightarrow \mu^+ \mu^- \nu$	> 79	90%	458
$p \rightarrow \mu^+ e^+ e^-$	> 23000	90%	463
$p \rightarrow \mu^- e^+ e^+$	> 19000	90%	463
$p \rightarrow \mu^+ \mu^+ \mu^-$	> 10000	90%	439
$p \rightarrow \mu^+ \nu \nu$	> 220	90%	463
$p \rightarrow e^- \mu^+ \mu^+$	> 11000	90%	457
$n \rightarrow 3\nu$	> $5 \times 10^{-4}$	90%	470

**Inclusive modes**

$N \rightarrow e^+$ anything	> 0.6 ( $n, p$ )	90%	—
$N \rightarrow \mu^+$ anything	> 12 ( $n, p$ )	90%	—
$N \rightarrow e^+ \pi^0$ anything	> 0.6 ( $n, p$ )	90%	—

 **$\Delta B = 2$  dinucleon modes**

The following are lifetime limits per iron nucleus.

$pp \rightarrow \pi^+ \pi^+$	> 72.2	90%	—
$pn \rightarrow \pi^+ \pi^0$	> 170	90%	—
$nn \rightarrow \pi^+ \pi^-$	> 0.7	90%	—

$nn \rightarrow \pi^0 \pi^0$	> 404	90%	—
$pp \rightarrow K^+ K^+$	> 170	90%	—
$pp \rightarrow e^+ e^+$	> 5.8	90%	—
$pp \rightarrow e^+ \mu^+$	> 3.6	90%	—
$pp \rightarrow \mu^+ \mu^+$	> 1.7	90%	—
$pn \rightarrow e^+ \bar{\nu}$	> 260	90%	—
$pn \rightarrow \mu^+ \bar{\nu}$	> 200	90%	—
$pn \rightarrow \tau^+ \bar{\nu}_\tau$	> 29	90%	—
$nn \rightarrow$ invisible	> 1.4	90%	—
$nn \rightarrow \nu_e \bar{\nu}_e$	> 1.4	90%	—
$nn \rightarrow \nu_\mu \bar{\nu}_\mu$	> 1.4	90%	—
$pn \rightarrow$ invisible	> 0.06	90%	—
$pp \rightarrow$ invisible	> 0.11	90%	—

**$\bar{p}$  DECAY MODES**

Mode	Partial mean life (years)	Confidence level	$\rho$ (MeV/c)
$\bar{p} \rightarrow e^- \gamma$	> $7 \times 10^5$	90%	469
$\bar{p} \rightarrow \mu^- \gamma$	> $5 \times 10^4$	90%	463
$\bar{p} \rightarrow e^- \pi^0$	> $4 \times 10^5$	90%	459
$\bar{p} \rightarrow \mu^- \pi^0$	> $5 \times 10^4$	90%	453
$\bar{p} \rightarrow e^- \eta$	> $2 \times 10^4$	90%	309
$\bar{p} \rightarrow \mu^- \eta$	> $8 \times 10^3$	90%	297
$\bar{p} \rightarrow e^- K_S^0$	> 900	90%	337
$\bar{p} \rightarrow \mu^- K_S^0$	> $4 \times 10^3$	90%	326
$\bar{p} \rightarrow e^- K_L^0$	> $9 \times 10^3$	90%	337
$\bar{p} \rightarrow \mu^- K_L^0$	> $7 \times 10^3$	90%	326
$\bar{p} \rightarrow e^- \gamma \gamma$	> $2 \times 10^4$	90%	469
$\bar{p} \rightarrow \mu^- \gamma \gamma$	> $2 \times 10^4$	90%	463
$\bar{p} \rightarrow e^- \omega$	> 200	90%	143

**$n$**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass  $m = 1.0086649160 \pm 0.0000000005$  u

Mass  $m = 939.5654205 \pm 0.0000005$  MeV [a]

$$(m_n - m_{\bar{n}}) / m_n = (9 \pm 5) \times 10^{-5}$$

$$m_n - m_p = 1.2933324 \pm 0.0000005 \text{ MeV} \\ = 0.00138844919(45) \text{ u}$$

Mean life  $\tau = 878.4 \pm 0.5$  s (S = 1.8)

$$c\tau = 2.6335 \times 10^8 \text{ km}$$

Magnetic moment  $\mu = -1.9130427 \pm 0.0000005 \mu_N$

Electric dipole moment  $d < 0.18 \times 10^{-25}$  e cm, CL = 90%

Mean-square charge radius  $\langle r_n^2 \rangle = -0.1155 \pm 0.0017 \text{ fm}^2$

Magnetic radius  $\sqrt{\langle r_M^2 \rangle} = 0.864_{-0.008}^{+0.009} \text{ fm}$

Electric polarizability  $\alpha = (11.8 \pm 1.1) \times 10^{-4} \text{ fm}^3$

Magnetic polarizability  $\beta = (3.7 \pm 1.2) \times 10^{-4} \text{ fm}^3$

Charge  $q = (-0.2 \pm 0.8) \times 10^{-21} e$

Mean  $n\bar{n}$ -oscillation time >  $8.6 \times 10^7$  s, CL = 90% (free  $n$ )

Mean  $n\bar{n}$ -oscillation time >  $4.7 \times 10^8$  s, CL = 90% [f] (bound  $n$ )

Mean  $nn'$ -oscillation time > 448 s, CL = 90% [g]

**$p e^- \nu_e$  decay parameters** <sup>[h]</sup>

$$\lambda \equiv g_A / g_V = -1.2754 \pm 0.0013 \quad (S = 2.7)$$

$$A = -0.11958 \pm 0.00021 \quad (S = 1.2)$$

$$B = 0.9807 \pm 0.0030$$

$$C = -0.2377 \pm 0.0026$$

$$a = -0.1049 \pm 0.0013 \quad (S = 1.8)$$

$$\phi_{AV} = (180.017 \pm 0.026)^\circ \text{ [l]}$$

$$D = (-1.2 \pm 2.0) \times 10^{-4} \text{ [l]}$$

$$R = 0.004 \pm 0.013 \text{ [l]}$$

$$\text{Fierz interference term } b = 0.017 \pm 0.020$$

<b>n DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$p e^- \bar{\nu}_e$	100 %		1
$p e^- \bar{\nu}_e \gamma$	[k] ( $9.2 \pm 0.7$ ) $\times 10^{-3}$		1
hydrogen-atom $\bar{\nu}_e$	< 2.7 $\times 10^{-3}$	95%	1.19
<b>Charge conservation (Q) violating mode</b>			
$p \nu_e \bar{\nu}_e$	Q < 8 $\times 10^{-27}$	68%	1

 **$N(1440) 1/2^+$** 

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$$\text{Re(pole position)} = 1360 \text{ to } 1380 (\approx 1370) \text{ MeV}$$

$$-2\text{Im(pole position)} = 180 \text{ to } 205 (\approx 190) \text{ MeV}$$

$$\text{Breit-Wigner mass} = 1410 \text{ to } 1470 (\approx 1440) \text{ MeV}$$

$$\text{Breit-Wigner full width} = 250 \text{ to } 450 (\approx 350) \text{ MeV}$$

The following branching fractions are our estimates, not fits or averages.

<b><math>N(1440)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$N\pi$	55–75 %	398
$N\eta$	<1 %	†
$N\pi\pi$	17–50 %	347
$\Delta(1232)\pi$ , P-wave	6–27 %	147
$N\sigma$	11–23 %	–
$p\gamma$ , helicity=1/2	0.035–0.048 %	414
$n\gamma$ , helicity=1/2	0.02–0.04 %	413

 **$N(1520) 3/2^-$** 

$$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$$

$$\text{Re(pole position)} = 1505 \text{ to } 1515 (\approx 1510) \text{ MeV}$$

$$-2\text{Im(pole position)} = 105 \text{ to } 120 (\approx 110) \text{ MeV}$$

$$\text{Breit-Wigner mass} = 1510 \text{ to } 1520 (\approx 1515) \text{ MeV}$$

$$\text{Breit-Wigner full width} = 100 \text{ to } 120 (\approx 110) \text{ MeV}$$

The following branching fractions are our estimates, not fits or averages.

<b><math>N(1520)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$N\pi$	55–65 %	453
$N\eta$	0.07–0.09 %	142
$N\pi\pi$	25–35 %	410
$\Delta(1232)\pi$	22–34 %	225
$\Delta(1232)\pi$ , S-wave	15–23 %	225

$\Delta(1232)\pi$ , <i>D</i> -wave	7-11 %	225
$N\rho$	10-16 %	†
$N\rho$ , $S=3/2$ , <i>S</i> -wave	10-16 %	†
$N\rho$ , $S=1/2$ , <i>D</i> -wave	0.2-0.4 %	†
$N\sigma$	<10 %	—
$p\gamma$	0.31-0.52 %	467
$p\gamma$ , helicity=1/2	0.01-0.02 %	467
$p\gamma$ , helicity=3/2	0.30-0.50 %	467
$n\gamma$	0.30-0.53 %	466
$n\gamma$ , helicity=1/2	0.04-0.10 %	466
$n\gamma$ , helicity=3/2	0.25-0.45 %	466

**$N(1535) 1/2^-$**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$$

Re(pole position) = 1500 to 1520 ( $\approx$  1510) MeV

-2Im(pole position) = 80 to 130 ( $\approx$  110) MeV

Breit-Wigner mass = 1515 to 1545 ( $\approx$  1530) MeV

Breit-Wigner full width = 125 to 175 ( $\approx$  150) MeV

The following branching fractions are our estimates, not fits or averages.

<b><math>N(1535)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$N\pi$	32-52 %	464
$N\eta$	30-55 %	176
$N\pi\pi$	4-31 %	422
$\Delta(1232)\pi$ , <i>D</i> -wave	1-4 %	240
$N\rho$	2-17 %	†
$N\rho$ , $S=1/2$ , <i>S</i> -wave	2-16 %	†
$N\rho$ , $S=3/2$ , <i>D</i> -wave	<1 %	†
$N\sigma$	2-10 %	—
$N(1440)\pi$	5-12 %	†
$p\gamma$ , helicity=1/2	0.15-0.30 %	477
$n\gamma$ , helicity=1/2	0.01-0.25 %	477

**$N(1650) 1/2^-$ ,  $N(1675) 5/2^-$ ,  $N(1680) 5/2^+$ ,  $N(1700) 3/2^-$ ,  $N(1710) 1/2^+$ ,  
 $N(1720) 3/2^+$ ,  $N(1875) 3/2^-$ ,  $N(1880) 1/2^+$ ,  $N(1895) 1/2^-$ ,  $N(1900) 3/2^+$   
 $N(2060) 5/2^-$ ,  $N(2100) 1/2^+$ ,  $N(2120) 3/2^-$ ,  $N(2190) 7/2^-$ ,  $N(2220) 9/2^+$   
 $N(2250) 9/2^-$ ,  $N(2600) 11/2^-$**

The  $N$  resonances listed above are omitted from this Booklet but not from the Summary Table in the full *Review*.

## Δ BARYONS

### ( $S = 0, I = 3/2$ )

$$\Delta^{++} = uuu, \quad \Delta^+ = uud, \quad \Delta^0 = udd, \quad \Delta^- = ddd$$

#### Δ(1232) 3/2<sup>+</sup>

$$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$$

Re(pole position) = 1209 to 1211 ( $\approx 1210$ ) MeV

-2Im(pole position) = 98 to 102 ( $\approx 100$ ) MeV

Breit-Wigner mass (mixed charges) = 1230 to 1234 ( $\approx 1232$ ) MeV

Breit-Wigner full width (mixed charges) = 114 to 120 ( $\approx 117$ ) MeV

The following branching fractions are our estimates, not fits or averages.

Δ(1232) DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$N\pi$	99.4 %	229
$N\gamma$	0.55-0.65 %	259
$N\gamma$ , helicity=1/2	0.11-0.13 %	259
$N\gamma$ , helicity=3/2	0.44-0.52 %	259
$pe^+e^-$	( $4.2 \pm 0.7$ ) $\times 10^{-5}$	259

#### Δ(1600) 3/2<sup>+</sup>

$$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$$

Re(pole position) = 1470 to 1590 ( $\approx 1520$ ) MeV

-2Im(pole position) = 150 to 320 ( $\approx 280$ ) MeV

Breit-Wigner mass = 1500 to 1640 ( $\approx 1570$ ) MeV

Breit-Wigner full width = 200 to 300 ( $\approx 250$ ) MeV

The following branching fractions are our estimates, not fits or averages.

Δ(1600) DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$N\pi$	8-24%	492
$N\pi\pi$	58-84 %	454
$\Delta(1232)\pi$	58-82 %	276
$\Delta(1232)\pi$ , P-wave	72-82%	276
$\Delta(1232)\pi$ , F-wave	<2%	276
$N(1440)\pi$	17-27%	†
$N\gamma$	0.001-0.035 %	505
$N\gamma$ , helicity=1/2	0.0-0.02 %	505
$N\gamma$ , helicity=3/2	0.001-0.015 %	505

#### Δ(1620) 1/2<sup>-</sup>

$$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$$

Re(pole position) = 1590 to 1610 ( $\approx 1600$ ) MeV

-2Im(pole position) = 80 to 140 ( $\approx 110$ ) MeV

Breit-Wigner mass = 1590 to 1630 ( $\approx 1610$ ) MeV

Breit-Wigner full width = 110 to 150 ( $\approx 130$ ) MeV

The following branching fractions are our estimates, not fits or averages.

$\Delta(1620)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$N\pi$	25–35 %	520
$N\pi\pi$	>67 %	484
$\Delta(1232)\pi$ , $D$ -wave	44–72 %	311
$N\rho$	23–32%	†
$N\rho$ , $S=1/2$ , $S$ -wave	23–32%	†
$N\rho$ , $S=3/2$ , $D$ -wave	<0.04%	†
$N(1440)\pi$	<9 %	98
$N\gamma$ , helicity=1/2	0.03–0.10 %	532

$\Delta(1700)$   $3/2^-$ ,  $\Delta(1900)$   $1/2^-$ ,  $\Delta(1905)$   $5/2^+$ ,  $\Delta(1910)$   $1/2^+$ ,  $\Delta(1920)$   $3/2^+$ ,  
 $\Delta(1930)$   $5/2^-$ ,  $\Delta(1950)$   $7/2^+$ ,  $\Delta(2200)$   $7/2^-$ ,  $\Delta(2420)$   $11/2^+$

The  $\Delta$  resonances listed above are omitted from this Booklet but not from the Summary Table in the full *Review*.

## $\Lambda$ BARYONS

### ( $S = -1, I = 0$ )

$$\Lambda^0 = uds$$

$\Lambda$

$$I(J^P) = 0(\frac{1}{2}^+)$$

Mass  $m = 1115.683 \pm 0.006$  MeV

$$(m_\Lambda - m_{\bar{\Lambda}}) / m_\Lambda = (-0.1 \pm 1.1) \times 10^{-5} \quad (S = 1.6)$$

$$\text{Mean life } \tau = (2.617 \pm 0.010) \times 10^{-10} \text{ s} \quad (S = 1.5)$$

$$(\tau_\Lambda - \tau_{\bar{\Lambda}}) / \tau_\Lambda = (0.9 \pm 3.2) \times 10^{-3}$$

$$c\tau = 7.845 \text{ cm}$$

Magnetic moment  $\mu = -0.613 \pm 0.004 \mu_N$

Electric dipole moment  $d < 1.5 \times 10^{-16} \text{ e cm}$ , CL = 95%

#### Decay parameters

$$\rho\pi^- \quad \alpha_- = 0.747 \pm 0.009 \quad (S = 2.5)$$

$$\bar{\rho}\pi^+ \quad \alpha_+ = -0.757 \pm 0.004$$

$$\bar{\alpha}_0 \text{ FOR } \bar{\Lambda} \rightarrow \bar{n}\pi^0 = -0.692 \pm 0.017$$

$$\alpha_\gamma \text{ FOR } \Lambda \rightarrow n\gamma = -0.16 \pm 0.11$$

$$\rho\pi^- \quad \phi_- = (-6.5 \pm 3.5)^\circ$$

$$" \quad \gamma_- = 0.76 \text{ [I]}$$

$$" \quad \Delta_- = (8 \pm 4)^\circ \text{ [I]}$$

$$\bar{\alpha}_0 / \alpha_+ \text{ in } \bar{\Lambda} \rightarrow \bar{n}\pi^0, \bar{\Lambda} \rightarrow \bar{p}\pi^+ = 0.913 \pm 0.030$$

$$R = |G_E/G_M| \text{ in } \Lambda \rightarrow \rho\pi^-, \bar{\Lambda} \rightarrow \bar{\rho}\pi^+ = 0.96 \pm 0.14$$

$$\Delta\Phi = \Phi_E - \Phi_M \text{ in } \Lambda \rightarrow \rho\pi^-, \bar{\Lambda} \rightarrow \bar{\rho}\pi^+ = 37 \pm 13 \text{ degrees}$$

$$n\pi^0 \quad \alpha_0 = 0.75 \pm 0.05$$

$$\rho e^- \bar{\nu}_e \quad g_A/g_V = -0.718 \pm 0.015 \text{ [h]}$$

$\Lambda$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\rho\pi^-$	(64.1 $\pm$ 0.5 ) %		101
$n\pi^0$	(35.9 $\pm$ 0.5 ) %		104

$n\gamma$		$(8.3 \pm 0.7) \times 10^{-4}$	162
$p\pi^-\gamma$	[n]	$(8.5 \pm 1.4) \times 10^{-4}$	101
$pe^-\bar{\nu}_e$		$(8.34 \pm 0.14) \times 10^{-4}$	163
$p\mu^-\bar{\nu}_\mu$		$(1.51 \pm 0.19) \times 10^{-4}$	131

## Lepton (L) and/or Baryon (B) number violating decay modes

$\pi^+e^-$	$L, B$	$< 6$	$\times 10^{-7}$	90%	549
$\pi^+\mu^-$	$L, B$	$< 6$	$\times 10^{-7}$	90%	544
$\pi^-e^+$	$L, B$	$< 4$	$\times 10^{-7}$	90%	549
$\pi^-\mu^+$	$L, B$	$< 6$	$\times 10^{-7}$	90%	544
$K^+e^-$	$L, B$	$< 2$	$\times 10^{-6}$	90%	449
$K^+\mu^-$	$L, B$	$< 3$	$\times 10^{-6}$	90%	441
$K^-e^+$	$L, B$	$< 2$	$\times 10^{-6}$	90%	449
$K^-\mu^+$	$L, B$	$< 3$	$\times 10^{-6}$	90%	441
$K_S^0\nu$	$L, B$	$< 2$	$\times 10^{-5}$	90%	447
$\bar{p}\pi^+$	$B$	$< 9$	$\times 10^{-7}$	90%	101
invisible		$< 7.4$	$\times 10^{-5}$	90%	—

 **$\Lambda(1405) 1/2^-$** 

$$I(J^P) = 0(\frac{1}{2}^-)$$

Mass  $m = 1405.1_{-1.0}^{+1.3}$  MeVFull width  $\Gamma = 50.5 \pm 2.0$  MeVBelow  $\bar{K}N$  threshold

$\Lambda(1405)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$\Sigma\pi$	100 %	155

 **$\Lambda(1520) 3/2^-$** 

$$I(J^P) = 0(\frac{3}{2}^-)$$

Mass  $m = 1518$  to  $1520$  ( $\approx 1519$ ) MeV [o]Full width  $\Gamma = 15$  to  $17$  ( $\approx 16$ ) MeV [o]

$\Lambda(1520)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$N\bar{K}$	$(45 \pm 1) \%$	242
$\Sigma\pi$	$(42 \pm 1) \%$	268
$\Lambda\pi\pi$	$(10 \pm 1) \%$	259
$\Sigma\pi\pi$	$(0.9 \pm 0.1) \%$	168
$\Lambda\gamma$	$(0.85 \pm 0.15) \%$	350

**$\Lambda(1600) 1/2^+$ ,  $\Lambda(1670) 1/2^-$ ,  $\Lambda(1690) 3/2^-$ ,  $\Lambda(1800) 1/2^-$ ,  $\Lambda(1810) 1/2^+$ ,  
 $\Lambda(1820) 5/2^+$ ,  $\Lambda(1830) 5/2^-$ ,  $\Lambda(1890) 3/2^+$ ,  $\Lambda(2100) 7/2^-$ ,  $\Lambda(2110) 5/2^+$ ,  
 $\Lambda(2350) 9/2^+$**

The  $\Lambda$  resonances listed above are omitted from this Booklet but not from the Summary Table in the full Review.

# Σ BARYONS (S = -1, I = 1)

$$\Sigma^+ = uus, \quad \Sigma^0 = uds, \quad \Sigma^- = dds$$

**Σ<sup>+</sup>**

$$I(J^P) = 1(\frac{1}{2}^+)$$

Mass  $m = 1189.37 \pm 0.07$  MeV (S = 2.2)

Mean life  $\tau = (0.8018 \pm 0.0026) \times 10^{-10}$  s

$c\tau = 2.404$  cm

$(\tau_{\Sigma^+} - \tau_{\Sigma^-}) / \tau_{\Sigma^+} = -0.0006 \pm 0.0012$

Magnetic moment  $\mu = 2.458 \pm 0.010 \mu_N$  (S = 2.1)

$(\mu_{\Sigma^+} + \mu_{\Sigma^-}) / \mu_{\Sigma^+} = 0.014 \pm 0.015$

$\Gamma(\Sigma^+ \rightarrow n\ell^+\nu) / \Gamma(\Sigma^- \rightarrow n\ell^-\bar{\nu}_\ell) < 0.043$

### Decay parameters

$\rho\pi^0 \quad \alpha_0 = -0.982 \pm 0.014$

$\bar{\rho}\pi^0 \quad \bar{\alpha}_0 = 0.99 \pm 0.04$

$(\alpha_0 + \bar{\alpha}_0) / (\alpha_0 - \bar{\alpha}_0) = 0.00 \pm 0.04$

$\rho\pi^0 \quad \phi_0 = (36 \pm 34)^\circ$

"  $\gamma_0 = 0.16$  [I]

"  $\Delta_0 = (187 \pm 6)^\circ$  [I]

$n\pi^+ \quad \alpha_+ = (4.89 \pm 0.26) \times 10^{-2}$

"  $\phi_+ = (167 \pm 20)^\circ$  (S = 1.1)

$\bar{\alpha}_-$  FOR  $\bar{\Sigma}^- \rightarrow \bar{n}\pi^- = (-5.7 \pm 0.5) \times 10^{-2}$

$\bar{\alpha}_- / \bar{\alpha}_0 = (-5.7 \pm 0.6) \times 10^{-2}$

$(\alpha_+ + \bar{\alpha}_-) / (\alpha_+ - \bar{\alpha}_-) = (-8 \pm 6) \times 10^{-2}$

"  $\gamma_+ = -0.97$  [I]

"  $\Delta_+ = (-73^{+133}_{-10})^\circ$  [I]

$\rho\gamma \quad \alpha_\gamma = -0.69 \pm 0.05$

### Σ<sup>+</sup> DECAY MODES

	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\rho\pi^0$	$(51.57 \pm 0.30) \%$		189
$n\pi^+$	$(48.31 \pm 0.30) \%$		185
$\rho\gamma$	$(1.23 \pm 0.05) \times 10^{-3}$		225
$n\pi^+\gamma$	[n] $(4.5 \pm 0.5) \times 10^{-4}$		185
$\Lambda e^+\nu_e$	$(2.3 \pm 0.4) \times 10^{-5}$		71

### ΔS = ΔQ (SQ) violating modes or ΔS = 1 weak neutral current (SI) modes

$ne^+\nu_e$	SQ	$< 5 \times 10^{-6}$	90%	224
$n\mu^+\nu_\mu$	SQ	$< 3.0 \times 10^{-5}$	90%	202
$\rho e^+ e^-$	SI	$< 7 \times 10^{-6}$		225
$\rho\mu^+\mu^-$	SI	$(2.4^{+1.7}_{-1.3}) \times 10^{-8}$		121

**Σ<sup>0</sup>**

$$I(J^P) = 1(\frac{1}{2}^+)$$

Mass  $m = 1192.642 \pm 0.024$  MeV

$m_{\Sigma^-} - m_{\Sigma^0} = 4.807 \pm 0.035$  MeV (S = 1.1)

$m_{\Sigma^0} - m_\Lambda = 76.959 \pm 0.023$  MeV



Mean life  $\tau = (7.4 \pm 0.7) \times 10^{-20}$  s

$c\tau = 2.22 \times 10^{-11}$  m

Transition magnetic moment  $|\mu_{\Sigma\Lambda}| = 1.61 \pm 0.08 \mu_N$

$\Sigma^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\Lambda\gamma$	100 %		74
$\Lambda\gamma\gamma$	< 3 %	90%	74
$\Lambda e^+ e^-$	[ $\rho$ ] $5 \times 10^{-3}$		74

$\Sigma^-$

$I(J^P) = 1(\frac{1}{2}^+)$

Mass  $m = 1197.449 \pm 0.029$  MeV (S = 1.1)

$m_{\Sigma^-} - m_{\Sigma^+} = 8.08 \pm 0.08$  MeV (S = 1.9)

$m_{\Sigma^-} - m_{\Lambda} = 81.766 \pm 0.029$  MeV (S = 1.1)

Mean life  $\tau = (1.479 \pm 0.011) \times 10^{-10}$  s (S = 1.3)

$c\tau = 4.434$  cm

Magnetic moment  $\mu = -1.160 \pm 0.025 \mu_N$  (S = 1.7)

$\Sigma^-$  charge radius =  $0.78 \pm 0.10$  fm

#### Decay parameters

$n\pi^-$   $\alpha_- = -0.068 \pm 0.008$

"  $\phi_- = (10 \pm 15)^\circ$

"  $\gamma_- = 0.98$  [f]

"  $\Delta_- = (249_{-120}^{+12})^\circ$  [f]

$ne^- \bar{\nu}_e$   $g_A/g_V = 0.340 \pm 0.017$  [h]

"  $f_2(0)/f_1(0) = 0.97 \pm 0.14$

"  $D = 0.11 \pm 0.10$

$\Lambda e^- \bar{\nu}_e$   $g_V/g_A = 0.01 \pm 0.10$  [h] (S = 1.5)

"  $g_{WM}/g_A = 2.4 \pm 1.7$  [h]

$\Sigma^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$n\pi^-$	(99.848 ± 0.005) %		193
$n\pi^- \gamma$	[n] (4.6 ± 0.6) × 10 <sup>-4</sup>		193
$ne^- \bar{\nu}_e$	(1.017 ± 0.034) × 10 <sup>-3</sup>		230
$n\mu^- \bar{\nu}_\mu$	(4.5 ± 0.4) × 10 <sup>-4</sup>		210
$\Lambda e^- \bar{\nu}_e$	(5.73 ± 0.27) × 10 <sup>-5</sup>		79
$\Sigma^+ X$	< 1.2 × 10 <sup>-4</sup>	90%	-

#### Lepton number (L) violating modes

$pe^- e^-$	L	< 6.7 × 10 <sup>-5</sup>	90%	231
------------	---	--------------------------	-----	-----

$\Sigma(1385) 3/2^+$

$I(J^P) = 1(\frac{3}{2}^+)$

$\Sigma(1385)^+$  mass  $m = 1382.83 \pm 0.34$  MeV (S = 1.9)

$\Sigma(1385)^0$  mass  $m = 1383.7 \pm 1.0$  MeV (S = 1.4)

$\Sigma(1385)^-$  mass  $m = 1387.2 \pm 0.5$  MeV (S = 2.2)

$\Sigma(1385)^+$  full width  $\Gamma = 36.2 \pm 0.7$  MeV

$\Sigma(1385)^0$  full width  $\Gamma = 36 \pm 5$  MeV

$\Sigma(1385)^-$  full width  $\Gamma = 39.4 \pm 2.1$  MeV (S = 1.7)

Below  $\bar{K}N$  threshold

$\Sigma(1385)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\Lambda\pi$	(87.0 $\pm$ 1.5 ) %		208
$\Sigma\pi$	(11.7 $\pm$ 1.5 ) %		129
$\Lambda\gamma$	( 1.25 $^{+0.13}$ $_{-0.12}$ ) %		241
$\Sigma^+\gamma$	( 7.0 $\pm$ 1.7 ) $\times 10^{-3}$		180
$\Sigma^-\gamma$	< 2.4 $\times 10^{-4}$	90%	173

 **$\Sigma(1660)$   $1/2^+$** 

$$I(J^P) = 1(\frac{1}{2}^+)$$

Re(pole position) = 1585  $\pm$  20 MeV

-2Im(pole position) = 290 $^{+140}$  $_{-40}$  MeV

Mass  $m$  = 1640 to 1680 ( $\approx$  1660) MeV

Full width  $\Gamma$  = 100 to 300 ( $\approx$  200) MeV

$\Sigma(1660)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$N\bar{K}$	0.05 to 0.15 ( $\approx$ 010)	405
$\Lambda\pi$	(35 $\pm$ 12 ) %	440
$\Sigma\pi$	(37 $\pm$ 10 ) %	387
$\Sigma\sigma$	(20 $\pm$ 8 ) %	-
$\Lambda(1405)\pi$	( 4.0 $\pm$ 2.0 ) %	199

**$\Sigma(1670)$   $3/2^-$ ,  $\Sigma(1750)$   $1/2^-$ ,  $\Sigma(1775)$   $5/2^-$ ,  $\Sigma(1915)$   $5/2^+$ ,  
 $\Sigma(1940)$   $3/2^-$ ,  $\Sigma(2030)$   $7/2^+$ ,  $\Sigma(2250)$**

The  $\Sigma$  resonances listed above are omitted from this Booklet but not from the Summary Table in the full *Review*.

## $\Xi$ BARYONS

### $(S = -2, I = 1/2)$

$$\Xi^0 = uss, \quad \Xi^- = dss$$

 **$\Xi^0$** 

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$P$  is not yet measured; + is the quark model prediction.

Mass  $m$  = 1314.86  $\pm$  0.20 MeV

$m_{\Xi^-} - m_{\Xi^0} = 6.85 \pm 0.21$  MeV

Mean life  $\tau = (2.90 \pm 0.09) \times 10^{-10}$  s

$c\tau = 8.71$  cm

Magnetic moment  $\mu = -1.250 \pm 0.014 \mu_N$

**Decay parameters**

$\Lambda\pi^0$   $\alpha = -0.349 \pm 0.009$

$\alpha$  FOR  $\Xi^0 \rightarrow \bar{\Lambda}\pi^0 = 0.379 \pm 0.004$

"  $\phi = (0.3 \pm 0.6)^\circ$

$\phi$  ANGLE FOR  $\Xi^0 \rightarrow \bar{\Lambda}\pi^0$  with  $\tan\phi = \beta/\gamma = -0.3 \pm 0.6$  degrees

$\Delta\phi_{CP}(\Xi^0) = (\phi_{\Xi^0} + \phi_{\bar{\Xi}^0})/2 = 0.0 \pm 0.4$  degrees

$A_{CP}$  FOR  $\Xi^0 \rightarrow \Lambda\pi^0, \bar{\Xi}^0 \rightarrow \bar{\Lambda}\pi^0 = (-5 \pm 7) \times 10^{-3}$

"	$\gamma = 0.85$ [I]
"	$\Delta = (218_{-19}^{+12})^\circ$ [I]
$\Lambda\gamma$	$\alpha = -0.70 \pm 0.07$
$\Lambda e^+ e^-$	$\alpha = -0.8 \pm 0.2$
$\Sigma^0\gamma$	$\alpha = -0.69 \pm 0.06$
$\Sigma^+ e^- \bar{\nu}_e$	$g_1(0)/f_1(0) = 1.22 \pm 0.05$
$\Sigma^+ e^- \bar{\nu}_e$	$f_2(0)/f_1(0) = 2.0 \pm 0.9$

$\Xi^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\Lambda\pi^0$	$(99.524 \pm 0.012) \%$		135
$\Lambda\gamma$	$(1.17 \pm 0.07) \times 10^{-3}$		184
$\Lambda e^+ e^-$	$(7.6 \pm 0.6) \times 10^{-6}$		184
$\Sigma^0\gamma$	$(3.33 \pm 0.10) \times 10^{-3}$		117
$\Sigma^+ e^- \bar{\nu}_e$	$(2.52 \pm 0.08) \times 10^{-4}$		120
$\Sigma^+ \mu^- \bar{\nu}_\mu$	$(2.33 \pm 0.35) \times 10^{-6}$		64

**$\Delta S = \Delta Q$  (SQ) violating modes or  
 $\Delta S = 2$  forbidden (S2) modes**

$\Sigma^- e^+ \nu_e$	SQ	$< 1.6$	$\times 10^{-4}$	90%	112
$\Sigma^- \mu^+ \nu_\mu$	SQ	$< 9$	$\times 10^{-4}$	90%	49
$p\pi^-$	S2	$< 8$	$\times 10^{-6}$	90%	299
$p e^- \bar{\nu}_e$	S2	$< 1.3$	$\times 10^{-3}$		323
$p \mu^- \bar{\nu}_\mu$	S2	$< 1.3$	$\times 10^{-3}$		309

**$\Xi^-$**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$P$  is not yet measured; + is the quark model prediction.

Mass  $m = 1321.71 \pm 0.07$  MeV

$$(m_{\Xi^-} - m_{\Xi^+}) / m_{\Xi^-} = (-3 \pm 9) \times 10^{-5}$$

$$\text{Mean life } \tau = (1.639 \pm 0.015) \times 10^{-10} \text{ s}$$

$$c\tau = 4.91 \text{ cm}$$

$$(\tau_{\Xi^-} - \tau_{\Xi^+}) / \tau_{\Xi^-} = -0.01 \pm 0.07$$

$$\text{Magnetic moment } \mu = -0.6507 \pm 0.0025 \mu_N$$

$$(\mu_{\Xi^-} + \mu_{\Xi^+}) / |\mu_{\Xi^-}| = +0.01 \pm 0.05$$

**Decay parameters**

$$\Lambda\pi^- \quad \alpha = -0.390 \pm 0.007 \quad (S = 2.0)$$

$$\alpha(\Xi^+) \text{ for } \Xi^+ \rightarrow \bar{\Lambda}\pi^+ = 0.371 \pm 0.007$$

$$(\alpha + \bar{\alpha}) / (\alpha - \bar{\alpha}) \text{ for } \Xi^- \rightarrow \Lambda\pi^-, \Xi^+ \rightarrow \bar{\Lambda}\pi^+ = (6 \pm 14) \times 10^{-3}$$

$$[\alpha(\Xi^-)\alpha_-(\Lambda) - \alpha(\Xi^+)\alpha_+(\bar{\Lambda})] / [\text{sum}] = (0 \pm 7) \times 10^{-4}$$

$$\phi = (-1.2 \pm 1.0)^\circ \quad (S = 1.4)$$

$$\phi \text{ ANGLE FOR } \Xi^+ \rightarrow \bar{\Lambda}\pi^+ \quad (\tan\phi = \beta/\gamma) = (-1.2 \pm 1.2)^\circ$$

$$\Delta\Phi_{CP} = (\Phi_- + \Phi_+)/2 = (-0.3 \pm 0.8)^\circ$$

$$\gamma = 0.89$$
 [I]

$$\Delta = (175.9 \pm 1.5)^\circ$$
 [I]

$$\Lambda e^- \bar{\nu}_e \quad g_A/g_V = -0.25 \pm 0.05$$
 [h]

$\Xi^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\Lambda\pi^-$	$(99.887 \pm 0.035) \%$		140
$\Sigma^- \gamma$	$(1.27 \pm 0.23) \times 10^{-4}$		118
$\Lambda e^- \bar{\nu}_e$	$(5.63 \pm 0.31) \times 10^{-4}$		190

$\Lambda\mu^-\bar{\nu}_\mu$	( 3.5 $\begin{smallmatrix} +3.5 \\ -2.2 \end{smallmatrix}$ ) $\times 10^{-4}$			163
$\Sigma^0 e^-\bar{\nu}_e$	( 8.7 $\pm 1.7$ ) $\times 10^{-5}$			123
$\Sigma^0\mu^-\bar{\nu}_\mu$	< 8 $\times 10^{-4}$	90%		70
$\Xi^0 e^-\bar{\nu}_e$	< 2.59 $\times 10^{-4}$	90%		7

 **$\Delta S = 2$  forbidden ( $S_2$ ) modes**

$n\pi^-$	$S_2$ < 1.9 $\times 10^{-5}$	90%		304
$ne^-\bar{\nu}_e$	$S_2$ < 3.2 $\times 10^{-3}$	90%		327
$n\mu^-\bar{\nu}_\mu$	$S_2$ < 1.5 %	90%		314
$\rho\pi^-\pi^-$	$S_2$ < 4 $\times 10^{-4}$	90%		223
$\rho\pi^-e^-\bar{\nu}_e$	$S_2$ < 4 $\times 10^{-4}$	90%		305
$\rho\pi^-\mu^-\bar{\nu}_\mu$	$S_2$ < 4 $\times 10^{-4}$	90%		251
$\rho\mu^-\mu^-$	$L$ < 4 $\times 10^{-8}$	90%		272

 **$\Xi(1530) 3/2^+$** 

$$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$$

$$\Xi(1530)^0 \text{ mass } m = 1531.80 \pm 0.32 \text{ MeV} \quad (S = 1.3)$$

$$\Xi(1530)^- \text{ mass } m = 1535.0 \pm 0.6 \text{ MeV}$$

$$\Xi(1530)^0 \text{ full width } \Gamma = 9.1 \pm 0.5 \text{ MeV}$$

$$\Xi(1530)^- \text{ full width } \Gamma = 9.9^{+1.7}_{-1.9} \text{ MeV}$$

<b><math>\Xi(1530)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\Xi\pi$	100 %		158
$\Xi\gamma$	<3.7 %	90%	202

 **$\Xi(1690)$ ,  $\Xi(1820) 3/2^-$ ,  $\Xi(1950)$ ,  $\Xi(2030)$** 

The  $\Xi$  resonances listed above are omitted from this Booklet but not from the Summary Table in the full *Review*.

## $\Omega$ BARYONS

### $(S = -3, I = 0)$

$$\Omega^- = sss$$

 **$\Omega^-$** 

$$I(J^P) = 0(\frac{3}{2}^+)$$

$J^P = \frac{3}{2}^+$  is the quark-model prediction; and  $J = 3/2$  is fairly well established.

$$\text{Mass } m = 1672.45 \pm 0.29 \text{ MeV}$$

$$(m_{\Omega^-} - m_{\bar{\Omega}^+}) / m_{\Omega^-} = (-1 \pm 8) \times 10^{-5}$$

$$\text{Mean life } \tau = (0.821 \pm 0.011) \times 10^{-10} \text{ s}$$

$$c\tau = 2.461 \text{ cm}$$

$$(\tau_{\Omega^-} - \tau_{\bar{\Omega}^+}) / \tau_{\Omega^-} = 0.00 \pm 0.05$$

$$\text{Magnetic moment } \mu = -2.02 \pm 0.05 \mu_N$$

**Decay parameters**

$$\alpha(\Omega^-) \alpha_-(\Lambda) \text{ FOR } \Omega^- \rightarrow \Lambda K^- = 0.0115 \pm 0.0015$$

$$\Lambda K^- \quad \alpha = 0.0154 \pm 0.0020$$

$$\Lambda K^-, \bar{\Lambda} K^+ \quad (\alpha + \bar{\alpha}) / (\alpha - \bar{\alpha}) = -0.02 \pm 0.13$$

$$\Xi^0 \pi^- \quad \alpha = 0.09 \pm 0.14$$

$$\Xi^- \pi^0 \quad \alpha = 0.05 \pm 0.21$$

$\Omega^-$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$\Lambda K^-$	(67.7 $\pm$ 0.7) %		211
$\Xi^0 \pi^-$	(24.3 $\pm$ 0.7) %	S=1.5	294
$\Xi^- \pi^0$	( 8.55 $\pm$ 0.33) %		289
$\Xi^- \pi^+ \pi^-$	( 3.7 $^{+0.7}_{-0.6}$ ) $\times 10^{-4}$		189
$\Xi(1530)^0 \pi^-$	< 7 $\times 10^{-5}$	CL=90%	17
$\Xi^0 e^- \bar{\nu}_e$	( 5.6 $\pm$ 2.8 ) $\times 10^{-3}$		319
$\Xi^- \gamma$	< 4.6 $\times 10^{-4}$	CL=90%	314
<b><math>\Delta S = 2</math> forbidden (<math>S2</math>) modes</b>			
$\Lambda \pi^-$	$S2$ < 2.9 $\times 10^{-6}$	CL=90%	449

**$\Omega(2012)^-$**

$$I(J^P) = 0(?^-)$$

Mass  $m = 2012.4 \pm 0.9$  MeV

Full width  $\Gamma = 6.4^{+3.0}_{-2.6}$  MeV

Branching fractions are given relative to the one **DEFINED AS 1**.

$\Omega(2012)^-$ DECAY MODES	Fraction ( $\Gamma_j/\Gamma$ )	Confidence level	$p$ (MeV/c)
$\Xi^0 K^-$	<b>DEFINED AS 1</b>		403
$\Xi^- \bar{K}^0$	0.83 $\pm$ 0.21		392
$\Xi^0 \pi^0 K^-$	< 0.30	90%	245
$\Xi^0 \pi^- \bar{K}^0$	< 0.21	90%	230
$\Xi^- \pi^0 \bar{K}^0$	< 0.7	90%	226
$\Xi^- \pi^+ K^-$	< 0.08	90%	224

**$\Omega(2250)^-$**

$$I(J^P) = 0(?^?)$$

Mass  $m = 2252 \pm 9$  MeV

Full width  $\Gamma = 55 \pm 18$  MeV

## CHARMED BARYONS

### ( $C = +1$ )

$$\Lambda_c^+ = udc, \quad \Sigma_c^{++} = uuc, \quad \Sigma_c^+ = udc, \quad \Sigma_c^0 = ddc,$$

$$\Xi_c^+ = usc, \quad \Xi_c^0 = dsc, \quad \Omega_c^0 = ssc$$

**$\Lambda_c^+$**

$$I(J^P) = 0(\frac{1}{2}^+)$$

Mass  $m = 2286.46 \pm 0.14$  MeV

Mean life  $\tau = (202.6 \pm 1.0) \times 10^{-15}$  s

$c\tau = 60.75$   $\mu$ m

#### Decay asymmetry parameters

$$\Lambda \pi^+ \quad \alpha = -0.755 \pm 0.006$$

$$\alpha \text{ FOR } \Lambda_c^+ \rightarrow \Lambda \rho^+ = -0.76 \pm 0.07$$

$$\Sigma^+ \pi^0 \quad \alpha = -0.484 \pm 0.027$$

$$\begin{aligned}
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Sigma^+ \eta = -0.99 \pm 0.06 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Sigma^+ \eta' = -0.46 \pm 0.07 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Sigma^0 \pi^+ = -0.466 \pm 0.018 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Sigma(1385)^+ \pi^0 = -0.92 \pm 0.09 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Sigma(1385)^0 \pi^+ = -0.79 \pm 0.11 \\
\Lambda \ell^+ \nu_\ell &\quad \alpha = -0.875 \pm 0.033 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow p K_S^0 = 0.2 \pm 0.5 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda K^+ = -0.58 \pm 0.05 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Sigma^0 K^+ = -0.54 \pm 0.20 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda(1405) \pi^+ = 0.58 \pm 0.28 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda(1520) \pi^+ = 0.93 \pm 0.09 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda(1600) \pi^+ = 0.2 \pm 0.5 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda(1670) \pi^+ = 0.82 \pm 0.08 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda(1690) \pi^+ = 0.958 \pm 0.034 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Lambda(2000) \pi^+ = -0.57 \pm 0.19 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Delta(1232)^{++} K^- = 0.55 \pm 0.04 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Delta(1600)^{++} K^- = -0.50 \pm 0.18 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \Delta(1700)^{++} K^- = 0.22 \pm 0.08 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \bar{K}_0^*(700)^0 p = -0.1 \pm 0.7 \\
\alpha \text{ FOR } \Lambda_c^+ &\rightarrow \bar{K}_0^*(1430)^0 p = 0.34 \pm 0.14 \\
(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \text{ in } \Lambda_c^+ &\rightarrow \Lambda \pi^+, \bar{\Lambda}_c^- \rightarrow \bar{\Lambda} \pi^- = 0.020 \pm 0.016 \\
(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \text{ in } \Lambda_c^+ &\rightarrow \Sigma^0 \pi^+, \bar{\Lambda}_c^- \rightarrow \bar{\Sigma}^0 \pi^- = -0.02 \pm 0.05 \\
(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \text{ in } \Lambda_c^+ &\rightarrow \Lambda e^+ \nu_e, \bar{\Lambda}_c^- \rightarrow \bar{\Lambda} e^- \bar{\nu}_e = 0.00 \pm 0.04 \\
(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \text{ in } \Lambda_c^+ &\rightarrow \Lambda K^+, \bar{\Lambda}_c^- \rightarrow \bar{\Lambda} K^- = -0.23 \pm 0.11 \\
(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \text{ in } \Lambda_c^+ &\rightarrow \Sigma^0 K^+, \bar{\Lambda}_c^- \rightarrow \bar{\Sigma}^0 K^- = 0.1 \pm 0.4 \\
A_{CP}(\Lambda X) \text{ in } \Lambda_c &\rightarrow \Lambda X, \bar{\Lambda}_c \rightarrow \bar{\Lambda} X = (2 \pm 7)\% \\
A_{CP}(\Lambda K^+) \text{ in } \Lambda_c &\rightarrow \Lambda K^+, \bar{\Lambda}_c \rightarrow \bar{\Lambda} K^- = 0.021 \pm 0.026 \\
A_{CP}(\Sigma^0 K^+) \text{ in } \Lambda_c &\rightarrow \Sigma^0 K^+, \bar{\Lambda}_c \rightarrow \bar{\Sigma}^0 K^- = 0.03 \pm 0.05 \\
\Delta A_{CP} = A_{CP}(\Lambda_c^+ &\rightarrow p K^+ K^-) - A_{CP}(\Lambda_c^+ \rightarrow p \pi^+ \pi^-) = \\
&\quad (0.3 \pm 1.1)\%
\end{aligned}$$

Branching fractions marked with a footnote, e.g. [a], have been corrected for decay modes not observed in the experiments. For example, the submode fraction  $\Lambda_c^+ \rightarrow p \bar{K}^*(892)^0$  seen in  $\Lambda_c^+ \rightarrow p K^- \pi^+$  has been multiplied up to include  $\bar{K}^*(892)^0 \rightarrow \bar{K}^0 \pi^0$  decays.

$\Lambda_c^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Hadronic modes with a <math>p</math> or <math>n</math>: <math>S = -1</math> final states</b>			
$p K_S^0$	( 1.59 ± 0.07 ) %	S=1.1	873
$p K^- \pi^+$	( 6.24 ± 0.28 ) %	S=1.4	823
$p \bar{K}_0^*(700)^0$	( 1.9 ± 0.6 ) × 10 <sup>-3</sup>		715
$p \bar{K}^*(892)^0$	[q] ( 1.39 ± 0.07 ) %		685
$p \bar{K}_0^*(1430)$	( 9.2 ± 1.8 ) × 10 <sup>-3</sup>		†
$\Delta(1232)^{++} K^-$	( 1.76 ± 0.09 ) %		710
$\Delta(1600)^{++} K^-$	( 2.8 ± 1.0 ) × 10 <sup>-3</sup>		—
$\Delta(1700)^{++} K^-$	( 2.4 ± 0.6 ) × 10 <sup>-3</sup>		—
$\Lambda(1405)^0 \pi^+$	( 4.8 ± 1.9 ) × 10 <sup>-3</sup>		—
$\Lambda(1520) \pi^+$	[q] ( 1.16 ± 0.16 ) × 10 <sup>-3</sup>		628
$\Lambda(1600) \pi^+$	( 3.2 ± 1.2 ) × 10 <sup>-3</sup>		571

$\Lambda(1670)\pi^+$	$(7.4 \pm 2.1) \times 10^{-4}$		516
$\Lambda(1690)\pi^+$	$(7.4 \pm 2.2) \times 10^{-4}$		504
$\Lambda(2000)\pi^+$	$(6.0 \pm 0.7) \times 10^{-3}$		234
$\rho K^- \pi^+$ nonresonant	$(3.5 \pm 0.4) \%$		823
$\rho K_S^0 \pi^0$	$(1.96 \pm 0.12) \%$		823
$n K_S^0 \pi^+$	$(1.82 \pm 0.25) \%$		821
$n K^- \pi^+ \pi^+$	$(1.90 \pm 0.12) \%$		756
$\rho \bar{K}^0 \eta$	$(8.8 \pm 0.6) \times 10^{-3}$	S=1.1	568
$\rho K_S^0 \pi^+ \pi^-$	$(1.59 \pm 0.11) \%$	S=1.1	754
$\rho K^- \pi^+ \pi^0$	$(4.43 \pm 0.28) \%$	S=1.5	759
$\rho K^*(892)^- \pi^+$	[q] $(1.4 \pm 0.5) \%$		580
$\rho(K^- \pi^+)$ nonresonant $\pi^0$	$(4.6 \pm 0.8) \%$		759
$\rho K^- 2\pi^+ \pi^-$	$(1.4 \pm 0.9) \times 10^{-3}$		671
$\rho K^- \pi^+ 2\pi^0$	$(10 \pm 5) \times 10^{-3}$		678

### Hadronic modes with a $\rho$ or $n$ : $S = 0$ final states

$\rho \pi^0$	$< 8$	$\times 10^{-5}$	CL=90%	945
$n \pi^+$	$(6.6 \pm 1.3) \times 10^{-4}$			944
$\rho \eta$	$(1.57 \pm 0.12) \times 10^{-3}$			856
$\rho \eta'$	$(4.8 \pm 0.9) \times 10^{-4}$			639
$\rho \omega(782)^0$	$(1.11 \pm 0.21) \times 10^{-3}$			751
$\rho \pi^+ \pi^-$	$(4.59 \pm 0.25) \times 10^{-3}$			927
$\rho f_0(980)$	[q] $(3.4 \pm 2.3) \times 10^{-3}$			614
$n \pi^+ \pi^0$	$(6.4 \pm 0.9) \times 10^{-3}$			927
$n \pi^+ \pi^- \pi^+$	$(4.5 \pm 0.8) \times 10^{-3}$			895
$\rho 2\pi^+ 2\pi^-$	$(2.2 \pm 1.4) \times 10^{-3}$			852
$\rho K^+ K^-$	$(1.06 \pm 0.05) \times 10^{-3}$			616
$\rho \phi$	[q] $(1.06 \pm 0.14) \times 10^{-3}$			590
$\rho K^+ K^-$ non- $\phi$	$(5.2 \pm 1.1) \times 10^{-4}$			616
$\rho K_S^0 K_S^0$	$(2.35 \pm 0.18) \times 10^{-4}$			610
$\rho \phi \pi^0$	$(10 \pm 4) \times 10^{-5}$			460
$\rho K^+ K^- \pi^0$ nonresonant	$< 6.3$	$\times 10^{-5}$	CL=90%	494

### Hadronic modes with a hyperon: $S = -1$ final states

$\Lambda \pi^+$	$(1.29 \pm 0.05) \%$	S=1.1	864
$\Lambda(1670)\pi^+, \Lambda(1670) \rightarrow \eta \Lambda$	$(3.5 \pm 0.5) \times 10^{-3}$		—
$\Lambda \pi^+ \pi^0$	$(7.02 \pm 0.35) \%$	S=1.1	844
$\Lambda \rho^+$	$(4.0 \pm 0.5) \%$		636
$\Sigma(1385)^+ \pi^0, \Sigma^+ \rightarrow \Lambda \pi^+$	$(5.0 \pm 0.7) \times 10^{-3}$		—
$\Sigma(1385)^0 \pi^+, \Sigma^0 \rightarrow \Lambda \pi^0$	$(5.6 \pm 0.8) \times 10^{-3}$		—
$\Lambda \pi^- 2\pi^+$	$(3.61 \pm 0.26) \%$	S=1.4	807
$\Sigma(1385)^+ \pi^+ \pi^-, \Sigma^{*+} \rightarrow$	$(1.0 \pm 0.5) \%$		688
$\Lambda \pi^+$			
$\Sigma(1385)^- 2\pi^+, \Sigma^{*-} \rightarrow \Lambda \pi^-$	$(7.6 \pm 1.4) \times 10^{-3}$		688
$\Lambda \pi^+ \rho^0$	$(1.4 \pm 0.6) \%$		524
$\Sigma(1385)^+ \rho^0, \Sigma^{*+} \rightarrow \Lambda \pi^+$	$(5 \pm 4) \times 10^{-3}$		363
$\Lambda \pi^- 2\pi^+$ nonresonant	$< 1.1$	$\%$	CL=90%
$\Lambda \pi^- \pi^0 2\pi^+$ total	$(2.2 \pm 0.8) \%$		757
$\Lambda \pi^+ \eta$	[q] $(1.84 \pm 0.11) \%$	S=1.1	691
$\Sigma(1385)^+ \eta$	[q] $(9.1 \pm 2.0) \times 10^{-3}$		570
$\Lambda \pi^+ \omega$	[q] $(1.5 \pm 0.5) \%$		517
$\Lambda \pi^- \pi^0 2\pi^+, \text{ no } \eta \text{ or } \omega$	$< 8$	$\times 10^{-3}$	CL=90%
$\Lambda K^+ \bar{K}^0$	$(5.6 \pm 1.1) \times 10^{-3}$	S=1.9	443
$\Xi(1690)^0 K^+, \Xi^{*0} \rightarrow \Lambda \bar{K}^0$	$(1.6 \pm 0.5) \times 10^{-3}$		286
$\Sigma^0 \pi^+$	$(1.27 \pm 0.06) \%$	S=1.1	825

$\Sigma^0 \pi^+ \eta$		$( 7.5 \pm 0.8 ) \times 10^{-3}$		635
$\Sigma^+ \pi^0$		$( 1.24 \pm 0.09 ) \%$		827
$\Sigma^+ \eta$		$( 3.2 \pm 0.5 ) \times 10^{-3}$		713
$\Sigma^+ \eta'$		$( 4.1 \pm 0.8 ) \times 10^{-3}$		391
$\Sigma^+ \pi^+ \pi^-$		$( 4.47 \pm 0.22 ) \%$	S=1.2	804
$\Sigma^+ \rho^0$		$< 1.7 \%$	CL=95%	575
$\Sigma^- 2\pi^+$		$( 1.86 \pm 0.18 ) \%$		799
$\Sigma^0 \pi^+ \pi^0$		$( 3.5 \pm 0.4 ) \%$		803
$\Sigma^+ \pi^0 \pi^0$		$( 1.54 \pm 0.14 ) \%$		806
$\Sigma^0 \pi^- 2\pi^+$		$( 1.10 \pm 0.30 ) \%$		763
$\Sigma^+ \omega$		$( 1.69 \pm 0.20 ) \%$		569
$\Sigma^- \pi^0 2\pi^+$		$( 2.1 \pm 0.4 ) \%$		762
$\Sigma^+ K^+ K^-$		$( 3.59 \pm 0.35 ) \times 10^{-3}$	S=1.1	349
$\Sigma^+ \phi$	[q]	$( 3.9 \pm 0.5 ) \times 10^{-3}$	S=1.1	295
$\Xi(1690)^0 K^+, \Xi^{*0} \rightarrow \Sigma^+ K^-$		$( 1.01 \pm 0.25 ) \times 10^{-3}$		286
$\Sigma^+ K^+ K^-$ nonresonant		$< 8 \times 10^{-4}$	CL=90%	349
$\Xi^0 K^+$		$( 5.5 \pm 0.7 ) \times 10^{-3}$		653
$\Xi^- K^+ \pi^+$		$( 6.2 \pm 0.5 ) \times 10^{-3}$	S=1.1	565
$\Xi(1530)^0 K^+$		$( 4.3 \pm 0.9 ) \times 10^{-3}$	S=1.1	473

**Hadronic modes with a hyperon: S = 0 final states**

$\Lambda K^+$		$( 6.42 \pm 0.31 ) \times 10^{-4}$		781
$\Lambda K^+ \pi^+ \pi^-$		$< 5 \times 10^{-4}$	CL=90%	637
$\Sigma^0 K^+$		$( 3.70 \pm 0.31 ) \times 10^{-4}$		735
$\Sigma^+ K_S^0$		$( 4.7 \pm 1.4 ) \times 10^{-4}$		736
$\Sigma^0 K^+ \pi^+ \pi^-$		$< 2.5 \times 10^{-4}$	CL=90%	574
$\Sigma^+ K^+ \pi^-$		$( 2.00 \pm 0.26 ) \times 10^{-3}$		670
$\Sigma^+ K^* (892)^0$	[q]	$( 3.5 \pm 1.0 ) \times 10^{-3}$		470
$\Sigma^+ K^+ \pi^- \pi^0$		$< 1.1 \times 10^{-3}$	CL=90%	581
$\Sigma^- K^+ \pi^+$		$< 1.2 \times 10^{-3}$	CL=90%	664

**Doubly Cabibbo-suppressed modes**

$\rho K^+ \pi^-$		$( 1.11 \pm 0.17 ) \times 10^{-4}$		823
------------------	--	------------------------------------	--	-----

**Semileptonic modes**

$\Lambda e^+ \nu_e$		$( 3.56 \pm 0.13 ) \%$		871
$\Lambda \pi^+ \pi^- e^+ \nu_e$		$< 3.9 \times 10^{-4}$	CL=90%	843
$\rho K^- e^+ \nu_e$		$( 8.8 \pm 1.8 ) \times 10^{-4}$		874
$\rho K_S^0 \pi^- e^+ \nu_e$		$< 3.3 \times 10^{-4}$	CL=90%	821
$\Lambda(1520) e^+ \nu_e$		$( 1.0 \pm 0.5 ) \times 10^{-3}$		639
$\Lambda(1405)^0 e^+ \nu_e, \Lambda^0 \rightarrow \rho K^-$		$( 4.2 \pm 1.9 ) \times 10^{-4}$		—
$\Lambda \mu^+ \nu_\mu$		$( 3.48 \pm 0.17 ) \%$		867

**Inclusive modes**

$e^+$ anything		$( 4.06 \pm 0.13 ) \%$		—
$\rho$ anything		$( 50 \pm 16 ) \%$		—
$n$ anything		$( 32.6 \pm 1.6 ) \%$		—
$\Lambda$ anything		$( 38.2 \pm 2.9 ) \%$		—
$K_S^0$ anything		$( 9.9 \pm 0.7 ) \%$		—
3prongs		$( 24 \pm 8 ) \%$		—

**$\Delta C = 1$  weak neutral current (C1) modes, or Lepton Family number (LF), or Lepton number (L), or Baryon number (B) violating modes**

$\rho e^+ e^-$	C1	$< 5.5 \times 10^{-6}$	CL=90%	951
$\rho \mu^+ \mu^-$ non-resonant	C1	$< 7.7 \times 10^{-8}$	CL=90%	937
$\rho e^+ \mu^-$	LF	$< 9.9 \times 10^{-6}$	CL=90%	947



$p e^- \mu^+$	$LF$	$< 1.9$	$\times 10^{-5}$	CL=90%	947
$\bar{p} 2 e^+$	$L, B$	$< 2.7$	$\times 10^{-6}$	CL=90%	951
$\bar{p} 2 \mu^+$	$L, B$	$< 9.4$	$\times 10^{-6}$	CL=90%	937
$\bar{p} e^+ \mu^+$	$L, B$	$< 1.6$	$\times 10^{-5}$	CL=90%	947
$\Sigma^- \mu^+ \mu^+$	$L$	$< 7.0$	$\times 10^{-4}$	CL=90%	812

**Radiative modes**

$\Sigma^+ \gamma$		$< 2.5$	$\times 10^{-4}$	CL=90%	834
-------------------	--	---------	------------------	--------	-----

**Exotic modes**

$P \gamma D$		$[r] < 8.0$	$\times 10^{-5}$	CL=90%	—
--------------	--	-------------	------------------	--------	---

See Particle Listings for 1 decay modes that have been seen / not seen.

 **$\Lambda_c(2595)^+$** 

$$I(J^P) = 0(\frac{1}{2}^-)$$

The spin-parity follows from the fact that  $\Sigma_c(2455)\pi$  decays, with little available phase space, are dominant. This assumes that  $J^P = 1/2^+$  for the  $\Sigma_c(2455)$ .

$$\text{Mass } m = 2592.25 \pm 0.28 \text{ MeV}$$

$$m - m_{\Lambda_c^+} = 305.79 \pm 0.24 \text{ MeV}$$

$$\text{Full width } \Gamma = 2.6 \pm 0.6 \text{ MeV}$$

$\Lambda_c^+ \pi \pi$  and its submode  $\Sigma_c(2455)\pi$  — the latter just barely — are the only strong decays allowed to an excited  $\Lambda_c^+$  having this mass; and the submode seems to dominate.

<b><math>\Lambda_c(2595)^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$\Lambda_c^+ \pi^+ \pi^-$	[s] —	117
$\Sigma_c(2455)^{++} \pi^-$	$24 \pm 7\%$	3
$\Sigma_c(2455)^0 \pi^+$	$24 \pm 7\%$	3
$\Lambda_c^+ \pi^+ \pi^-$ 3-body	$18 \pm 10\%$	117

See Particle Listings for 2 decay modes that have been seen / not seen.

 **$\Lambda_c(2625)^+$** 

$$I(J^P) = 0(\frac{3}{2}^-)$$

$J^P$  has not been measured;  $\frac{3}{2}^-$  is the quark-model prediction.

$$\text{Mass } m = 2628.00 \pm 0.15 \text{ MeV}$$

$$m - m_{\Lambda_c^+} = 341.54 \pm 0.05 \text{ MeV}$$

$$\text{Full width } \Gamma < 0.52 \text{ MeV, CL} = 90\%$$

$\Lambda_c^+ \pi \pi$  and its submode  $\Sigma(2455)\pi$  are the only strong decays allowed to an excited  $\Lambda_c^+$  having this mass.

<b><math>\Lambda_c(2625)^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$\Lambda_c^+ \pi^+ \pi^-$	[t] 66.67 %		184
$\Sigma_c(2455)^{++} \pi^-$	( 3.42 ± 0.27 ) %		103
$\Sigma_c(2455)^0 \pi^+$	( 3.46 ± 0.31 ) %		103
$\Lambda_c^+ \pi^+ \pi^-$ 3-body	large		184
$\Lambda_c^+ \pi^0$	[u] < 60 %	90%	293
$\Lambda_c^+ \gamma$	< 35 %	90%	319

**$\Lambda_c(2860)^+$** 

$$I(J^P) = 0(\frac{3}{2}^+)$$

$$\text{Mass } m = 2856.1_{-6.0}^{+2.3} \text{ MeV}$$

$$\text{Full width } \Gamma = 68_{-22}^{+12} \text{ MeV}$$

 **$\Lambda_c(2880)^+$** 

$$I(J^P) = 0(\frac{5}{2}^+)$$

$$\text{Mass } m = 2881.63 \pm 0.24 \text{ MeV}$$

$$m - m_{\Lambda_c^+} = 595.17 \pm 0.28 \text{ MeV}$$

$$\text{Full width } \Gamma = 5.6_{-0.6}^{+0.8} \text{ MeV}$$

 **$\Lambda_c(2940)^+$** 

$$I(J^P) = 0(\frac{3}{2}^-)$$

 $J^P = 3/2^-$  is favored, but is not certain

$$\text{Mass } m = 2939.6_{-1.5}^{+1.3} \text{ MeV}$$

$$\text{Full width } \Gamma = 20_{-5}^{+6} \text{ MeV}$$

 **$\Sigma_c(2455)$** 

$$I(J^P) = 1(\frac{1}{2}^+)$$

$$\Sigma_c(2455)^{++} \text{ mass } m = 2453.97 \pm 0.14 \text{ MeV}$$

$$\Sigma_c(2455)^+ \text{ mass } m = 2452.65_{-0.16}^{+0.22} \text{ MeV}$$

$$\Sigma_c(2455)^0 \text{ mass } m = 2453.75 \pm 0.14 \text{ MeV}$$

$$m_{\Sigma_c(2455)^{++}} - m_{\Lambda_c^+} = 167.510 \pm 0.017 \text{ MeV}$$

$$m_{\Sigma_c(2455)^+} - m_{\Lambda_c^+} = 166.19_{-0.08}^{+0.16} \text{ MeV}$$

$$m_{\Sigma_c(2455)^0} - m_{\Lambda_c^+} = 167.290 \pm 0.017 \text{ MeV}$$

$$m_{\Sigma_c(2455)^{++}} - m_{\Sigma_c(2455)^0} = 0.220 \pm 0.013 \text{ MeV}$$

$$m_{\Sigma_c(2455)^+} - m_{\Sigma_c(2455)^0} = -1.10_{-0.08}^{+0.16} \text{ MeV}$$

$$\Sigma_c(2455)^{++} \text{ full width } \Gamma = 1.89_{-0.18}^{+0.09} \text{ MeV} \quad (S = 1.1)$$

$$\Sigma_c(2455)^+ \text{ full width } \Gamma = 2.3 \pm 0.4 \text{ MeV}$$

$$\Sigma_c(2455)^0 \text{ full width } \Gamma = 1.83_{-0.19}^{+0.11} \text{ MeV} \quad (S = 1.2)$$

 $\Lambda_c^+ \pi$  is the only strong decay allowed to a  $\Sigma_c$  having this mass.

 **$\Sigma_c(2455)$  DECAY MODES**

 Fraction ( $\Gamma_i/\Gamma$ )

 $p$  (MeV/c)

 $\Lambda_c^+ \pi$ 
 $\approx 100 \%$ 

94

 **$\Sigma_c(2520)$** 

$$I(J^P) = 1(\frac{3}{2}^+)$$

 $J^P$  has not been measured;  $\frac{3}{2}^+$  is the quark-model prediction.

$$\Sigma_c(2520)^{++} \text{ mass } m = 2518.41 \pm 0.22 \text{ MeV} \quad (S = 1.3)$$

$$\Sigma_c(2520)^+ \text{ mass } m = 2517.4_{-0.5}^{+0.7} \text{ MeV}$$

$$\Sigma_c(2520)^0 \text{ mass } m = 2518.48 \pm 0.21 \text{ MeV} \quad (S = 1.2)$$

$$m_{\Sigma_c(2520)^{++}} - m_{\Lambda_c^+} = 231.95 \pm 0.18 \text{ MeV} \quad (S = 1.8)$$

$$m_{\Sigma_c(2520)^+} - m_{\Lambda_c^+} = 230.9_{-0.5}^{+0.7} \text{ MeV}$$

$$m_{\Sigma_c(2520)^0} - m_{\Lambda_c^+} = 232.02 \pm 0.15 \text{ MeV} \quad (S = 1.4)$$

$$m_{\Sigma_c(2520)^{++}} - m_{\Sigma_c(2520)^0} = 0.01 \pm 0.15 \text{ MeV}$$

$$\Sigma_c(2520)^{++} \text{ full width } \Gamma = 14.78_{-0.40}^{+0.30} \text{ MeV}$$

$$\Sigma_c(2520)^+ \text{ full width } \Gamma = 17.2_{-2.2}^{+4.0} \text{ MeV}$$

$$\Sigma_c(2520)^0 \text{ full width } \Gamma = 15.3_{-0.5}^{+0.4} \text{ MeV}$$

$\Lambda_c^+ \pi$  is the only strong decay allowed to a  $\Sigma_c$  having this mass.

$\Sigma_c(2520)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$\Lambda_c^+ \pi$	$\approx 100 \%$	179

### $\Sigma_c(2800)$

$$I(J^P) = 1(?^?)$$

$$\Sigma_c(2800)^{++} \text{ mass } m = 2801_{-6}^{+4} \text{ MeV}$$

$$\Sigma_c(2800)^+ \text{ mass } m = 2792_{-5}^{+14} \text{ MeV}$$

$$\Sigma_c(2800)^0 \text{ mass } m = 2806_{-7}^{+5} \text{ MeV} \quad (S = 1.3)$$

$$m_{\Sigma_c(2800)^{++}} - m_{\Lambda_c^+} = 514_{-6}^{+4} \text{ MeV}$$

$$m_{\Sigma_c(2800)^+} - m_{\Lambda_c^+} = 505_{-5}^{+14} \text{ MeV}$$

$$m_{\Sigma_c(2800)^0} - m_{\Lambda_c^+} = 519_{-7}^{+5} \text{ MeV} \quad (S = 1.3)$$

$$\Sigma_c(2800)^{++} \text{ full width } \Gamma = 75_{-17}^{+22} \text{ MeV}$$

$$\Sigma_c(2800)^+ \text{ full width } \Gamma = 60_{-40}^{+60} \text{ MeV}$$

$$\Sigma_c(2800)^0 \text{ full width } \Gamma = 72_{-15}^{+22} \text{ MeV}$$

### $\Xi_c^+$

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$J^P$  has not been measured;  $\frac{1}{2}^+$  is the quark-model prediction.

$$\text{Mass } m = 2467.71 \pm 0.23 \text{ MeV} \quad (S = 1.3)$$

$$\text{Mean life } \tau = (453 \pm 5) \times 10^{-15} \text{ s}$$

$$c\tau = 135.8 \text{ } \mu\text{m}$$

Branching fractions marked with a footnote, e.g. [a], have been corrected for decay modes not observed in the experiments. For example, the submode fraction  $\Xi_c^+ \rightarrow \Sigma^+ \bar{K}^*(892)^0$  seen in  $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$  has been multiplied up to include  $\bar{K}^*(892)^0 \rightarrow \bar{K}^0 \pi^0$  decays.

$\Xi_c^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
-----------------------	--------------------------------	-----------------------------------	----------------

#### Cabibbo-favored ( $S = -2$ ) decays

$p2K_S^0$	$(2.5 \pm 1.3) \times 10^{-3}$		766
$\Lambda \bar{K}^0 \pi^+$	—		852
$\Sigma(1385)^+ \bar{K}^0$	[q] $(2.9 \pm 2.0) \%$		746
$\Lambda K^- 2\pi^+$	$(9 \pm 4) \times 10^{-3}$		787
$\Lambda \bar{K}^*(892)^0 \pi^+$	[q] $< 5 \times 10^{-3}$	CL=90%	608
$\Sigma(1385)^+ K^- \pi^+$	[q] $< 6 \times 10^{-3}$	CL=90%	678
$\Sigma^+ K^- \pi^+$	$(2.7 \pm 1.2) \%$		810
$\Sigma^+ \bar{K}^*(892)^0$	[q] $(2.3 \pm 1.1) \%$		658
$\Sigma^0 K^- 2\pi^+$	$(8 \pm 5) \times 10^{-3}$		735
$\Xi^0 \pi^+$	$(1.6 \pm 0.8) \%$		876

$\Xi^- 2\pi^+$	$(2.9 \pm 1.3) \%$		851
$\Xi(1530)^0 \pi^+$	$[q] < 2.9 \times 10^{-3}$	CL=90%	749
$\Xi^0 \pi^+ \pi^0$	$(6.7 \pm 3.5) \%$		856
$\Xi^0 \pi^- 2\pi^+$	$(5.0 \pm 2.6) \%$		818
$\Xi^0 e^+ \nu_e$	$(7 \pm 4) \%$		884
$\Omega^- K^+ \pi^+$	$(2.0 \pm 1.5) \times 10^{-3}$		399

**Cabibbo-suppressed decays**

$p K^- \pi^+$	$(6.2 \pm 3.0) \times 10^{-3}$	S=1.5	944
$p \bar{K}^*(892)^0$	$[q] (3.3 \pm 1.7) \times 10^{-3}$		828
$\Sigma^+ \pi^+ \pi^-$	$(1.4 \pm 0.8) \%$		922
$\Sigma^- 2\pi^+$	$(5.1 \pm 3.4) \times 10^{-3}$		918
$\Sigma^+ K^+ K^-$	$(4.3 \pm 2.5) \times 10^{-3}$		579
$\Sigma^+ \phi$	$[q] < 3.2 \times 10^{-3}$	CL=90%	549
$\Xi(1690)^0 K^+, \Xi^0 \rightarrow \Sigma^+ K^-$	$< 1.3 \times 10^{-3}$	CL=90%	501
$\rho \phi(1020)$	$(1.2 \pm 0.6) \times 10^{-4}$		751

See Particle Listings for 2 decay modes that have been seen / not seen.



$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$J^P$  has not been measured;  $\frac{1}{2}^+$  is the quark-model prediction.

Mass  $m = 2470.44 \pm 0.28$  MeV (S = 1.2)

$m_{\Xi_c^0} - m_{\Xi_c^+} = 2.72 \pm 0.23$  MeV (S = 1.1)

Mean life  $\tau = (150.4 \pm 2.8) \times 10^{-15}$  s (S = 1.4)

$c\tau = 45.1$   $\mu$ m

**Decay asymmetry parameters**

$\Xi^- \pi^+ \quad \alpha = -0.64 \pm 0.05$

$\alpha$  FOR  $\Xi_c^0 \rightarrow \Xi^+ \pi^- = 0.61 \pm 0.05$

$\alpha$  FOR  $\Xi_c^0 \rightarrow \Lambda \bar{K}^*(892)^0 = 0.15 \pm 0.22$

$\alpha$  FOR  $\Xi_c^0 \rightarrow \Sigma^+ K^*(892)^- = -0.52 \pm 0.30$

**$\Xi_c^0$  DECAY MODES**

Fraction ( $\Gamma_i/\Gamma$ )

Confidence level (MeV/c)

**Cabibbo-favored decays**

$p K^- K^- \pi^+$	$(4.9 \pm 1.0) \times 10^{-3}$		676
$p K^- \bar{K}^*(892)^0, \bar{K}^{*0} \rightarrow K^- \pi^+$	$(2.0 \pm 0.6) \times 10^{-3}$		413
$p K^- K^- \pi^+$ (no $\bar{K}^{*0}$ )	$(3.0 \pm 0.8) \times 10^{-3}$		676
$\Lambda K_S^0$	$(3.2 \pm 0.6) \times 10^{-3}$		906
$\Lambda K^- \pi^+$	$(1.45 \pm 0.28) \%$		856
$\Lambda \bar{K}^*(892)^0$	$(2.6 \pm 0.6) \times 10^{-3}$		717
$\Sigma^0 K_S^0$	$(5.4 \pm 1.4) \times 10^{-4}$		864
$\Sigma^+ K^-$	$(1.8 \pm 0.4) \times 10^{-3}$		868
$\Sigma^0 \bar{K}^*(892)^0$	$(9.9 \pm 1.9) \times 10^{-3}$		658
$\Sigma^+ K^*(892)^-$	$(4.9 \pm 1.3) \times 10^{-3}$		661
$\Xi^- \pi^+$	$(1.43 \pm 0.27) \%$		875
$\Xi^- \pi^+ \pi^+ \pi^-$	$(4.8 \pm 2.3) \%$		816
$\Xi^0 \phi, \phi \rightarrow K^+ K^-$	$(5.2 \pm 1.2) \times 10^{-4}$		-
$\Xi^0 K^+ K^-$ nonresonant	$(5.6 \pm 1.2) \times 10^{-4}$		444
$\Omega^- K^+$	$(4.2 \pm 0.9) \times 10^{-3}$		522
$\Xi^- e^+ \nu_e$	$(1.05 \pm 0.20) \%$		882
$\Xi^- \mu^+ \nu_\mu$	$(1.01 \pm 0.21) \%$		878
$\Xi^0 \gamma$	$< 1.7 \times 10^{-4}$	90%	885

## Cabibbo-suppressed decays

$\Lambda_c^+ \pi^-$	$(5.5 \pm 1.1) \times 10^{-3}$	115
$\Xi^- K^+$	$(3.9 \pm 1.1) \times 10^{-4}$	789
$\Lambda K^+ K^-$ (no $\phi$ )	$(4.1 \pm 1.3) \times 10^{-4}$	648
$\Lambda \phi$	$(4.9 \pm 1.3) \times 10^{-4}$	621

See Particle Listings for 2 decay modes that have been seen / not seen.

 $\Xi_c^{'+}$ 

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$J^P$  has not been measured;  $\frac{1}{2}^+$  is the quark-model prediction.

$$\text{Mass } m = 2578.2 \pm 0.5 \text{ MeV} \quad (S = 1.1)$$

$$m_{\Xi_c^{'+}} - m_{\Xi_c^+} = 110.5 \pm 0.4 \text{ MeV}$$

$$m_{\Xi_c^{'+}} - m_{\Xi_c^0} = -0.5 \pm 0.6 \text{ MeV}$$

 $\Xi_c^{'0}$ 

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

$J^P$  has not been measured;  $\frac{1}{2}^+$  is the quark-model prediction.

$$\text{Mass } m = 2578.7 \pm 0.5 \text{ MeV}$$

$$m_{\Xi_c^{'0}} - m_{\Xi_c^0} = 108.3 \pm 0.4 \text{ MeV}$$

 $\Xi_c(2645)$ 

$$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$$

$J^P$  has not been measured;  $\frac{3}{2}^+$  is the quark-model prediction.

$$\Xi_c(2645)^+ \text{ mass } m = 2645.10 \pm 0.30 \text{ MeV} \quad (S = 1.2)$$

$$\Xi_c(2645)^0 \text{ mass } m = 2646.16 \pm 0.25 \text{ MeV} \quad (S = 1.3)$$

$$m_{\Xi_c(2645)^+} - m_{\Xi_c^0} = 174.67 \pm 0.09 \text{ MeV}$$

$$m_{\Xi_c(2645)^0} - m_{\Xi_c^+} = 178.45 \pm 0.10 \text{ MeV}$$

$$m_{\Xi_c(2645)^+} - m_{\Xi_c(2645)^0} = -1.06 \pm 0.27 \text{ MeV} \quad (S = 1.1)$$

$$\Xi_c(2645)^+ \text{ full width } \Gamma = 2.14 \pm 0.19 \text{ MeV} \quad (S = 1.1)$$

$$\Xi_c(2645)^0 \text{ full width } \Gamma = 2.35 \pm 0.22 \text{ MeV}$$

 $\Xi_c(2790)$ 

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$$

$J^P$  has not been measured;  $\frac{1}{2}^-$  is the quark-model prediction.

$$\Xi_c(2790)^+ \text{ mass} = 2791.9 \pm 0.5 \text{ MeV}$$

$$\Xi_c(2790)^0 \text{ mass} = 2793.9 \pm 0.5 \text{ MeV}$$

$$m_{\Xi_c(2790)^+} - m_{\Xi_c^0} = 213.20 \pm 0.22 \text{ MeV}$$

$$m_{\Xi_c(2790)^0} - m_{\Xi_c^+} = 215.70 \pm 0.22 \text{ MeV}$$

$$m_{\Xi_c(2790)^+} - m_{\Xi_c(2790)^0} = -2.0 \pm 0.7 \text{ MeV}$$

$$\Xi_c(2790)^+ \text{ width} = 8.9 \pm 1.0 \text{ MeV}$$

$$\Xi_c(2790)^0 \text{ width} = 10.0 \pm 1.1 \text{ MeV}$$

**$\Xi_c(2815)$** 

$$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$$

$J^P$  has not been measured;  $\frac{3}{2}^-$  is the quark-model prediction.

$$\Xi_c(2815)^+ \text{ mass } m = 2816.51 \pm 0.25 \text{ MeV} \quad (S = 1.2)$$

$$\Xi_c(2815)^0 \text{ mass } m = 2819.79 \pm 0.30 \text{ MeV} \quad (S = 1.1)$$

$$m_{\Xi_c(2815)^+} - m_{\Xi_c^+} = 348.80 \pm 0.10 \text{ MeV}$$

$$m_{\Xi_c(2815)^0} - m_{\Xi_c^0} = 349.35 \pm 0.11 \text{ MeV}$$

$$m_{\Xi_c(2815)^+} - m_{\Xi_c(2815)^0} = -3.27 \pm 0.27 \text{ MeV}$$

$$\Xi_c(2815)^+ \text{ full width } \Gamma = 2.43 \pm 0.26 \text{ MeV}$$

$$\Xi_c(2815)^0 \text{ full width } \Gamma = 2.54 \pm 0.25 \text{ MeV}$$

 **$\Xi_c(2970)$** 

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

was  $\Xi_c(2980)$

$$\Xi_c(2970)^+ m = 2964.3 \pm 1.5 \text{ MeV} \quad (S = 3.9)$$

$$\Xi_c(2970)^0 m = 2967.1 \pm 1.7 \text{ MeV} \quad (S = 6.7)$$

$$m_{\Xi_c(2970)^+} - m_{\Xi_c^+} = 496.6 \pm 1.5 \text{ MeV} \quad (S = 3.7)$$

$$m_{\Xi_c(2970)^0} - m_{\Xi_c^0} = 496.7 \pm 1.8 \text{ MeV} \quad (S = 5.3)$$

$$m_{\Xi_c(2970)^+} - m_{\Xi_c(2970)^0} = -2.8 \pm 1.9 \text{ MeV} \quad (S = 4.8)$$

$$\Xi_c(2970)^+ \text{ width } \Gamma = 20.9_{-3.5}^{+2.4} \text{ MeV} \quad (S = 1.2)$$

 **$\Xi_c(3055)$** 

$$I(J^P) = ?(??)$$

$$\text{Mass } m = 3055.9 \pm 0.4 \text{ MeV}$$

$$\text{Full width } \Gamma = 7.8 \pm 1.9 \text{ MeV}$$

 **$\Xi_c(3080)$** 

$$I(J^P) = \frac{1}{2}(??)$$

$$\Xi_c(3080)^+ m = 3077.2 \pm 0.4 \text{ MeV}$$

$$\Xi_c(3080)^0 m = 3079.9 \pm 1.4 \text{ MeV} \quad (S = 1.3)$$

$$\Xi_c(3080)^+ \text{ width } \Gamma = 3.6 \pm 1.1 \text{ MeV} \quad (S = 1.5)$$

$$\Xi_c(3080)^0 \text{ width } \Gamma = 5.6 \pm 2.2 \text{ MeV}$$

 **$\Omega_c^0$** 

$$I(J^P) = 0(\frac{1}{2}^+)$$

$J^P$  has not been measured;  $\frac{1}{2}^+$  is the quark-model prediction.

$$\text{Mass } m = 2695.2 \pm 1.7 \text{ MeV} \quad (S = 1.3)$$

$$\text{Mean life } \tau = (273 \pm 12) \times 10^{-15} \text{ s}$$

$$c\tau = 82 \mu\text{m}$$

No absolute branching fractions have been measured. The following are branching ratios relative to  $\Omega^- \pi^+$ .

$\Omega_c^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
--------------------------	--------------------------------	------------------	-------------------

**Cabibbo-favored ( $S = -3$ ) decays — relative to  $\Omega^- \pi^+$** 

$\Omega^- \pi^+$	<b>DEFINED AS 1</b>		821
$\Omega^- \pi^+ \pi^0$	$1.80 \pm 0.33$		797
$\Omega^- \rho^+$	$>1.3$	90%	532

$\Omega^- \pi^- 2\pi^+$	$0.31 \pm 0.05$	753
$\Omega^- e^+ \nu_e$	$1.98 \pm 0.15$	829
$\Omega^- \mu^+ \nu_\mu$	$1.94 \pm 0.21$	824
$\Xi^0 \bar{K}^0$	$1.64 \pm 0.29$	950
$\Xi^0 K^- \pi^+$	$1.20 \pm 0.18$	901
$\Xi^0 \bar{K}^{*0}, \bar{K}^{*0} \rightarrow K^- \pi^+$	$0.68 \pm 0.16$	764
$\Omega(2012)^- \pi^+, \Omega(2012)^- \rightarrow$	$0.12 \pm 0.05$	—
$\Xi^0 K^-$		
$\Xi^- \bar{K}^0 \pi^+$	$2.12 \pm 0.28$	895
$\Omega(2012)^- \pi^+, \Omega(2012)^- \rightarrow$	$0.12 \pm 0.06$	—
$\Xi^- \bar{K}^0$		
$\Xi^- K^- 2\pi^+$	$0.63 \pm 0.09$	830
$\Xi(1530)^0 K^- \pi^+, \Xi^{*0} \rightarrow \Xi^- \pi^+$	$0.21 \pm 0.06$	757
$\Xi^- \bar{K}^{*0} \pi^+$	$0.34 \pm 0.11$	653
$\Sigma^+ K^- K^- \pi^+$	$< 0.32$	90% 689
$\Lambda \bar{K}^0 \bar{K}^0$	$1.72 \pm 0.35$	837

**Singly Cabibbo-suppressed modes — relative to  $\Omega^- \pi^+$**

$\Xi^- \pi^+$	$0.25 \pm 0.06$	—
$\Omega^- K^+$	$< 0.29$	90% —

**Doubly Cabibbo-suppressed modes — relative to  $\Omega^- \pi^+$**

$\Xi^- K^+$	$< 0.07$	90% —
-------------	----------	-------

See Particle Listings for 1 decay modes that have been seen / not seen.

**$\Omega_c(2770)^0$**

$$I(J^P) = 0(\frac{3}{2}^+)$$

$J^P$  has not been measured;  $\frac{3}{2}^+$  is the quark-model prediction.

$$\text{Mass } m = 2765.9 \pm 2.0 \text{ MeV} \quad (S = 1.2)$$

$$m_{\Omega_c(2770)^0} - m_{\Omega_c^0} = 70.7_{-0.9}^{+0.8} \text{ MeV}$$

The  $\Omega_c(2770)^0 - \Omega_c^0$  mass difference is too small for any strong decay to occur.

**$\Omega_c(2770)^0$  DECAY MODES**

	Fraction ( $\Gamma_j/\Gamma$ )	$p$ (MeV/c)
$\Omega_c^0 \gamma$	presumably 100%	70

**$\Omega_c(3000)^0$**

$$I(J^P) = ?(??)$$

$$\text{Mass } m = 3000.46 \pm 0.25 \text{ MeV}$$

$$\text{Full width } \Gamma = 3.8_{-0.4}^{+1.6} \text{ MeV}$$

**$\Omega_c(3050)^0$**

$$I(J^P) = ?(??)$$

$$\text{Mass } m = 3050.17 \pm 0.19 \text{ MeV}$$

$$\text{Full width } \Gamma < 1.8 \text{ MeV, CL} = 95\%$$

**$\Omega_c(3065)^0$**

$$I(J^P) = ?(??)$$

$$\text{Mass } m = 3065.58 \pm 0.21 \text{ MeV}$$

$$\text{Full width } \Gamma = 3.4_{-0.8}^{+0.7} \text{ MeV} \quad (S = 1.7)$$

$\Omega_c(3090)^0$ 

$I(J^P) = ?(??)$

Mass  $m = 3090.15 \pm 0.26$  MeVFull width  $\Gamma = 8.5_{-1.7}^{+0.8}$  MeV $\Omega_c(3120)^0$ 

$I(J^P) = ?(??)$

Mass  $m = 3118.98_{-0.35}^{+0.27}$  MeVFull width  $\Gamma < 2.5$  MeV, CL = 95% $\Omega_c(3185)^0$ 

$I(J^P) = ?(??)$

Mass  $m = 3185_{-1.9}^{+7.6}$  MeVFull width  $\Gamma = 50_{-21}^{+12}$  MeV $\Omega_c(3327)^0$ 

$I(J^P) = ?(??)$

Mass  $m = 3327.1_{-1.8}^{+1.2}$  MeVFull width  $\Gamma = 20_{-5}^{+14}$  MeV

## DOUBLY CHARMED BARYONS ( $C = +2$ )

$$\Xi_{cc}^{++} = ucc, \Xi_{cc}^+ = dcc, \Omega_{cc}^+ = scc$$

 $\Xi_{cc}^{++}$ 

$I(J^P) = ?(??)$

Mass  $m = 3621.6 \pm 0.4$  MeVMean life  $\tau = (256 \pm 27) \times 10^{-15}$  s $\Xi_{cc}^{++}$  DECAY MODESFraction ( $\Gamma_i/\Gamma$ )

Confidence level

 $p$ 

(MeV/c)

 $\Lambda_c^+ K^- \pi^+ \pi^+$ **DEFINED AS 1**

880

 $\Xi_c^+ \pi^+, \Xi_c^+ \rightarrow p K^- \pi^+$ 

0.0022 ± 0.0006

-

 $\Xi_c^{\prime+} \pi^+, \Xi_c^{\prime+} \rightarrow \Xi_c^+ \gamma, \Xi_c^+ \rightarrow$ 

0.0031 ± 0.0009

-

 $p K^- \pi^+$  $D^+ p K^- \pi^+$ 

&lt;0.017

90%

562



# BOTTOM BARYONS

## ( $B = -1$ )

$$\Lambda_b^0 = udb, \Sigma_b^0 = udb, \Sigma_b^+ = uub, \Sigma_b^- = ddb$$

$$\Xi_b^0 = usb, \Xi_b^- = dsb, \Omega_b^- = ssb$$

 $\Lambda_b^0$ 

$$I(J^P) = 0(\frac{1}{2}^+)$$

$I(J^P)$  not yet measured;  $0(\frac{1}{2}^+)$  is the quark model prediction.

$$\text{Mass } m = 5619.60 \pm 0.17 \text{ MeV}$$

$$m_{\Lambda_b^0} - m_{B^0} = 339.2 \pm 1.4 \text{ MeV}$$

$$m_{\Lambda_b^0} - m_{B^+} = 339.72 \pm 0.28 \text{ MeV}$$

$$\text{Mean life } \tau = (1.471 \pm 0.009) \times 10^{-12} \text{ s}$$

$$c\tau = 441.0 \text{ } \mu\text{m}$$

$$A_{CP}(\Lambda_b \rightarrow p\pi^-) = -0.025 \pm 0.029 \quad (S = 1.2)$$

$$A_{CP}(\Lambda_b \rightarrow pK^-) = -0.025 \pm 0.022$$

$$A_{CP}(\Lambda_b \rightarrow DpK^-) = 0.12 \pm 0.09$$

$$\Delta A_{CP}(pK^-/\pi^-) = 0.014 \pm 0.024$$

$$A_{CP}(\Lambda_b \rightarrow p\bar{K}^0\pi^-) = 0.22 \pm 0.13$$

$$\Delta A_{CP}(J/\psi p\pi^-/K^-) = (5.7 \pm 2.7) \times 10^{-2}$$

$$A_{CP}(\Lambda_b \rightarrow \Lambda K^+\pi^-) = -0.53 \pm 0.25$$

$$A_{CP}(\Lambda_b \rightarrow \Lambda K^+K^-) = -0.28 \pm 0.12$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow pK^-\mu^+\mu^-) = (-4 \pm 5) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-) = (1.1 \pm 2.6) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow (p\pi^-\pi^+\pi^-)_{LBM}) = (4 \pm 4) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow p a_1(1260)^-) = (-1 \pm 4) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow N(1520)^0 \rho(770)^0) = (2 \pm 5) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow \Delta(1232)^{++} \pi^-\pi^-) = (0.1 \pm 3.3) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-) = (3.2 \pm 1.3) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow (pK^-\pi^+\pi^-)_{LBM}) = (3.5 \pm 1.6) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow N(1520)^0 K^*(892)^0) = (5.5 \pm 2.5) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow \Lambda(1520)\rho(770)^0) = (1 \pm 6) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow \Delta(1232)^{++} K^-\pi^-) = (4.4 \pm 2.7) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow pK_1(1410)^-) = (5 \pm 4) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow pK^-K^+\pi^-) = (-7 \pm 5) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow pK^-K^+K^-) = (0.2 \pm 1.9) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow \Lambda(1520)\phi(1020)) = (4 \pm 6) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow (pK^-)_{highmass} \phi(1020)) = (-0.7 \pm 3.4) \times 10^{-2}$$

$$\Delta A_{CP}(\Lambda_b^0 \rightarrow (pK^-K^+K^-)_{LBM}) = (2.7 \pm 2.4) \times 10^{-2}$$

$$A_{FB}^{\ell}(\mu\mu) \text{ in } \Lambda_b \rightarrow \Lambda\mu^+\mu^- = -0.39 \pm 0.04$$

$$\Delta(A_{FB}^{\ell}(\mu\mu)) \text{ in } \Lambda_b \rightarrow \Lambda\mu^+\mu^- = -0.05 \pm 0.09$$

$$A_{FB}^h(p\pi) \text{ in } \Lambda_b \rightarrow \Lambda(p\pi)\mu^+\mu^- = -0.30 \pm 0.05$$

$$A_{FB}^{th} \text{ in } \Lambda_b \rightarrow \Lambda\mu^+\mu^- = 0.25 \pm 0.04$$

The branching fractions  $B(b\text{-baryon} \rightarrow \Lambda \ell^- \bar{\nu}_\ell \text{ anything})$  and  $B(\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \bar{\nu}_\ell \text{ anything})$  are not pure measurements because the underlying measured products of these with  $B(b \rightarrow b\text{-baryon})$  were used to determine  $B(b \rightarrow b\text{-baryon})$ , as described in the note "Production and Decay of  $b$ -Flavored Hadrons."

For inclusive branching fractions, e.g.,  $\Lambda_b \rightarrow \bar{\Lambda}_c \text{ anything}$ , the values usually are multiplicities, not branching fractions. They can be greater than one.

$\Lambda_b^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$J/\psi(1S)\Lambda \times B(b \rightarrow \Lambda_b^0)$	$(5.8 \pm 0.8) \times 10^{-5}$		1740
$pD^0\pi^-$	$(6.2 \pm 0.6) \times 10^{-4}$		2370
$pD^+\pi^-\pi^-$	$(2.7 \pm 0.4) \times 10^{-4}$		2332
$pD^*(2010)^+\pi^-\pi^-$	$(5.2 \pm 1.0) \times 10^{-4}$		2277
$pD^0K^-$	$(4.5 \pm 0.8) \times 10^{-5}$		2269
$pJ/\psi\pi^-$	$(2.6^{+0.5}_{-0.4}) \times 10^{-5}$		1755
$p\pi^-J/\psi, J/\psi \rightarrow \mu^+\mu^-$	$(1.6 \pm 0.8) \times 10^{-6}$		—
$pJ/\psi K^-$	$(3.2^{+0.6}_{-0.5}) \times 10^{-4}$		1589
$p\eta_c(1S)K^-$	$(1.06 \pm 0.26) \times 10^{-4}$		1670
$P_{c\bar{c}}(4312)^+K^-, P_{c\bar{c}}^+ \rightarrow$ $p\eta_c(1S)$	$< 2.5 \times 10^{-5}$	CL=95%	—
$P_{c\bar{c}}(4380)^+K^-, P_{c\bar{c}}^+ \rightarrow$ $pJ/\psi$	[v] $(2.7 \pm 1.4) \times 10^{-5}$		—
$P_c(4450)^+K^-, P_c \rightarrow pJ/\psi$	[v] $(1.3 \pm 0.4) \times 10^{-5}$		—
$\chi_{c1}(1P)pK^-$	$(7.6^{+1.5}_{-1.3}) \times 10^{-5}$		1242
$\chi_{c1}(1P)p\pi^-$	$(5.0^{+1.3}_{-1.1}) \times 10^{-6}$		1462
$\chi_{c2}(1P)pK^-$	$(7.7^{+1.6}_{-1.4}) \times 10^{-5}$		1198
$\chi_{c2}(1P)p\pi^-$	$(4.8 \pm 1.9) \times 10^{-6}$		1427
$pJ/\psi(1S)\pi^+\pi^-K^-$	$(6.6^{+1.3}_{-1.1}) \times 10^{-5}$		1410
$p\psi(2S)K^-$	$(6.6^{+1.2}_{-1.0}) \times 10^{-5}$		1063
$\chi_{c1}(3872)pK^-$	$(3.5 \pm 1.3) \times 10^{-5}$		837
$\chi_{c1}(3872)\Lambda(1520)$	$(2.0 \pm 0.9) \times 10^{-5}$		721
$\psi(2S)p\pi^-$	$(7.5^{+1.6}_{-1.4}) \times 10^{-6}$		1320
$p\bar{K}^0\pi^-$	$(1.3 \pm 0.4) \times 10^{-5}$		2693
$pK^0K^-$	$< 3.5 \times 10^{-6}$	CL=90%	2639
$\Lambda_c^+\pi^-$	$(4.9 \pm 0.4) \times 10^{-3}$	S=1.2	2342
$\Lambda_c^+K^-$	$(3.56 \pm 0.28) \times 10^{-4}$	S=1.2	2314
$\Lambda_c^+D^-$	$(4.6 \pm 0.6) \times 10^{-4}$		1886
$\Lambda_c^+D_s^-$	$(1.10 \pm 0.10) \%$		1833
$\Lambda_c^+\pi^+\pi^-\pi^-$	$(7.6 \pm 1.1) \times 10^{-3}$	S=1.1	2323
$\Lambda_c(2595)^+\pi^-, \Lambda_c(2595)^+ \rightarrow$ $\Lambda_c^+\pi^+\pi^-$	$(3.4 \pm 1.4) \times 10^{-4}$		2210
$\Lambda_c(2625)^+\pi^-, \Lambda_c(2625)^+ \rightarrow$ $\Lambda_c^+\pi^+\pi^-$	$(3.3 \pm 1.3) \times 10^{-4}$		2193
$\Sigma_c(2455)^0\pi^+\pi^-, \Sigma_c^0 \rightarrow$ $\Lambda_c^+\pi^-$	$(5.7 \pm 2.2) \times 10^{-4}$		2265
$\Sigma_c(2455)^{++}\pi^-\pi^-, \Sigma_c^{++} \rightarrow$ $\Lambda_c^+\pi^+$	$(3.2 \pm 1.5) \times 10^{-4}$		2265

$\Lambda_c^+ K^+ K^- \pi^-$	$(1.02 \pm 0.11) \times 10^{-3}$	2184
$\Lambda_c^+ p \bar{p} \pi^-$	$(2.63 \pm 0.27) \times 10^{-4}$	1805
$\Sigma_c(2455)^0 p \bar{p}, \Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$	$(2.3 \pm 0.5) \times 10^{-5}$	—
$\Sigma_c(2520)^0 p \bar{p}, \Sigma_c(2520)^0 \rightarrow \Lambda_c^+ \pi^-$	$(3.1 \pm 0.7) \times 10^{-5}$	—
$\Lambda_c^+ \ell^- \bar{\nu}_\ell$ anything	[x] $(10.9 \pm 2.2) \%$	—
$\Lambda_c^+ \ell^- \bar{\nu}_\ell$	$(6.2 \pm 1.4_{-1.3}) \%$	2345
$\Lambda_c^+ \tau^- \bar{\nu}_\tau$	$(1.9 \pm 0.5) \%$	1933
$\Lambda_c^+ \pi^+ \pi^- \ell^- \bar{\nu}_\ell$	$(5.6 \pm 3.1) \%$	2335
$\Lambda_c(2595)^+ \ell^- \bar{\nu}_\ell$	$(7.9 \pm 4.0_{-3.5}) \times 10^{-3}$	2212
$\Lambda_c(2625)^+ \ell^- \bar{\nu}_\ell$	$(1.3 \pm 0.6_{-0.5}) \%$	2195
$p h^-$	$[y] < 2.3 \times 10^{-5}$	CL=90% 2730
$p \pi^-$	$(4.6 \pm 0.8) \times 10^{-6}$	2730
$p K^-$	$(5.5 \pm 1.0) \times 10^{-6}$	2709
$p D_s^-$	$(1.25 \pm 0.13) \times 10^{-5}$	2364
$p \mu^- \bar{\nu}_\mu$	$(4.1 \pm 1.0) \times 10^{-4}$	2730
$\Lambda \mu^+ \mu^-$	$(1.08 \pm 0.28) \times 10^{-6}$	2695
$p \pi^- \mu^+ \mu^-$	$(6.9 \pm 2.5) \times 10^{-8}$	2720
$p K^- e^+ e^-$	$(3.1 \pm 0.6) \times 10^{-7}$	2708
$p K^- \mu^+ \mu^-$	$(2.6 \pm 0.5_{-0.4}) \times 10^{-7}$	2685
$\Lambda \gamma$	$(7.1 \pm 1.7) \times 10^{-6}$	2699
$\Lambda \eta$	$(9 \pm 7_{-5}) \times 10^{-6}$	2670
$\Lambda \eta'(958)$	$< 3.1 \times 10^{-6}$	CL=90% 2611
$\Lambda \pi^+ \pi^-$	$(4.6 \pm 1.9) \times 10^{-6}$	2692
$\Lambda K^+ \pi^-$	$(5.6 \pm 1.2) \times 10^{-6}$	2660
$\Lambda K^+ K^-$	$(1.60 \pm 0.21) \times 10^{-5}$	2605
$\Lambda \phi$	$(9.8 \pm 2.6) \times 10^{-6}$	2599
$p \pi^- \pi^+ \pi^-$	$(2.08 \pm 0.21) \times 10^{-5}$	2715
$p K^- K^+ \pi^-$	$(4.0 \pm 0.6) \times 10^{-6}$	2612
$p K^- \pi^+ \pi^-$	$(5.0 \pm 0.5) \times 10^{-5}$	2675
$p K^- K^+ K^-$	$(1.25 \pm 0.13) \times 10^{-5}$	2524

See Particle Listings for 1 decay modes that have been seen / not seen.

**$\Lambda_b(5912)^0$**

$$J^P = \frac{1}{2}^-$$

Mass  $m = 5912.19 \pm 0.17$  MeV

Full width  $\Gamma < 0.25$  MeV, CL = 90%

**$\Lambda_b(5920)^0$**

$$J^P = \frac{3}{2}^-$$

Mass  $m = 5920.09 \pm 0.17$  MeV

Full width  $\Gamma < 0.19$  MeV, CL = 90%

**$\Lambda_b(6070)^0$**

$$J^P = \frac{1}{2}^+$$

Quantum numbers based on quark model expectations.

Mass  $m = 6072.3 \pm 2.9$  MeV

Full width  $\Gamma = 72 \pm 11$  MeV

**$\Lambda_b(6146)^0$** 

$$J^P = \frac{3}{2}^+$$

Mass  $m = 6146.2 \pm 0.4$  MeV

$$m_{\Lambda_b(6146)^0} - m_{\Lambda_b^0} = 526.55 \pm 0.34$$
 MeV

Full width  $\Gamma = 2.9 \pm 1.3$  MeV **$\Lambda_b(6152)^0$** 

$$J^P = \frac{5}{2}^+$$

Mass  $m = 6152.5 \pm 0.4$  MeV

$$m_{\Lambda_b(6152)^0} - m_{\Lambda_b^0} = 532.89 \pm 0.28$$
 MeV

$$m_{\Lambda_b(6152)^0} - m_{\Lambda_b(6146)^0} = 6.34 \pm 0.32$$
 MeV

Full width  $\Gamma = 2.1 \pm 0.9$  MeV **$\Sigma_b$** 

$$I(J^P) = 1(\frac{1}{2}^+)$$

 $I, J, P$  need confirmation.Mass  $m(\Sigma_b^+) = 5810.56 \pm 0.25$  MeVMass  $m(\Sigma_b^-) = 5815.64 \pm 0.27$  MeV

$$m_{\Sigma_b^+} - m_{\Sigma_b^-} = -5.06 \pm 0.18$$
 MeV

 $\Gamma(\Sigma_b^+) = 5.0 \pm 0.5$  MeV $\Gamma(\Sigma_b^-) = 5.3 \pm 0.5$  MeV **$\Sigma_b$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ ) $p$  (MeV/c) $\Lambda_b^0 \pi$ 

dominant

133

 **$\Sigma_b^*$** 

$$I(J^P) = 1(\frac{3}{2}^+)$$

 $I, J, P$  need confirmation.Mass  $m(\Sigma_b^{*+}) = 5830.32 \pm 0.27$  MeVMass  $m(\Sigma_b^{*-}) = 5834.74 \pm 0.30$  MeV

$$m_{\Sigma_b^{*+}} - m_{\Sigma_b^{*-}} = -4.37 \pm 0.33$$
 MeV ( $S = 1.6$ )

$$m_{\Sigma_b^{*+}} - m_{\Sigma_b^+} = 19.73 \pm 0.18$$

$$m_{\Sigma_b^{*-}} - m_{\Sigma_b^-} = 19.09 \pm 0.22$$

 $\Gamma(\Sigma_b^{*+}) = 9.4 \pm 0.5$  MeV $\Gamma(\Sigma_b^{*-}) = 10.4 \pm 0.8$  MeV ( $S = 1.3$ )

$$m_{\Sigma_b^*} - m_{\Sigma_b} = 21.2 \pm 2.0$$
 MeV

 **$\Sigma_b^*$  DECAY MODES**Fraction ( $\Gamma_i/\Gamma$ ) $p$  (MeV/c) $\Lambda_b^0 \pi$ 

dominant

159

 **$\Sigma_b(6097)^+$** 

$$J^P = ?^?$$

Mass  $m = 6095.8 \pm 1.7$  MeVFull width  $\Gamma = 31 \pm 6$  MeV

$\Sigma_b(6097)^-$ 

$J^P = ??$

Mass  $m = 6098.0 \pm 1.8$  MeVFull width  $\Gamma = 29 \pm 4$  MeV $\Xi_b^-$ 

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

 $I, J, P$  need confirmation. $m(\Xi_b^-) = 5797.0 \pm 0.6$  MeV ( $S = 1.7$ ) $m_{\Xi_b^-} - m_{\Lambda_b^0} = 177.46 \pm 0.31$  MeV ( $S = 1.3$ ) $m_{\Xi_b^-} - m_{\Xi_b^0} = 5.9 \pm 0.6$  MeVMean life  $\tau_{\Xi_b^-} = (1.572 \pm 0.040) \times 10^{-12}$  s

$\Xi_b^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$J/\psi \Xi^- \times B(b \rightarrow \Xi_b^-)$	$(1.02^{+0.26}_{-0.21}) \times 10^{-5}$		1782
$J/\psi \Lambda K^- \times B(b \rightarrow \Xi_b^-)$	$(2.5 \pm 0.4) \times 10^{-6}$		1631
$p K^- K^- \times B(b \rightarrow \Xi_b^-)$	$(3.7 \pm 0.8) \times 10^{-8}$		2731
$\Lambda_b^0 \pi^- \times B(b \rightarrow \Xi_b^-)/B(b \rightarrow \Lambda_b^0)$	$(7.0 \pm 0.9) \times 10^{-4}$		99
$\Sigma(1385) K^-$	$(2.6 \pm 2.3) \times 10^{-7}$		2707
$\Lambda(1405) K^-$	$(1.9 \pm 1.2) \times 10^{-7}$		2702
$\Lambda(1520) K^-$	$(7.6 \pm 3.2) \times 10^{-7}$		2673
$\Lambda(1670) K^-$	$(4.5 \pm 2.3) \times 10^{-7}$		2629
$\Sigma(1775) K^-$	$(2.2 \pm 1.5) \times 10^{-7}$		2599
$\Sigma(1915) K^-$	$(2.6 \pm 2.5) \times 10^{-7}$		2553
$\Xi^- \gamma$	$< 1.3 \times 10^{-4}$	95%	-

See Particle Listings for 3 decay modes that have been seen / not seen.

 $\Xi_b^0$ 

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

 $I, J, P$  need confirmation. $m(\Xi_b^0) = 5791.9 \pm 0.5$  MeV $m_{\Xi_b^0} - m_{\Lambda_b^0} = 172.5 \pm 0.4$  MeVMean life  $\tau_{\Xi_b^0} = (1.480 \pm 0.030) \times 10^{-12}$  s

$\Xi_b^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\rho$ (MeV/c)
$p D^0 K^- \times B(b \rightarrow \Xi_b^0)$	$(1.7 \pm 0.5) \times 10^{-6}$		2374
$p \bar{K}^0 \pi^- \times B(b \rightarrow \Xi_b^0)/B(\bar{b} \rightarrow B^0)$	$< 1.6 \times 10^{-6}$	90%	2783
$p K^0 K^- \times B(b \rightarrow \Xi_b^0)/B(\bar{b} \rightarrow B^0)$	$< 1.1 \times 10^{-6}$	90%	2730
$\Lambda \pi^+ \pi^- \times B(b \rightarrow \Xi_b^0)/B(b \rightarrow \Lambda_b^0)$	$< 1.7 \times 10^{-6}$	90%	2781
$\Lambda K^- \pi^+ \times B(b \rightarrow \Xi_b^0)/B(b \rightarrow \Lambda_b^0)$	$< 8 \times 10^{-7}$	90%	2751
$\Lambda K^+ K^- \times B(b \rightarrow \Xi_b^0)/B(b \rightarrow \Lambda_b^0)$	$< 3 \times 10^{-7}$	90%	2698
$\Lambda_c^+ K^- \times B(b \rightarrow \Xi_b^0)$	$(6 \pm 4) \times 10^{-7}$		2416
$p K^- \pi^+ \pi^- \times B(b \rightarrow \Xi_b^0)/B(b \rightarrow \Lambda_b^0)$	$(1.9 \pm 0.4) \times 10^{-6}$		2766

$\rho K^- K^- \pi^+ \times B(b \rightarrow \Xi_b^0)/B(b \rightarrow \Lambda_b^0)$	$(1.70 \pm 0.30) \times 10^{-6}$	2704
$\rho K^- K^+ K^- \times B(b \rightarrow \Xi_b^0)/B(b \rightarrow \Lambda_b^0)$	$(1.7 \pm 0.9) \times 10^{-7}$	2620

See Particle Listings for 2 decay modes that have been seen / not seen.

**$\Xi'_b(5935)^-$**

$$J^P = \frac{1}{2}^+$$

Mass  $m = 5935.1 \pm 0.5$  MeV

Full width  $\Gamma = 0.03 \pm 0.032$  MeV

**$\Xi'_b(5935)^-$  DECAY MODES**

Fraction ( $\Gamma_i/\Gamma$ )

$\rho$  (MeV/c)

$\Xi_b^0 \pi^- \times B(\bar{b} \rightarrow \Xi'_b(5935)^-)/B(\bar{b} \rightarrow \Xi_b^0)$	$(11.8 \pm 1.8) \%$	31
---	---------------------	----

**$\Xi_b(5945)^0$**

$$J^P = \frac{3}{2}^+$$

Mass  $m = 5952.3 \pm 0.6$  MeV

Full width  $\Gamma = 0.87 \pm 0.08$  MeV

**$\Xi_b(5955)^-$**

$$J^P = \frac{3}{2}^+$$

Mass  $m = 5955.7 \pm 0.5$  MeV

Full width  $\Gamma = 1.43 \pm 0.11$  MeV

**$\Xi_b(5955)^-$  DECAY MODES**

Fraction ( $\Gamma_i/\Gamma$ )

$\rho$  (MeV/c)

$\Xi_b^0 \pi^- \times B(\bar{b} \rightarrow \Xi_b^*(5955)^-)/B(\bar{b} \rightarrow \Xi_b^0)$	$(20.7 \pm 3.5) \%$	84
--	---------------------	----

**$\Xi_b(6087)^0$**

$$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$$

$J, P$  need confirmation.

Mass  $m = 6087.2 \pm 0.5$  MeV

Full width  $\Gamma = 2.4 \pm 0.5$  MeV

**$\Xi_b(6095)^0$**

$$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$$

$J, P$  need confirmation.

Mass  $m = 6095.3 \pm 0.5$  MeV

Full width  $\Gamma = 0.50 \pm 0.35$  MeV

**$\Xi_b(6100)^-$**

$$J^P = \frac{3}{2}^-$$

$J, P$  need confirmation.

Mass  $m = 6099.8 \pm 0.6$  MeV

Full width  $\Gamma = 0.94 \pm 0.31$  MeV

**$\Xi_b(6227)^-$** 

$J^P = ??$

Mass  $m = 6227.9 \pm 0.9$  MeVFull width  $\Gamma = 19.9 \pm 2.6$  MeV

$\Xi_b(6227)^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor	$\rho$ (MeV/c)
$\Lambda_b^0 K^- \times B(b \rightarrow \Xi_b(6227))/B(b \rightarrow \Lambda_b^0)$	$(3.20 \pm 0.35) \times 10^{-3}$		336
$\Xi_b^0 \pi^- \times B(b \rightarrow \Xi_b(6227))/B(b \rightarrow \Xi_b^0)$	$(2.8 \pm 1.1) \%$	1.8	398

 **$\Xi_b(6227)^0$** 

$J^P = ??$

Mass  $m = 6226.8 \pm 1.6$  MeVFull width  $\Gamma = 19_{-4}^{+5}$  MeV

$\Xi_b(6227)^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$\Xi_b^- \pi^+ \times B(b \rightarrow \Xi_b(6227)^0)/B(b \rightarrow \Xi_b^-)$	$(4.5 \pm 0.9) \%$	398

 **$\Xi_b(6327)^0$** 

$J^P = ??$

Mass  $m = 6327.28 \pm 0.35$  MeVFull width  $\Gamma < 2.56$  MeV, CL = 95% **$\Xi_b(6333)^0$** 

$J^P = ??$

Mass  $m = 6332.69 \pm 0.28$  MeVFull width  $\Gamma < 1.92$  MeV, CL = 95% **$\Omega_b^-$** 

$I(J^P) = 0(\frac{1}{2}^+)$

 $I, J, P$  need confirmation.Mass  $m = 6045.8 \pm 0.8$  MeV

$m_{\Omega_b^-} - m_{\Lambda_b^0} = 426.4 \pm 2.2$  MeV

$m_{\Omega_b^-} - m_{\Xi_b^-} = 248.5 \pm 0.6$  MeV

Mean life  $\tau = (1.64_{-0.17}^{+0.18}) \times 10^{-12}$  s

$\tau(\Omega_b^-)/\tau(\Xi_b^-)$  mean life ratio =  $1.11 \pm 0.16$

$\Omega_b^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
$J/\psi \Omega^- \times B(b \rightarrow \Omega_b)$	$(1.4_{-0.4}^{+0.5}) \times 10^{-6}$	S=1.6	1805
$p K^- K^- \times B(\bar{b} \rightarrow \Omega_b)$	$< 2.3 \times 10^{-9}$	CL=90%	2865
$p \pi^- \pi^- \times B(\bar{b} \rightarrow \Omega_b)$	$< 1.5 \times 10^{-8}$	CL=90%	2943
$p K^- \pi^- \times B(\bar{b} \rightarrow \Omega_b)$	$< 7 \times 10^{-9}$	CL=90%	2915

See Particle Listings for 3 decay modes that have been seen / not seen.

**$\Omega_b(6316)^-$** 

$$I(J^P) = ?(??)$$

 $I, J, P$  need confirmation.

Mass  $m = 6315.6 \pm 0.6$  MeV

Full width  $\Gamma < 4.2$  MeV, CL = 95%

 **$\Omega_b(6330)^-$** 

$$I(J^P) = ?(??)$$

 $I, J, P$  need confirmation.

Mass  $m = 6330.3 \pm 0.6$  MeV

Full width  $\Gamma < 4.7$  MeV, CL = 95%

 **$\Omega_b(6340)^-$** 

$$I(J^P) = ?(??)$$

 $I, J, P$  need confirmation.

Mass  $m = 6339.7 \pm 0.6$  MeV

Full width  $\Gamma < 1.8$  MeV, CL = 95%

 **$\Omega_b(6350)^-$** 

$$I(J^P) = ?(??)$$

 $I, J, P$  need confirmation.

Mass  $m = 6349.8 \pm 0.6$  MeV

Full width  $\Gamma < 3.2$  MeV, CL = 95%

 **$b$ -baryon ADMIXTURE ( $\Lambda_b, \Xi_b, \Omega_b$ )**

These branching fractions are actually an average over weakly decaying  $b$ -baryons weighted by their production rates at the LHC, LEP, and Tevatron, branching ratios, and detection efficiencies. They scale with the  $b$ -baryon production fraction  $B(b \rightarrow b\text{-baryon})$ .

The branching fractions  $B(b\text{-baryon} \rightarrow \Lambda \ell^- \bar{\nu}_\ell \text{ anything})$  and  $B(\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \bar{\nu}_\ell \text{ anything})$  are not pure measurements because the underlying measured products of these with  $B(b \rightarrow b\text{-baryon})$  were used to determine  $B(b \rightarrow b\text{-baryon})$ , as described in the note "Production and Decay of  $b$ -Flavored Hadrons."

For inclusive branching fractions, e.g.,  $B \rightarrow D^\pm \text{ anything}$ , the values usually are multiplicities, not branching fractions. They can be greater than one.

 **$b$ -baryon ADMIXTURE DECAY MODES**  
**( $\Lambda_b, \Xi_b, \Omega_b$ )**

	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor	$\rho$ (MeV/c)
$\rho \mu^- \bar{\nu}$ anything	( $5.8^+_{-2.0}$ ) %		—
$\rho \ell \bar{\nu}_\ell$ anything	( $5.6 \pm 1.2$ ) %		—
$\rho$ anything	( $70 \pm 22$ ) %		—
$\Lambda \ell^- \bar{\nu}_\ell$ anything	( $3.8 \pm 0.6$ ) %		—
$\Lambda \ell^+ \nu_\ell$ anything	( $3.2 \pm 0.8$ ) %		—
$\Lambda$ anything	( $39 \pm 7$ ) %		—
$\Xi^- \ell^- \bar{\nu}_\ell$ anything	( $4.6 \pm 1.4$ ) $\times 10^{-3}$	1.2	—



## NOTES

This Summary Table only includes established baryons. The Particle Listings include evidence for other baryons. The masses, widths, and branching fractions for the resonances in this Table are Breit-Wigner parameters, but pole positions are also given for most of the  $N$  and  $\Delta$  resonances.

For most of the resonances, the parameters come from various partial-wave analyses of more or less the same sets of data, and it is not appropriate to treat the results of the analyses as independent or to average them together.

When a quantity has “(S = ...)” to its right, the error on the quantity has been enlarged by the “scale factor” S, defined as  $S = \sqrt{\chi^2/(N-1)}$ , where  $N$  is the number of measurements used in calculating the quantity.

A decay momentum  $p$  is given for each decay mode. For a 2-body decay,  $p$  is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay,  $p$  is the largest momentum any of the products can have in this frame. For any resonance, the *nominal* mass is used in calculating  $p$ .

- [a] The masses of the  $p$  and  $n$  are most precisely known in  $u$  (unified atomic mass units). The conversion factor to MeV,  $1 u = 931.494061(21)$  MeV, is less well known than are the masses in  $u$ .
- [b] The  $|m_p - m_{\bar{p}}|/m_p$  and  $|q_p + q_{\bar{p}}|/e$  are not independent, and both use the more precise measurement of  $|q_{\bar{p}}/m_{\bar{p}}|/(q_p/m_p)$ .
- [c] The limit is from neutrality-of-matter experiments; it assumes  $q_n = q_p + q_e$ . See also the charge of the neutron.
- [d] The  $\mu p$  and  $e p$  values for the charge radius are much too different to average them. The disagreement is not yet understood.
- [e] There is a lot of disagreement about the value of the proton magnetic charge radius. See the Listings.
- [f] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). The first limit here is from reactor experiments with free neutrons.
- [g] Lee and Yang in 1956 proposed the existence of a mirror world in an attempt to restore global parity symmetry—thus a search for oscillations between the two worlds. Oscillations between the worlds would be maximal when the magnetic fields  $B$  and  $B'$  were equal. The limit for any  $B'$  in the range 0 to  $12.5 \mu\text{T}$  is  $>12$  s (95% CL).
- [h] The parameters  $g_A$ ,  $g_V$ , and  $g_{WM}$  for semileptonic modes are defined by  $\bar{B}_f[\gamma_\lambda(g_V + g_A\gamma_5) + i(g_{WM}/m_{B_i})\sigma_{\lambda\nu}q^\nu]B_i$ , and  $\phi_{AV}$  is defined by  $g_A/g_V = |g_A/g_V|e^{i\phi_{AV}}$ . See the “Note on Baryon Decay Parameters” in the neutron Particle Listings in the Full *Review of Particle Physics*.
- [i] Time-reversal invariance requires this to be  $0^\circ$  or  $180^\circ$ .
- [j] This coefficient is zero if time invariance is not violated.
- [k] This limit is for  $\gamma$  energies between 0.4 and 782 keV.
- [l] The decay parameters  $\gamma$  and  $\Delta$  are calculated from  $\alpha$  and  $\phi$  using

$$\gamma = \sqrt{1-\alpha^2} \cos\phi, \quad \tan\Delta = -\frac{1}{\alpha} \sqrt{1-\alpha^2} \sin\phi.$$

See the “Note on Baryon Decay Parameters” in the neutron Particle Listings in the Full *Review of Particle Physics*.

- [n] See Particle Listings in the Full *Review of Particle Physics* for the pion momentum range used in this measurement.
- [o] Our estimate. See the Particle Listings for details.
- [p] A theoretical value using QED.

- [q] This branching fraction includes all the decay modes of the final-state resonance.
- [r] Here  $\gamma_D$  stands for a dark photon.
- [s] See AALTONEN 11H, Fig. 8, for the calculated ratio of  $\Lambda_c^+ \pi^0 \pi^0$  and  $\Lambda_c^+ \pi^+ \pi^-$  partial widths as a function of the  $\Lambda_c(2595)^+ - \Lambda_c^+$  mass difference. At our value of the mass difference, the ratio is about 4.
- [t] Assuming isospin conservation, so that the other third is  $\Lambda_c^+ \pi^0 \pi^0$ .
- [u] A test that the isospin is indeed 0, so that the particle is indeed a  $\Lambda_c^+$ .
- [v]  $P_c^+$  is a pentaquark-charmonium state.
- [x] Not a pure measurement. See note at head of  $\Lambda_b^0$  Decay Modes.
- [y] Here  $h^-$  means  $\pi^-$  or  $K^-$ .

# SEARCHES not in other sections

## Magnetic Monopole Searches

The most sensitive experiments obtain negative results.

Best cosmic-ray supermassive monopole flux limit:

$$< 1.4 \times 10^{-16} \text{ cm}^{-2}\text{sr}^{-1}\text{s}^{-1} \quad \text{for } 1.1 \times 10^{-4} < \beta < 1$$

## Supersymmetric Particle Searches

All supersymmetric mass bounds here are model dependent.

The limits assume:

1)  $\tilde{\chi}_1^0$  is the lightest supersymmetric particle; 2)  $R$ -parity is conserved, unless stated otherwise;

See the Particle Listings in the Full *Review of Particle Physics* for a Note giving details of supersymmetry.

$\tilde{\chi}_i^0$  — neutralinos (mixtures of  $\tilde{\gamma}$ ,  $\tilde{Z}^0$ , and  $\tilde{H}_i^0$ )

Mass  $m_{\tilde{\chi}_1^0} > 0$  GeV, CL = 95%

[general MSSM, non-universal gaugino masses]

Mass  $m_{\tilde{\chi}_1^0} > 46$  GeV, CL = 95%

[all  $\tan\beta$ , all  $m_0$ , all  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ ]

Mass  $m_{\tilde{\chi}_2^0} > 62.4$  GeV, CL = 95%

[ $1 < \tan\beta < 40$ , all  $m_0$ , all  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ ]

Mass  $m_{\tilde{\chi}_3^0} > 99.9$  GeV, CL = 95%

[ $1 < \tan\beta < 40$ , all  $m_0$ , all  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ ]

Mass  $m_{\tilde{\chi}_4^0} > 116$  GeV, CL = 95%

[ $1 < \tan\beta < 40$ , all  $m_0$ , all  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ ]

Mass  $m_{\tilde{\chi}}$  none 200–670 GeV, CL = 95% [R-Parity Violating]

[wino production,  $\tilde{\chi} \rightarrow b + \ell/\nu + t/b$  via  $\lambda'_{33}$  coupling]

$\tilde{\chi}_i^\pm$  — charginos (mixtures of  $\tilde{W}^\pm$  and  $\tilde{H}_i^\pm$ )

Mass  $m_{\tilde{\chi}_1^\pm} > 94$  GeV, CL = 95%

[ $\tan\beta < 40$ ,  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > 3$  GeV, all  $m_0$ ]

Mass  $m_{\tilde{\chi}_1^\pm} > 1000$  GeV, CL = 95%

[ $2\ell + \cancel{E}_T$ , Tchi1chi1C,  $m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m_{\tilde{\chi}_1^\pm} > 1600$  GeV, CL = 95% [R-Parity Violating]

[Tchi1n2l,  $\tilde{\chi}_1^0 \rightarrow \ell^\pm \ell^\mp \nu$ ,  $\lambda_{12k} \neq 0$ ,  $m_{\tilde{\chi}_1^0} = 1200$  GeV]

$\tilde{\chi}^\pm$  — long-lived chargino

Mass  $m_{\tilde{\chi}^\pm} > 1050$  GeV, CL = 95%

[ $\tilde{\chi}^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ , wino LSP, stable]

Mass  $m_{\tilde{\chi}^\pm} > 1050$  GeV, CL = 95%

[ $\tilde{\chi}^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ , wino LSP,  $\tau = 20$  ns]

$\tilde{\nu}$  — sneutrino

Mass  $m > 41$  GeV, CL = 95% [model independent]

Mass  $m > 94$  GeV, CL = 95%

[CMSSM,  $1 \leq \tan\beta \leq 40$ ,  $m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0} > 10$  GeV]

Mass  $m > 4200$  GeV, CL = 95% [R-Parity Violating]

[ $1e + 1\mu, \nu_\tau \rightarrow e\mu, \lambda = \lambda' = 0.1$ ]

$\tilde{e}$  — scalar electron (selectron)

Mass  $m > 107$  GeV, CL = 95% [all  $m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0}$ ]

Mass  $m > 700$  GeV, CL = 95%

[ $2\ell + \cancel{E}_T$ ,  $m_{\tilde{\ell}_R} = m_{\tilde{\ell}_L}$  and  $\tilde{\ell} = \tilde{e}, \tilde{\mu}, m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m > 250$  GeV, CL = 95%

[ $\ell^\pm \ell^\mp + \cancel{E}_T, \tilde{e}_R, m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m > 410$  GeV, CL = 95% [R-Parity Violating]

[ $\geq 4\ell^\pm, \tilde{\ell} \rightarrow l\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell^\pm \ell^\mp \nu$ ]

Mass  $m > 1200$  GeV, CL = 95% [R-Parity Violating]

[ $\geq 4\ell, \lambda_{12k} \neq 0, m_{\tilde{\chi}_1^0} = 900$  GeV (m-degenerate  $\tilde{\ell}_L, \tilde{\nu}$ )]

$\tilde{\mu}$  — scalar muon (smuon)

Mass  $m > 700$  GeV, CL = 95%

[ $2\ell + \cancel{E}_T$ ,  $m_{\tilde{\ell}_R} = m_{\tilde{\ell}_L}$  and  $\tilde{\ell} = \tilde{e}, \tilde{\mu}, m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m > 210$ , CL = 95%

[ $\ell^\pm \ell^\mp + \cancel{E}_T, \tilde{\mu}_R, m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m > 94$  GeV, CL = 95%

[CMSSM,  $1 \leq \tan\beta \leq 40$ ,  $m_{\tilde{\mu}_R} - m_{\tilde{\chi}_1^0} > 10$  GeV]

Mass  $m > 410$  GeV, CL = 95% [R-Parity Violating]

[ $\geq 4\ell^\pm, \tilde{\ell} \rightarrow l\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell^\pm \ell^\mp \nu$ ]

Mass  $m > 1200$  GeV, CL = 95% [R-Parity Violating]

[ $\geq 4\ell, \lambda_{12k} \neq 0, m_{\tilde{\chi}_1^0} = 900$  GeV (m-degenerate  $\tilde{\ell}_L, \tilde{\nu}$ )]

$\tilde{\tau}$  — scalar tau (stau)

Mass  $m > 81.9$  GeV, CL = 95%

[ $m_{\tilde{\tau}_R} - m_{\tilde{\chi}_1^0} > 15$  GeV, all  $\theta_\tau$ ,  $B(\tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0) = 100\%$ ]

Mass  $m > 400$  GeV, CL = 95%

[2 hadronic  $\tau + \cancel{E}_T, \tilde{\tau}_{R,L} \rightarrow \tau\tilde{\chi}_1^0, m_{\tilde{\chi}_1^0} = 1$  GeV]

Mass  $m > 90$  GeV, CL = 95% [R-Parity Violating]

[ $\tilde{\tau}_R$ , indirect,  $\Delta m > 5$  GeV]

Mass  $m > 1200$ , CL = 95% [R-Parity Violating]

[ $\geq 4\ell, \lambda_{12k} \neq 0, m_{\tilde{\chi}_1^0} = 900$  GeV (m-degenerate  $\tilde{\ell}_L, \tilde{\nu}$ )]

Mass  $m > 286$  GeV, CL = 95% [long-lived  $\tilde{\tau}$ ]

$\tilde{q}$  — squarks of the first two quark generations

Mass  $m > 1.220 \times 10^3$  GeV, CL = 95%

[jets +  $\cancel{E}_T$ , Tsqk1, 1 non-degenerate  $\tilde{q}, m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m > 1.600 \times 10^3$  GeV, CL = 95% [R-Parity Violating]

[ $\tilde{q} \rightarrow q\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\ell\nu, \lambda_{121}, \lambda_{122} \neq 0, m_{\tilde{g}} = 2400$  GeV]

$\tilde{q}$  — long-lived squark

Mass  $m > 1340$ , CL = 95% [ $\tilde{t}$  R-hadrons]

Mass  $m > 1250$ , CL = 95% [ $\tilde{b}$  R-hadrons]

$\tilde{b}$  — scalar bottom (sbottom)

Mass  $m > 1.270 \times 10^3$  GeV, CL = 95%

[ $b$ -jets +  $\cancel{E}_T$ , T<sub>bot1</sub>,  $m_{\tilde{\chi}_1^0} = 0$  GeV]

Mass  $m > 307$  GeV, CL = 95% [R-Parity Violating]

[ $\tilde{b} \rightarrow t d$  or  $t s$ ,  $\lambda''_{332}$  or  $\lambda''_{331}$  coupling]

$\tilde{t}$  — scalar top (stop)

Mass  $m > 1.310 \times 10^3$  GeV, CL = 95%

[jets +  $\cancel{E}_T$ , T<sub>stop1</sub>,  $m_{\tilde{\chi}_1^0} < 300$  GeV]

Mass  $m > 1100$  GeV, CL = 95% [R-Parity Violating]

[ $\tilde{t} \rightarrow b e$ , T<sub>stop2RPV</sub>, prompt]

Mass  $m > 460$  GeV, CL = 95%

[R-Parity Violating, long-lived  $\tilde{t}$ ,  $\tilde{t} \rightarrow d \bar{\ell}$ ,  $0.01 \text{ cm} < c\tau < 1000$  cm]

$\tilde{g}$  — gluino

Mass  $m > 2.300 \times 10^3$  GeV, CL = 95%

[jets +  $\cancel{E}_T$ , T<sub>glu1A</sub>,  $m_{\tilde{\chi}_1^0} < 200$  GeV]

Mass  $m > 2.260 \times 10^3$  GeV, CL = 95% [R-Parity Violating]

[ $\geq 4\ell$ ,  $\lambda_{12k} \neq 0$ ,  $m_{\tilde{\chi}_1^0} > 1000$  GeV]

## Technicolor

The limits for technicolor (and top-color) particles are quite varied depending on assumptions. See the Technicolor section of the full *Review* (the data listings).

## Quark and Lepton Compositeness, Searches for

### Scale Limits $\Lambda$ for Contact Interactions (the lowest dimensional interactions with four fermions)

If the Lagrangian has the form

$$\pm \frac{g^2}{2\Lambda^2} \bar{\psi}_L \gamma_\mu \psi_L \bar{\psi}_L \gamma^\mu \psi_L$$

(with  $g^2/4\pi$  set equal to 1), then we define  $\Lambda \equiv \Lambda_{LL}^\pm$ . For the full definitions and for other forms, see the Note in the Listings on Searches for Quark and Lepton Compositeness in the full *Review* and the original literature.

$$\Lambda_{LL}^+(e e e e) > 8.3 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^-(e e e e) > 10.3 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^+(e e \mu \mu) > 8.5 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^-(e e \mu \mu) > 9.5 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^+(e e \tau \tau) > 7.9 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^-(e e \tau \tau) > 7.2 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^+(\ell \ell \ell \ell) > 9.1 \text{ TeV, CL} = 95\%$$

$$\Lambda_{LL}^-(\ell \ell \ell \ell) > 10.3 \text{ TeV, CL} = 95\%$$

$\Lambda_{LL}^+(eeqq)$	$> 24$ TeV, CL = 95%
$\Lambda_{LL}^-(eeqq)$	$> 37$ TeV, CL = 95%
$\Lambda_{LL}^+(eeuu)$	$> 23.3$ TeV, CL = 95%
$\Lambda_{LL}^-(eeuu)$	$> 12.5$ TeV, CL = 95%
$\Lambda_{LL}^+(eedd)$	$> 11.1$ TeV, CL = 95%
$\Lambda_{LL}^-(eedd)$	$> 26.4$ TeV, CL = 95%
$\Lambda_{LL}^+(eccc)$	$> 9.4$ TeV, CL = 95%
$\Lambda_{LL}^-(eccc)$	$> 5.6$ TeV, CL = 95%
$\Lambda_{LL}^+(eebb)$	$> 9.4$ TeV, CL = 95%
$\Lambda_{LL}^-(eebb)$	$> 10.2$ TeV, CL = 95%
$\Lambda_{LL}^+(\mu\mu qq)$	$> 23.3$ TeV, CL = 95%
$\Lambda_{LL}^-(\mu\mu qq)$	$> 40.0$ TeV, CL = 95%
$\Lambda(\ell\nu\ell\nu)$	$> 3.10$ TeV, CL = 90%
$\Lambda(e\nu qq)$	$> 2.81$ TeV, CL = 95%
$\Lambda_{LL}^+(qqqq)$	$> 13.1$ none 17.4–29.5 TeV, CL = 95%
$\Lambda_{LL}^-(qqqq)$	$> 21.8$ TeV, CL = 95%
$\Lambda_{LL}^+(\nu\nu qq)$	$> 5.0$ TeV, CL = 95%
$\Lambda_{LL}^-(\nu\nu qq)$	$> 5.4$ TeV, CL = 95%

### Excited Leptons

The limits from  $\ell^{*+}\ell^{*-}$  do not depend on  $\lambda$  (where  $\lambda$  is the  $\ell\ell^*$  transition coupling). The  $\lambda$ -dependent limits assume chiral coupling.

$e^{*\pm}$  — excited electron

Mass  $m > 103.2$  GeV, CL = 95% (from  $e^*e^*$ )

Mass  $m > 5.600 \times 10^3$  GeV, CL = 95% (from  $e e^*$ )

Mass  $m > 356$  GeV, CL = 95% (if  $\lambda_\gamma = 1$ )

$\mu^{*\pm}$  — excited muon

Mass  $m > 103.2$  GeV, CL = 95% (from  $\mu^*\mu^*$ )

Mass  $m > 5.700 \times 10^3$  GeV, CL = 95% (from  $\mu\mu^*$ )

$\tau^{*\pm}$  — excited tau

Mass  $m > 103.2$  GeV, CL = 95% (from  $\tau^*\tau^*$ )

Mass  $m > 4.600 \times 10^3$  GeV, CL = 95% (from  $\tau\tau^*$ )

$\nu^*$  — excited neutrino

Mass  $m > 1.600 \times 10^3$  GeV, CL = 95% (from  $\nu^*\nu^*$ )

Mass  $m > 213$  GeV, CL = 95% (from  $\nu^*X$ )

$q^*$  — excited quark

Mass  $m > 338$  GeV, CL = 95% (from  $q^*q^*$ )

Mass  $m > 6700$  GeV, CL = 95% (from  $q^*X$ )

### Color Sextet and Octet Particles

Color Sextet Quarks ( $q_6$ )

Mass  $m > 84$  GeV, CL = 95% (Stable  $q_6$ )

Color Octet Charged Leptons ( $\ell_8$ )

Mass  $m > 86$  GeV, CL = 95% (Stable  $\ell_8$ )

Color Octet Neutrinos ( $\nu_8$ )

Mass  $m > 110$  GeV, CL = 90% ( $\nu_8 \rightarrow \nu g$ )

## Extra Dimensions

Please refer to the Extra Dimensions section of the full *Review* for a discussion of the model-dependence of these bounds, and further constraints.

### Constraints on the radius of the extra dimensions, for the case of two-flat dimensions of equal radii

(direct tests of Newton's law)

$R < 3.8 \mu\text{m}$ , CL = 95% ( $pp \rightarrow jG$ )

$R < 0.16\text{--}916$  nm (astrophysics; limits depend on technique and assumptions)

### Constraints on the fundamental gravity scale

$M_{TT} > 9.02$  TeV, CL = 95% ( $pp \rightarrow$  dijet, angular distribution)

$M_c > 4.16$  TeV, CL = 95% ( $pp \rightarrow \ell\bar{\ell}$ )

### Constraints on the Kaluza-Klein graviton in warped extra dimensions

$M_G > 4.78$  TeV, CL = 95% ( $pp \rightarrow e^+e^-, \mu^+\mu^-$ )

### Constraints on the Kaluza-Klein gluon in warped extra dimensions

$M_{g_{KK}} > 3.8$  TeV, CL = 95% ( $g_{KK} \rightarrow t\bar{t}$ )

## WIMP and Dark Matter Searches

No confirmed evidence found for galactic WIMPs from the GeV to the TeV mass scales and down to  $1 \times 10^{-10}$  pb spin independent cross section at  $M = 100$  GeV.

## Tests of Conservation Laws

Revised April 2024 by A. Pich (IFIC, Valencia) and M. Ramsey-Musolf (Tsung-Dao Lee Inst.; SJTU; U. Massachusetts).

The following text discusses the best limits among those included in the full Review, where more complete details can be found. Unless otherwise specified, all limits quoted here are given at a C.L. of 90%.

### DISCRETE SPACE-TIME SYMMETRIES

Charge conjugation ( $C$ ), parity ( $P$ ) and time reversal ( $T$ ) are empirically found to be symmetries of the electromagnetic (QED) and strong (QCD) interactions, but they are violated by the weak forces. The product of the three discrete symmetries,  $CPT$ , is an exact symmetry of any local and Lorentz-invariant quantum field theory with a positive-definite Hermitian Hamiltonian that preserves micro-causality.

#### 1 Violations of $CP$ and $T$

The first evidence of  $CP$  non-invariance in particle physics was the observation in 1964 of  $K_L^0 \rightarrow \pi^+\pi^-$  decays. The non-zero ratio  $|\eta_{+-}| \equiv |\mathcal{M}(K_L^0 \rightarrow \pi^+\pi^-)/\mathcal{M}(K_S^0 \rightarrow \pi^+\pi^-)| = (2.232 \pm 0.011) \times 10^{-3}$  could be explained as a  $K^0-\bar{K}^0$  mixing effect ( $\eta_{+-} = \epsilon$ ), which would imply an identical ratio  $\eta_{00} \equiv \mathcal{M}(K_L^0 \rightarrow \pi^0\pi^0)/\mathcal{M}(K_S^0 \rightarrow \pi^0\pi^0)$  in the neutral decay mode and successfully predicts the observed  $CP$ -violating semileptonic asymmetry  $[\Gamma(K_L^0 \rightarrow \pi^-e^+\nu_e) - \Gamma(K_L^0 \rightarrow \pi^+e^-\bar{\nu}_e)]/[\text{sum}] = (3.34 \pm 0.07) \times 10^{-3}$ . A tiny difference between  $\eta_{+-}$  and  $\eta_{00}$  was reported for the first time in 1988 by the CERN NA31 experiment, and later established at the  $7.2\sigma$  level with the full data samples from the NA31, E731, NA48 and KTeV experiments:  $\text{Re}(\epsilon'/\epsilon) = \frac{1}{3}(1 - |\eta_{00}/\eta_{+-}|) = (1.66 \pm 0.23) \times 10^{-3}$ . This important measurement confirmed that  $CP$  violation is associated with a  $\Delta S = 1$  transition, as predicted by the CKM mechanism. The Standard Model (SM) prediction,  $\text{Re}(\epsilon'/\epsilon) = (1.4 \pm 0.5) \times 10^{-3}$ , is in good agreement with the measured ratio, although the theoretical uncertainty is unfortunately large.

Much larger  $CP$  asymmetries have been later measured in  $B$  meson decays, many of them involving the interference between  $B^0-\bar{B}^0$  mixing and the decay amplitude. They provide many successful tests of the CKM unitarity structure, validating the SM mechanism of  $CP$  violation (see the review on  $CP$  violation in the quark sector). Prominent signals of direct  $CP$  violation have been also clearly established in several  $B_{\pm}^{\pm}$ ,  $B_d^0$  and  $B_s^0$  decays, and, very recently, in charm decays.

While  $CP$  violation implies a breaking of time-reversal symmetry, direct tests of  $T$  violation are much more difficult. The CPLEAR experiment observed longtime ago a non-zero difference between the oscillation probabilities of  $K^0 \rightarrow \bar{K}^0$  and  $\bar{K}^0 \rightarrow K^0$ . More recently, the exchange of initial and final states has been made possible in  $B$  decays, taking advantage of the entanglement of the two daughter mesons produced in the decay  $\Upsilon(4S) \rightarrow B\bar{B}$  which allows for both flavor ( $B^0 \rightarrow \ell^+X$ ,  $\bar{B}^0 \rightarrow \ell^-X$ ) and  $CP$  ( $B_+ \rightarrow J/\psi K_L^0$ ,  $B_- \rightarrow J/\psi K_S^0$ ) tagging. Comparing the rates of the  $\bar{B}^0 \rightarrow B_{\pm}$  and  $B^0 \rightarrow B_{\pm}$  transitions with their  $T$ -reversed  $B_{\pm} \rightarrow \bar{B}^0$  and  $B_{\pm} \rightarrow B^0$  processes, the BABAR experiment has reported the first direct observation of  $T$  violation in the  $B$  system, with a significance of  $14\sigma$ .

Among the most powerful tests of  $P$  ( $CP$ ) and  $T$  invariance is the search for a permanent electric dipole moment (EDM) of an elementary fermion or non-degenerate quantum system. No positive signal has been detected so far. The most stringent limits have been obtained for the EDMs of the electron,  $|d_e| < 4.1 \times 10^{-30}$  e cm, mercury atom,  $|d_{\text{Hg}}| < 7.4 \times 10^{-30}$  e cm (95% C.L.), and neutron,  $|d_n| < 1.8 \times 10^{-26}$  e cm.



## 2 Tests of *CPT*

*CPT* symmetry implies the equality of the masses and widths of a particle and its antiparticle. The most constraining limits are extracted from the neutral kaons:  $2|m_{K^0} - m_{\bar{K}^0}|/(m_{K^0} + m_{\bar{K}^0}) < 6 \times 10^{-19}$  and  $2|\Gamma_{K^0} - \Gamma_{\bar{K}^0}|/(\Gamma_{K^0} + \Gamma_{\bar{K}^0}) = (8 \pm 8) \times 10^{-18}$ . The measured masses and electric charges of the electron, the proton and their antiparticles provide also strong limits on *CPT* violation:  $2|m_{e^+} - m_{e^-}|/(m_{e^+} + m_{e^-}) < 8 \times 10^{-9}$ ,  $|q_{e^+} + q_{e^-}|/e < 4 \times 10^{-8}$  and  $|q_{\bar{p}}m_p/(q_p m_{\bar{p}})| - 1 = (0.3 \pm 1.6) \times 10^{-11}$ . Worth mentioning are also the tight constraints derived from the lepton and antilepton magnetic moments,  $2(g_{e^+} - g_{e^-})(g_{e^+} + g_{e^-}) = (-0.5 \pm 2.1) \times 10^{-12}$  and  $2(g_{\mu^+} - g_{\mu^-})(g_{\mu^+} + g_{\mu^-}) = (-0.11 \pm 0.12) \times 10^{-8}$ , those of the proton and antiproton,  $(\mu_p + \mu_{\bar{p}})/\mu_p = (2 \pm 4) \times 10^{-9}$ , and the measurement of the 1S-2S atomic transition in antihydrogen which agrees with the corresponding frequency spectral line in hydrogen at a relative precision of  $2 \times 10^{-12}$ .

## QUANTUM-NUMBER CONSERVATION LAWS

Conservation laws of several quantum numbers have been empirically established with a high degree of confidence. However, while some of them are deeply rooted in basic principles such as gauge invariance or Lorentz symmetry, others appear to be accidental symmetries of the SM Lagrangian and could be broken by new physics interactions.

### 3 Electric charge

The conservation of electric charges is associated with the QED gauge symmetry. The most precise tests are the non-observation of the decays  $e \rightarrow \nu_e \gamma$  ( $\tau > 6.6 \times 10^{28}$  yr) and  $n \rightarrow p \nu_e \bar{\nu}_e$  ( $\text{Br} < 8 \times 10^{-27}$ , 68% C.L.).

### 4 Lepton family numbers

Neutrino oscillations show that neutrinos have tiny masses and there are sizable mixings among the lepton flavors. Nevertheless, lepton-flavor violation (LFV) in neutrinoless transitions from one charged lepton flavor to another has never been observed. Among the most sensitive probes are searches for the LFV decays of the muon,  $\text{Br}(\mu \rightarrow e \gamma) < 4.2 \times 10^{-13}$  and  $\text{Br}(\mu \rightarrow 3e) < 1.0 \times 10^{-12}$ , as well as the conversion process  $\sigma(\mu^- \text{Au} \rightarrow e^- \text{Au})/\sigma(\mu^- \text{Au} \rightarrow \text{all}) < 7 \times 10^{-13}$ . Stringent limits have been also set on the LFV decay modes of the  $\tau$  lepton. The large  $\tau$  data samples collected at the *B* factories have made possible to reach a  $10^{-8}$  sensitivity for many of its leptonic ( $\tau \rightarrow \ell \gamma$ ,  $\tau \rightarrow \ell' \ell^+ \ell^-$ ) and semileptonic ( $\tau \rightarrow \ell P^0$ ,  $\tau \rightarrow \ell V^0$ ,  $\tau \rightarrow \ell P^+ P^0$ ,  $\tau \rightarrow \ell P^+ P'^-$ ) neutrinoless LFV decays. Interesting limits on LFV are also obtained in meson decays. The best bounds come from kaon experiments, e.g.,  $\text{Br}(K_L^0 \rightarrow e^\pm \mu^\mp) < 4.7 \times 10^{-12}$  and  $\text{Br}(K^+ \rightarrow \pi^+ \mu^+ e^-) < 1.3 \times 10^{-11}$ .

The LFV decays of the *Z* boson were probed at LEP at the  $10^{-5}$  to  $10^{-6}$  level. The ATLAS collaboration has recently put the stronger (95% C.L.) bounds  $\text{Br}(Z \rightarrow e^\pm \mu^\mp) < 2.62 \times 10^{-7}$ ,  $\text{Br}(Z \rightarrow e^\pm \tau^\mp) < 5.0 \times 10^{-6}$  and  $\text{Br}(Z \rightarrow \mu^\pm \tau^\mp) < 6.5 \times 10^{-6}$ . LHC is now testing LFV in Higgs decays. The current (95% C.L.) experimental upper bounds,  $\text{Br}(H^0 \rightarrow e^\pm \mu^\mp) < 4.4 \times 10^{-5}$ ,  $\text{Br}(H^0 \rightarrow e^\pm \tau^\mp) < 0.20\%$  and  $\text{Br}(H^0 \rightarrow \mu^\pm \tau^\mp) < 0.15\%$ , constrain the LFV Yukawa couplings of the Higgs boson.

### 5 Baryon and Lepton Number

Many experiments have searched for *B*- and/or *L*-violating transitions, but no positive signal has been identified so far. The neutrinoless double- $\beta$  decay  $(Z, A) \rightarrow (Z+2, A) + e^- + e^-$  is a particularly interesting  $\Delta L = 2$  process, which could represent a spectacular signal of Majorana neutrinos. The current best limit,  $\tau_{1/2} > 1.07 \times 10^{26}$  yr, was obtained by the KamLAND-Zen experiment with  $^{136}\text{Xe}$ . Stringent constraints on vi-

violations of  $L$  have been also set in  $\mu^- \rightarrow e^+$  conversion in muonic atoms, the best limit being  $\sigma(\mu^- \text{Ti} \rightarrow e^+ \text{Ca})/\sigma(\mu^- \text{Ti} \rightarrow \text{all}) < 3.6 \times 10^{-11}$ , and at the flavor factories through  $L$ -violating decays of the  $\tau$  lepton and  $K$ ,  $D$  and  $B$  mesons, such as  $\text{Br}(\tau^- \rightarrow e^+ \pi^- \pi^-) < 2.0 \times 10^{-8}$ ,  $\text{Br}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ ,  $\text{Br}(D^+ \rightarrow \pi^- \mu^+ \mu^+) < 1.4 \times 10^{-8}$  and  $\text{Br}(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9}$  (95% CL).

Proton decay would be the most relevant violation of  $B$ , as it would imply the instability of matter. The current lower bound on the proton lifetime is  $9 \times 10^{29}$  yr. Stronger limits have been set for particular decay modes, such as  $\tau(p \rightarrow e^+ \pi^0) > 2.4 \times 10^{34}$  yr. Another spectacular signal would be  $n$ - $\bar{n}$  oscillations; the lower limit on the lifetime of this  $\Delta B = 2$  transition is  $8.6 \times 10^7$  s ( $4.7 \times 10^8$  s) for free (bound) neutrons.

The search for  $B$ -violating decays of short-lived particles such as  $Z$  bosons,  $\tau$  leptons and  $B$  mesons provides also relevant constraints. The best limits are  $\text{Br}(Z \rightarrow pe, p\mu) < 1.8 \times 10^{-6}$  (95% C.L.),  $\text{Br}(\tau^- \rightarrow \bar{p}\mu^- \mu^+) < 1.8 \times 10^{-8}$  and  $\text{Br}(B^0 \rightarrow p\mu^-) < 2.6 \times 10^{-9}$ .

## 6 Quark flavors

While strong and electromagnetic forces preserve the quark flavor, the charged-current weak interactions generate transitions among the different quark species. Since the SM flavor-changing mechanism is associated with the  $W^\pm$  fermionic vertices, the tree-level transitions satisfy a  $\Delta F = \Delta Q$  rule where  $\Delta Q$  denotes the change in charge of the relevant hadrons. The strongest tests on this conservation law have been obtained in kaon decays such as  $\text{Br}(K^+ \rightarrow \pi^+ \pi^+ e^- \bar{\nu}_e) < 1.3 \times 10^{-8}$ , and  $(\text{Re } x, \text{Im } x) = (-0.002 \pm 0.006, 0.0012 \pm 0.0021)$  where  $x \equiv \mathcal{M}(\bar{K}^0 \rightarrow \pi^- \ell^+ \nu)/\mathcal{M}(K^0 \rightarrow \pi^- \ell^+ \nu)$ .

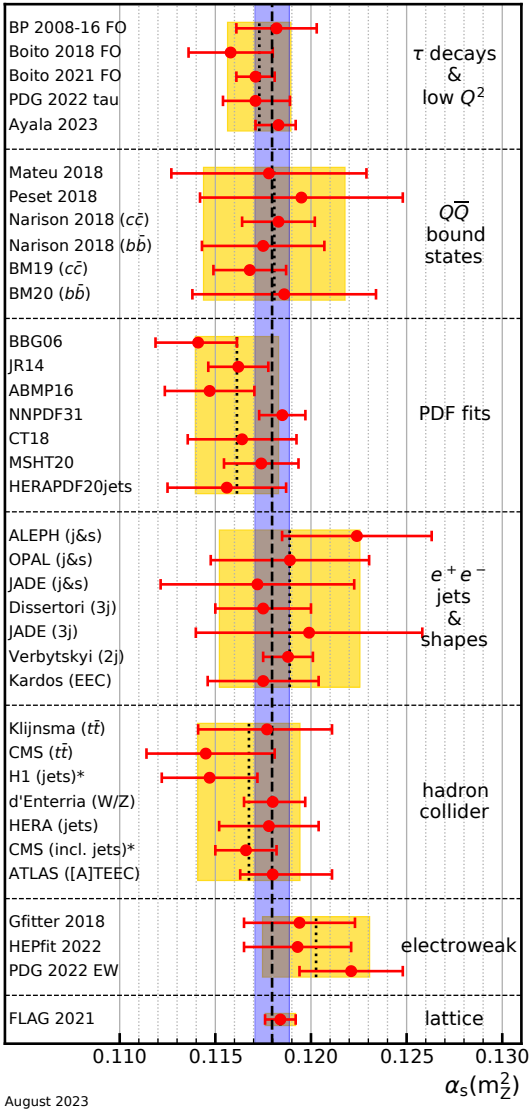
The  $\Delta F = \Delta Q$  rule can be violated through quantum loop contributions giving rise to flavor-changing neutral-current transitions (FCNCs). Owing to the GIM mechanism, processes of this type are very suppressed in the SM, which makes them a superb tool in the search for new physics associated with the flavor dynamics. Within the SM itself, these transitions are also sensitive to the heavy-quark mass scales and have played a crucial role identifying the size of the charm ( $K^0$ - $\bar{K}^0$  mixing) and top ( $B^0$ - $\bar{B}^0$  mixing) masses before the discovery of those quarks. In addition to the well-established  $\Delta F = 2$  mixings in neutral  $K$  and  $B$  mesons, there is now strong evidence for the mixing of the  $D^0$  meson and its antiparticle.

The FCNC kaon decays into lepton-antilepton pairs put stringent constraints on new flavor-changing interactions. The rate  $\text{Br}(K_L^0 \rightarrow \mu^+ \mu^-) = (6.84 \pm 0.11) \times 10^{-9}$  is completely dominated by the  $2\gamma$  absorptive contribution, leaving very little room for new-physics. Another very clean test of FCNCs is provided by the decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . The CERN NA62 experiment has already observed 20 signal candidates, providing the first evidence of this decay. This leads to  $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.14_{-0.33}^{+0.40}) \times 10^{-10}$ , in agreement with the predicted SM branching fraction of  $(7.73 \pm 0.61) \times 10^{-11}$ . Even more interesting is the  $CP$ -violating neutral mode  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ , but the current upper bound of  $3.0 \times 10^{-9}$  is still far away from the SM prediction.

The strongest bound on FCNC transitions in charm decays is  $\text{Br}(D^0 \rightarrow \mu^+ \mu^-) < 3.1 \times 10^{-9}$ , while in  $B$  decays the LHC experiments have recently reached the SM sensitivity:  $\text{Br}(B_d^0 \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-10}$  and  $\text{Br}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.34 \pm 0.27) \times 10^{-9}$ .

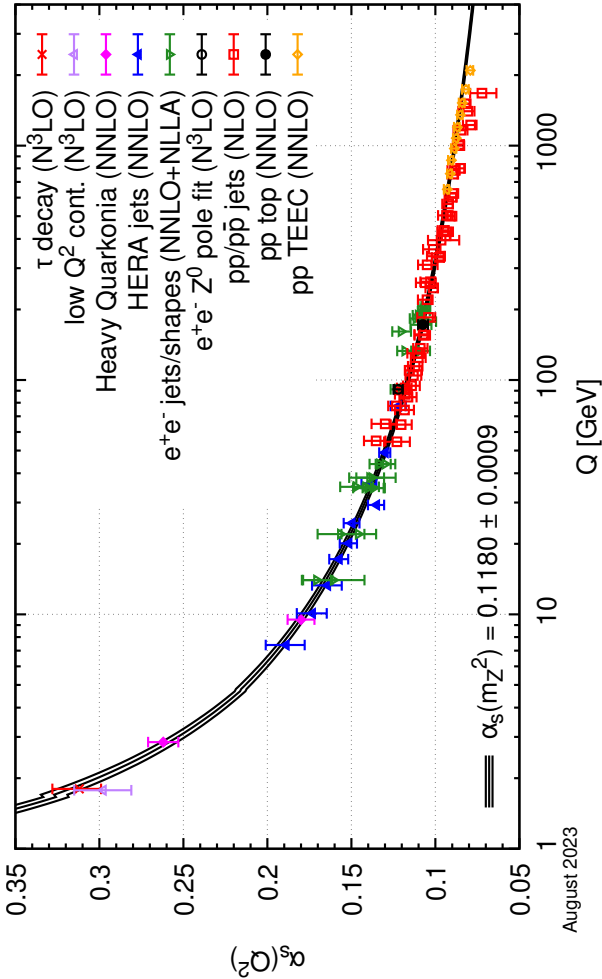
## 9. Quantum Chromodynamics

Revised August 2023 by J. Huston (Michigan State U.), K. Rabbertz (KIT) and G. Zanderighi (MPP, Garching; München Tech. U.).



**Figure 9.2:** Summary of determinations of  $\alpha_s(m_Z^2)$  with uncertainty in the seven sub-fields as discussed in the main review. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of  $\alpha_s(m_Z^2) = 0.1180 \pm 0.0009$ .

For our world average we combine the determinations from the upper six sub-fields shown in Fig. 9.2 to an unweighted average as discussed in the main review. The unweighted average of this combination with the FLAG2021 lattice estimate (sub-field seven) gives the final result of  $\alpha_s(m_Z^2) = 0.1180$  with an averaged uncertainty of  $\pm 0.0009$ . The  $Q$  dependence of  $\alpha_s$  as predicted by QCD is compared to a selected number of results for  $\alpha_s(Q^2)$  obtained at various energy scales  $Q$  in Fig. 9.5.

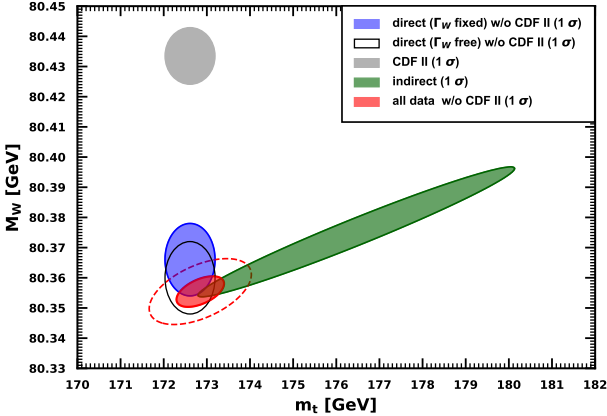


**Figure 9.5:** Summary of determinations of  $\alpha_s$  as a function of the energy scale  $Q$  compared to the running of the coupling computed at five loops taking as an input the current PDG average,  $\alpha_s(m_Z^2) = 0.1180 \pm 0.0009$ .

# 10. Electroweak Model and Constraints on New Physics

Revised April 2024 by J. Erler (KPH, JGU Mainz) and A. Freitas (Pittsburgh U.).

The standard model of the electroweak interactions (SM) [1–4] is based on the gauge group  $SU(2) \times U(1)$ , with gauge bosons  $W_\mu^i$ ,  $i = 1, 2, 3$ , and  $B_\mu$  for the  $SU(2)$  and  $U(1)$  factors, respectively, and the corresponding gauge coupling constants  $g$  and  $g'$ .



**Figure 10.5:** One-standard-deviation (39.35%) regions in the  $M_W$ – $m_t$  plane for the indirect data from the fit (green), the direct data for  $m_t$  and  $M_W$  without the CDF II measurement (blue and black contour, respectively, for two treatments of  $\Gamma_W$ ), and the combination thereof (red). For the latter, the 90% CL region ( $\Delta\chi^2 = 4.605$ ) is also shown as a red dashed contour. The grey region uses only the  $M_W$  value from CDF II. Compared to previous editions of this *Review*, this plot additionally includes theoretical uncertainties and subleading parameter dependencies.

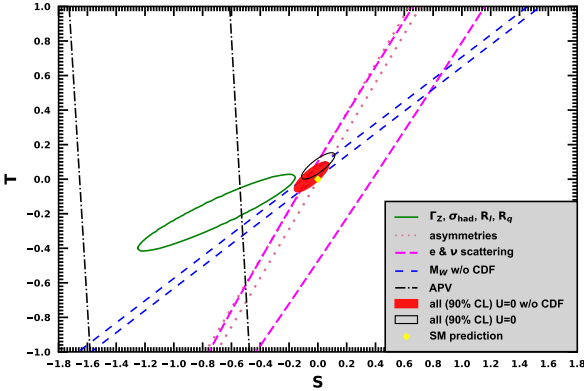
**Table 10.5:** A selection of  $Z$  pole observables and their SM predictions. The first  $\bar{s}_\ell^2$  is the combined value from the Tevatron [309], and the second is from the LHC [310–314]. The values of  $A_e$  is from  $A_{LR}$  for hadronic final states [315]. Note that the SM errors in  $\Gamma_Z$ , the  $R_\ell$ , and  $\sigma_{\text{had}}$  are largely dominated by the uncertainty in  $\alpha_s$ .

Quantity	Value	Standard Model	Pull
$M_Z$ [GeV]	$91.1880 \pm 0.0020$	$91.1884 \pm 0.0019$	–0.2
$\Gamma_Z$ [GeV]	$2.4955 \pm 0.0023$	$2.4940 \pm 0.0009$	0.7
$\sigma_{\text{had}}$ [nb]	$41.481 \pm 0.033$	$41.482 \pm 0.008$	0.0
$R_\mu$	$20.784 \pm 0.034$	$20.736 \pm 0.010$	1.4
$R_b$	$0.21629 \pm 0.00066$	$0.21582 \pm 0.00002$	0.7
$A_{FB}^{(0,b)}$	$0.0996 \pm 0.0016$	$0.1026 \pm 0.0002$	–1.8
$\bar{s}_\ell^2$	$0.23148 \pm 0.00033$	$0.23161 \pm 0.00004$	–0.4
	$0.23145 \pm 0.00028$		–0.6
$A_e$	$0.15138 \pm 0.00216$	$0.1463 \pm 0.0003$	2.1

**Table 10.8:** Values of  $\widehat{s}_Z^2$ ,  $s_W^2$ ,  $\alpha_s$ ,  $m_t$  and  $M_H$  for various data sets. In the fit to the LHC data, the  $\alpha_s$  constraint is from an NNLO analysis of the transverse momentum distribution of Z bosons [369]. For the Tevatron fit we use the  $\alpha_s$  result from the inclusive jet cross-section at  $D\bar{O}$  [370] and add the  $M_W$  result from CDF [289] as adjusted in Ref. [298].

data set	$\widehat{s}_Z^2$	$s_W^2$	$\alpha_s(M_Z)$	$m_t$ [GeV]	$M_H$ [GeV]
all data	0.23129(4)	0.22348(10)	0.1187(17)	$172.9 \pm 0.6$	125
all data except $M_H$	0.23118(8)	0.22327(18)	0.1190(17)	$172.6 \pm 0.6$	$97^{+18}_{-16}$
all data except $M_Z$	0.23121(6)	0.22346(10)	0.1187(17)	$172.6 \pm 0.6$	125
all data except $M_W, \Gamma_W$	0.23130(4)	0.22353(11)	0.1188(17)	$172.7 \pm 0.6$	125
all data except $m_t$	0.23123(6)	0.22324(20)	0.1191(17)	$175.2 \pm 1.8$	125
$M_{H,Z} + \Gamma_{H,Z} + m_t$	0.23134(8)	0.22361(16)	0.1221(45)	$172.6 \pm 0.6$	125
LHC	0.23122(8)	0.22349(11)	0.1183 (9)	$172.3 \pm 0.6$	125
Tevatron	0.23085(13)	0.22254(28)	0.1159(45)	$174.4 \pm 0.8$	$67^{+25}_{-20}$
LEP 1 + LEP 2	0.23138(19)	0.22350(46)	0.1233(29)	$177 \pm 11$	$173^{+237}_{-96}$
LEP 1 + SLD	0.23116(17)	0.22340(58)	0.1221(27)	$169 \pm 10$	$71^{+87}_{-33}$
SLD + $M_Z + \Gamma_Z + m_t$	0.23064(29)	0.22224(54)	0.1196(52)	$172.6 \pm 0.6$	$31^{+27}_{-22}$
$A_{FB}^{(b,c)} + M_Z + \Gamma_Z + m_t$	0.23190(30)	0.22492(70)	0.1279(49)	$172.6 \pm 0.6$	$306^{+164}_{-111}$
$M_{W,Z} + \Gamma_{W,Z} + m_t$	0.23119(11)	0.22329(23)	0.1212(42)	$172.6 \pm 0.6$	$96^{+23}_{-20}$
low energy + $M_{H,Z}$	0.23173(94)	0.2252(35)	0.1172(18)	$159 \pm 29$	125

The masses and decay properties of the electroweak bosons and low energy data can be used to search for and set limits on deviations from the SM.



**Figure 10.6:**  $1\sigma$  constraints (39.35% for the closed contours and 68% for the others) on  $S$  and  $T$  (for  $U = 0$ ) from various inputs combined with  $M_Z$ .  $S$  and  $T$  represent the contributions of new physics only. Data sets not involving  $M_W$  or  $\Gamma_W$  are insensitive to  $U$ . With the exception of the fit to all data, we fix  $\alpha_s = 0.1187$ . The yellow dot indicates the Standard Model values  $S = T = 0$ . The fits to all data are at the 90% CL, with the open black ellipse corresponding to an alternative scenario including the  $M_W$  result from CDF II.

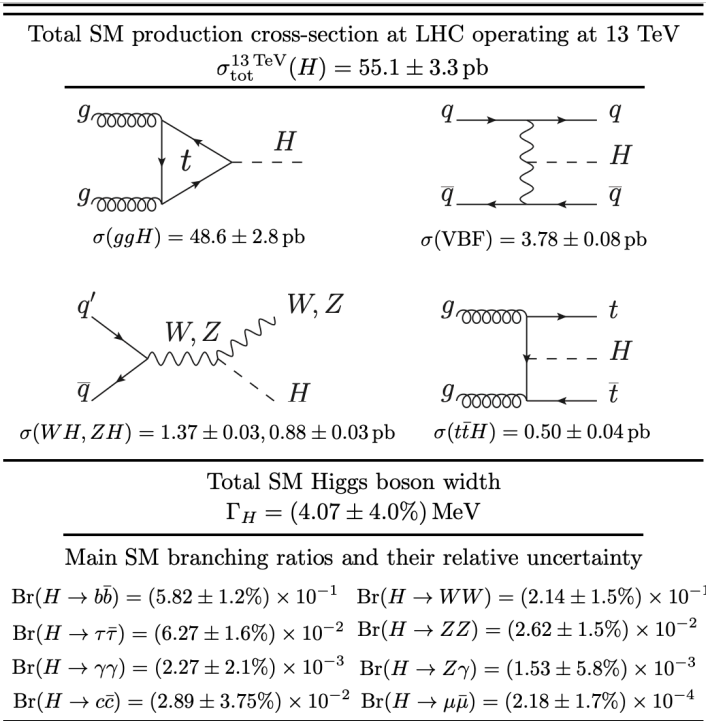
## 11. Status of Higgs Boson Physics

Revised November 2023 by M. Carena (FNAL; Chicago U.; Chicago U., Kavli Inst.), C. Grojean (DESY, Hamburg; Physik, Humboldt U.), M. Kado (MPI Munich) and V. Sharma (UC San Diego).

The discovery of the Higgs boson in 2012 confirmed our understanding of the fundamental interactions based on local symmetries spontaneously broken by a non-trivial vacuum structure. It also offered an explanation of the generation of mass in a chiral theory. However, new conundrums about what lies beyond the Standard Model (SM) have come fore.

Since 2012, substantial progress has been made, yielding an increasingly precise profile of the properties of the Higgs boson. The couplings of the Higgs boson to the third generation fermions (the  $\tau^\pm$  lepton and the b and top quarks) have been established by direct observation and sensitivity to the couplings to the second generation fermions (the  $\mu^\pm$  lepton and c quark) is being reached, while evidence for rare decays,  $H \rightarrow Z\gamma$  and  $H \rightarrow \gamma^* \ell^+ \ell^-$ , is accumulated.

Within the SM, all the production and decay rates of the Higgs boson can be predicted to high accuracy in terms of its mass and of other parameters already known with great accuracy, so the measurements in the Higgs sector appraise the robustness of the SM.



**Figure:** Main leading order Feynman diagrams contributing to the Higgs production at the LHC. The SM predictions for the production cross sections at a centre-of-mass energy of 13 TeV and the branching fractions for the dominant decay modes are indicated assuming a Higgs boson mass of 125 GeV. The cross sections increase by about 10% at 13.6-14 TeV.

The ATLAS and CMS experiments have measured the mass of the Higgs boson in the diphoton and the four-lepton channels at per mille precision,  $m_H = 125.20 \pm 0.11$  GeV. The quantum numbers of the Higgs boson have been probed in greater detail and show an excellent consistency with the  $J^{PC} = 0^{++}$  hypothesis.

The coupling structure of the Higgs boson has been studied in a large number of channels, in the main production mechanisms at the LHC which are illustrated in the Figure. The Table summarises the ATLAS and CMS measurements and limits on the cross sections times branching ratios, normalised to their SM expectations in the main Higgs analysis channels. Further information on the couplings of the Higgs boson are also obtained from differential cross sections (often reported in the form of simplified template cross sections - STXS) and searches for rare and exotic production and decay modes, including invisible decays. Interpretations of the data are made in the framework of the Standard Model Effective Field Theory (SMEFT). A major target of HL-LHC is the observation of double Higgs production which will give access to the Higgs boson self-coupling, a direct probe of the Higgs potential with important implications on our understanding of the electroweak phase transition.

All measurements are consistent with the SM predictions and provide stringent constraints on a large number of scenarios of new physics.

The review discusses in detail the latest developments in theories extending the SM to solve the fundamental questions raised by the existence of the Higgs boson.

**Table:** Summary of the ATLAS (A) and CMS (C) measurements of the signal strengths in the various channels (the products of the production rates times the branching ratios normalised to their SM values). Limits on the invisible (“Inv.”) are set at 95% confidence level, and the expected sensitivities are given in parentheses.

Decay mode	ggH+bbH	VBF	WH	ZH	$t\bar{t}H + tH$
$\gamma\gamma$ (A)	$1.04 \pm 0.10$	$1.36^{+0.30}_{-0.26}$	$1.53^{+0.56}_{-0.51}$	$-0.22^{+0.61}_{-0.54}$	$0.90^{+0.33}_{-0.31}$
$\gamma\gamma$ (C)	$1.08^{+0.12}_{-0.11}$	$1.00^{+0.35}_{-0.32}$	$1.4 \pm 0.5$	$1.2^{+0.7}_{-0.6}$	$1.38^{+0.34}_{-0.29}$
$4\ell$ (A)	$0.95^{+0.11}_{-0.10}$	$1.3^{+0.5}_{-0.4}$	$1.5^{+1.2}_{-0.9}$		$1.7^{+1.7}_{-1.1}$
$4\ell$ (C)	$0.93^{+0.14}_{-0.13}$	$0.3^{+0.5}_{-0.0}$			$0.00^{+0.7}_{-0.0}$
$WW^*$ (A)	$1.14^{+0.13}_{-0.13}$	$1.13^{+0.19}_{-0.18}$	$2.3^{+1.2}_{-1.0}$	$2.9^{+1.8}_{-1.3}$	$1.6^{+0.7}_{-0.6}$
$WW^*$ (C)	$0.90^{+0.11}_{-0.10}$	$0.73^{+0.28}_{-0.24}$	$2.4 \pm 0.7$	$1.8^{+0.8}_{-0.7}$	$1.44^{+0.32}_{-0.32}$
$\tau^+\tau^-$ (A)	$0.90^{+0.29}_{-0.26}$	$1.00^{+0.21}_{-0.18}$	$1.0 \pm 0.6$	$1.0 \pm 0.6$	$1.4^{+0.9}_{-0.7}$
$\tau^+\tau^-$ (C)	$0.66^{+0.21}_{-0.21}$	$0.86^{+0.17}_{-0.16}$	$1.9 \pm 0.6$	$1.3 \pm 0.6$	$0.4 \pm 0.4$
$b\bar{b}$ (A)		$0.99^{+0.35}_{-0.34}$	$1.06^{+0.28}_{-0.26}$	$1.00^{+0.25}_{-0.23}$	$0.35^{+0.34}_{-0.34}$
$b\bar{b}$ (C)		$1.0^{+0.5}_{-0.4}$	$1.3 \pm 0.4$	$0.90^{+0.36}_{-0.34}$	$0.9^{+0.5}_{-0.4}$
$\mu^+\mu^-$ (A)			$1.2 \pm 0.6$		
$\mu^+\mu^-$ (C)			$1.2 \pm 0.4$		
$Z\gamma$ (A-C)			$2.2 \pm 0.7$		
$\gamma^*\gamma$ (A)			$1.5 \pm 0.5$		
$\gamma^*\gamma$ (C)			< 3.9 at 95% CL		
Inv. (A)			<10.7% (7.7%)		
Inv. (C)			<15% (8%)		



## 12. CKM Quark-Mixing Matrix

Revised April 2024 by A. Ceccucci (CERN), Z. Ligeti (LBNL) and Y. Sakai (KEK).

Highlights from full review.

The Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2] is a  $3 \times 3$  unitary matrix. It can be parameterized [3] by three mixing angles and the  $CP$ -violating KM phase [2],

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (12.3)$$

Here  $s_{ij} = \sin\theta_{ij}$ ,  $c_{ij} = \cos\theta_{ij}$ , and  $\delta$  is the phase responsible for all  $CP$ -violating phenomena in flavor-changing processes in the SM. The angles  $\theta_{ij}$  can be chosen to lie in the first quadrant, so  $s_{ij}, c_{ij} \geq 0$ .

Motivated by the Wolfenstein parameterization to exhibit the hierarchical structure of the CKM matrix, we define [4–6]

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \quad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|, \\ s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar{\rho} + i\bar{\eta})\sqrt{1 - A^2\lambda^4}}{\sqrt{1 - \lambda^2} [1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})]}. \quad (12.4)$$

These ensure that  $\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$  is phase convention independent, and the CKM matrix written in terms of  $\lambda$ ,  $A$ ,  $\bar{\rho}$ , and  $\bar{\eta}$  is unitary to all orders in  $\lambda$ . To  $\mathcal{O}(\lambda^4)$  one can write  $V_{\text{CKM}}$  as

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \quad (12.5)$$

The unitarity implies  $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$  and  $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$ . The six vanishing combinations can be represented as triangles in a complex plane. The areas of all triangles are the same and are half of the Jarlskog invariant,  $J$  [7], which is a phase-convention-independent measure of  $CP$  violation, defined by  $\text{Im}[V_{ij}V_{kl}V_{il}^*V_{kj}^*] = J \sum_{m,n} \varepsilon_{ikm}\varepsilon_{jln}$ . The most commonly used unitarity triangle arises from

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \quad (12.6)$$

by dividing each side by the best-known one,  $V_{cd}V_{cb}^*$  (see Fig. 12.1).

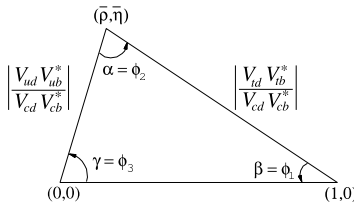


Figure 12.1: Sketch of the unitarity triangle.

The magnitudes of the independently measured CKM elements are

$$|V_{\text{CKM}}| = \begin{pmatrix} 0.97367 \pm 0.00032 & 0.22431 \pm 0.00085 & 0.00382 \pm 0.00020 \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & 0.0411 \pm 0.0012 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.010 \pm 0.027 \end{pmatrix},$$

and the angles of the unitarity triangle are

$$\sin(2\beta) = 0.709 \pm 0.011, \quad \alpha = (84.1_{-3.8}^{+4.5})^\circ, \quad \gamma = (65.7 \pm 3.0)^\circ.$$

Using those values, one can check the unitarity of the CKM matrix:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007 \text{ (1st row)}, \quad |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.001 \pm 0.012 \text{ (2nd row)}, \\ |V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9971 \pm 0.0020 \text{ (1st column)}, \quad \text{and } |V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1.003 \pm 0.012 \text{ (2nd column)}.$$

## 12.4 Global fit in the Standard Model

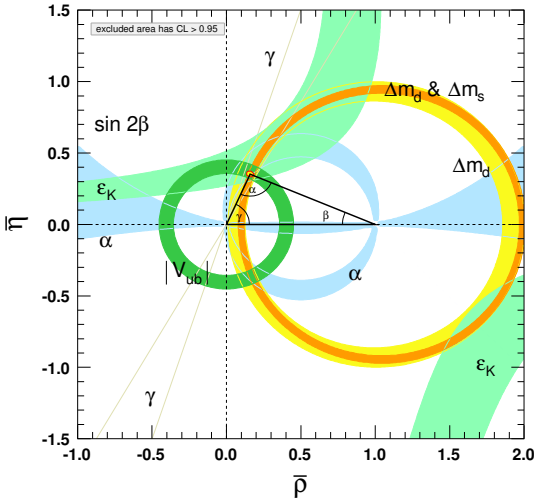
A global fit with three generation unitarity imposed gives

$$\lambda = 0.22501 \pm 0.00068, \quad A = 0.826_{-0.015}^{+0.016}, \\ \bar{\rho} = 0.1591 \pm 0.0094, \quad \bar{\eta} = 0.3523_{-0.0071}^{+0.0073}. \quad (12.26)$$

$$|V_{\text{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22501 \pm 0.00068 & 0.003732_{-0.000085}^{+0.000090} \\ 0.22487 \pm 0.00068 & 0.97349 \pm 0.00016 & 0.04183_{-0.00069}^{+0.00079} \\ 0.00858_{-0.00017}^{+0.00019} & 0.04111_{-0.00068}^{+0.00077} & 0.999118_{-0.000034}^{+0.000029} \end{pmatrix}, \quad (12.27)$$

and the Jarlskog invariant,  $J = (3.12_{-0.12}^{+0.13}) \times 10^{-5}$ . The parameters in Eq. (12.3) are

$$\sin \theta_{12} = 0.22501 \pm 0.00068, \quad \sin \theta_{13} = 0.003732_{-0.000085}^{+0.000090}, \\ \sin \theta_{23} = 0.04183_{-0.00069}^{+0.00079}, \quad \delta = 1.147 \pm 0.026. \quad (12.28)$$



**Figure 12.2:** Constraints on  $\bar{\rho}$  and  $\bar{\eta}$ . The shaded areas have 95% CL.

## 13. *CP* Violation in the Quark Sector

Revised August 2023 by T. Gershon (Warwick U.) and Y. Nir (Weizmann Inst.).

Within the Standard Model, *CP* symmetry is broken by complex phases in the Yukawa couplings (that is, the couplings of the Higgs scalar to quarks). When all transformations to remove unphysical phases in this model are exhausted, a single *CP*-violating parameter remains [19]. In the basis of mass eigenstates, this single phase appears in the  $3 \times 3$  unitary matrix that gives the *W*-boson couplings to an up-type anti-quark and a down-type quark. The beautifully consistent and economical Standard-Model description of *CP* violation in terms of Yukawa couplings, known as the Kobayashi-Maskawa (KM) mechanism [19], agrees with all measurements to date. Furthermore, one can fit the data allowing new physics contributions to loop processes to compete with, or even dominate over, the Standard Model amplitudes [20] [21]. Such analyses provide model-independent proof that the KM phase is different from zero, and that the matrix of three-generation quark mixing is the dominant source of *CP* violation in meson decays.

The current level of experimental accuracy and the theoretical uncertainties involved in the interpretation of the various observations leave room, however, for additional subdominant sources of *CP* violation from new physics. Indeed, almost all extensions of the Standard Model imply that there are such additional sources. Moreover, *CP* violation is a necessary condition for baryogenesis, the process of dynamically generating the matter-antimatter asymmetry of the Universe [22]. Despite the phenomenological success of the KM mechanism, it fails (by several orders of magnitude) to accommodate the observed asymmetry [23]. This discrepancy strongly suggests that Nature provides additional sources of *CP* violation beyond the KM mechanism. The expectation of new sources motivates the large ongoing experimental effort to find deviations from the predictions of the KM mechanism.

Using the notation  $M^0$  to represent generically one of the  $K^0$ ,  $D^0$ ,  $B^0$  or  $B_s^0$  particles, we denote the state of an initially pure  $|M^0\rangle$  or  $|\overline{M}^0\rangle$  after an elapsed proper time  $t$  as  $|M_{\text{phys}}^0(t)\rangle$  or  $|\overline{M}_{\text{phys}}^0(t)\rangle$ , respectively. Defining  $x \equiv \Delta m/\Gamma$  and  $y \equiv \Delta\Gamma/(2\Gamma)$ , where  $\Delta m$  and  $\Delta\Gamma$  are the mass and width differences between the two eigenstates of the effective Hamiltonian,  $|M_L\rangle \propto p|M^0\rangle + q|\overline{M}^0\rangle$  and  $|M_H\rangle \propto p|M^0\rangle - q|\overline{M}^0\rangle$ , and  $\Gamma$  is their average width, one obtains the following time-dependent rates for decay to a final state  $f$ :

$$\begin{aligned} & \frac{1}{e^{-\Gamma t} \mathcal{N}_f} d\Gamma [M_{\text{phys}}^0(t) \rightarrow f] / dt = \\ & |A_f|^2 \left\{ (1 + |\lambda_f|^2) \cosh(y\Gamma t) + (1 - |\lambda_f|^2) \cos(x\Gamma t) \right. \\ & \quad \left. + 2 \mathcal{R}e(\lambda_f) \sinh(y\Gamma t) - 2 \mathcal{I}m(\lambda_f) \sin(x\Gamma t) \right\} , \\ & \frac{1}{e^{-\Gamma t} \mathcal{N}_f} d\Gamma [\overline{M}_{\text{phys}}^0(t) \rightarrow f] / dt = \\ & |(p/q)A_f|^2 \left\{ (1 + |\lambda_f|^2) \cosh(y\Gamma t) - (1 - |\lambda_f|^2) \cos(x\Gamma t) \right. \\ & \quad \left. + 2 \mathcal{R}e(\lambda_f) \sinh(y\Gamma t) + 2 \mathcal{I}m(\lambda_f) \sin(x\Gamma t) \right\} , \end{aligned}$$

where  $\mathcal{N}_f$  is a normalization factor and  $\lambda_f = (q/p)(\overline{A}_f/A_f)$  with  $A_f$  ( $\overline{A}_f$ ) the amplitude for the  $M^0$  ( $\overline{M}^0$ )  $\rightarrow f$  decay. Considering the case that  $f$  is a *CP* eigenstate, we distinguish three types of *CP*-violating effects that can occur in the quark sector:

I. CP violation in decay, defined by  $|\bar{A}_f/A_f| \neq 1$ .

II. CP violation in mixing, defined by  $|q/p| \neq 1$ .

III. CP violation in interference between decays with and without mixing, defined by  $\arg(\lambda_f) \neq 0$ .

It is also common to refer to *indirect CP violation* effects, which are consistent with originating from a single CP violating phase in neutral meson mixing, and *direct CP violation* effects, which cannot be explained in this way. CP violation in mixing (type II) is indirect; CP violation in decay (type I) is direct.

Many CP violating observables have been studied by experiments. Here we summarise only a sample of the most important measurements, including some parameters defined using common notation for the asymmetry between  $\bar{B}_{\text{phys}}^0(t)$  and  $B_{\text{phys}}^0(t)$  time-dependent decay rates

$$\mathcal{A}_f(t) = S_f \sin(\Delta mt) - C_f \cos(\Delta mt),$$

where  $S_f \equiv 2\text{Im}(\lambda_f) / \left(1 + |\lambda_f|^2\right)$ ,  $C_f \equiv \left(1 - |\lambda_f|^2\right) / \left(1 + |\lambda_f|^2\right)$ .

- Indirect CP violation in  $K \rightarrow \pi\pi$  and  $K \rightarrow \pi l\nu$  decays, given by

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}.$$

- Direct CP violation in  $K \rightarrow \pi\pi$  decays, given by

$$\mathcal{R}e(\epsilon'/\epsilon) = (1.66 \pm 0.22) \times 10^{-3}.$$

- Direct CP violation has been established in the difference of asymmetries for  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays

$$\Delta a_{CP} = (-0.161 \pm 0.028) \times 10^{-2}.$$

- CP violation in the interference of mixing and decay in the tree-dominated  $b \rightarrow c\bar{c}s$  transitions, such as  $B^0 \rightarrow \psi K_S$ , given by

$$S_{\psi K^0} = +0.709 \pm 0.011.$$

Within the Standard Model, this result can be interpreted with low theoretical uncertainty as measurement of  $\sin(2\beta)$ , where  $\beta$  is an angle of the unitarity triangle.

- Direct CP violation in  $B^0 \rightarrow K^+\pi^-$  and  $B_s^0 \rightarrow K^-\pi^+$  decays is given by

$$\mathcal{A}_{B^0 \rightarrow K^+\pi^-} = -0.0836 \pm 0.0032, \quad \mathcal{A}_{B_s^0 \rightarrow K^-\pi^+} = +0.225 \pm 0.012.$$

- The CP violation parameters in the  $B^0 \rightarrow \pi^+\pi^-$  mode,

$$S_{\pi^+\pi^-} = -0.666 \pm 0.029, \quad C_{\pi^+\pi^-} = -0.311 \pm 0.030.$$

Together with measurements of other  $B \rightarrow \pi\pi$  and similar decays, these results can be used to obtain constraints on the angle  $\alpha$  of the unitarity triangle.

- Direct CP violation in  $B^+ \rightarrow DK^+$  decays, where  $D_+$  and  $D_{K^-\pi^+}$  represent that the  $D$  meson is reconstructed in a CP-even and the suppressed  $K^-\pi^+$  final state respectively,

$$\mathcal{A}_{B^+ \rightarrow D_+ K^+} = +0.139 \pm 0.009, \quad \mathcal{A}_{B^+ \rightarrow D_{K^-\pi^+} K^+} = -0.453 \pm 0.026.$$

Together with measurements of other  $B \rightarrow DK$  and similar decays, these results can be used to obtain constraints on the angle  $\gamma$  of the unitarity triangle.

## 14. Neutrino Masses, Mixing, and Oscillations

Revised August 2023 by M.C. Gonzalez-Garcia (YITP, Stony Brook; ICREA, Barcelona; ICC, U. of Barcelona) and M. Yokoyama (UTokyo; Kavli IPMU (WPI), UTokyo).

The weak neutrino eigenstates  $|\nu_\alpha\rangle$ , i. e. the states produced in the weak CC interaction by the charged leptons  $\ell_\alpha$  ( $\alpha = 1, 2, 3$ ), are linear combination of the mass eigenstates  $|\nu_i\rangle$  ( $i = 1, 2, 3$ ) (eigenvalues  $m_i$ )

$$|\nu_\alpha\rangle = \sum_{i=1}^n U_{\alpha i}^* |\nu_i\rangle, \quad (14.35)$$

where  $U$  is the mixing matrix.  $U$ , assumed to be unitary, can be expressed in terms of three mixing angles, taken by convention  $0 \leq \theta_{ij} \leq \pi/2$ , and phases  $\in (0, 2\pi)$ . Experimentally, two masses are close to one another, while the third is more separated. The former ones are defined as  $\nu_1$  and  $\nu_2$ , with the lighter being  $\nu_1$ . The sign of the larger mass difference defines two possible mass orderings, either “normal” (NO)  $m_3 > m_2 > m_1$ , or “inverted” (IO)  $m_2 > m_1 > m_3$ . Experiments show that  $|U_{e1}| \geq |U_{e2}| \geq |U_{e3}|$ . The mixing matrix is given by

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{13} s_{23} e^{i\delta} & c_{12} c_{23} - s_{12} s_{13} s_{23} e^{i\delta} & c_{13} s_{23} \\ s_{12} s_{23} - c_{12} s_{13} c_{23} e^{i\delta} & -c_{12} s_{23} - s_{12} s_{13} c_{23} e^{i\delta} & c_{13} c_{23} \end{pmatrix} \times \text{diag}(e^{i\eta_1}, e^{i\eta_2}, 1) \quad (14.33)$$

where  $c_{ij} = \cos \theta_{ij}$ ,  $s_{ij} = \sin \theta_{ij}$ ,  $\delta = \delta_{\text{CP}}$ . The phases  $\eta_1$  and  $\eta_2$  are physical if neutrinos are Majorana particles (but irrelevant for oscillations and matter effects), while can be absorbed in the wave functions in the Dirac case. For propagation in vacuum, assuming the state  $|\nu_\alpha(t)\rangle$  to be a plane monoenergetic ultra-relativistic wave (namely  $p \sim E$ ), the oscillation probability between two flavours  $\alpha$  and  $\beta$  is

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i<j}^n \Re[U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}] \sin^2 X_{ij} + 2 \sum_{i<j}^n \Im[U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}] \sin 2X_{ij}, \quad (14.39)$$

where

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.267 \frac{\Delta m_{ij}^2}{\text{eV}^2} \frac{L/E}{\text{m/MeV}}. \quad (14.40)$$

When neutrinos propagate in a dense medium, while absorption is negligible, the effect of coherent interaction with matter, being proportional to  $G_F$ , rather than to  $G_F^2$ , is not; it affects neutrino phase velocity. In a neutral medium containing nuclei and electrons, the effective potential at point  $x$ , with electron density  $n_e(x)$ , is

$$V = \text{diag}(\pm\sqrt{2}G_F n_e(x), 0, 0) \quad (14.58)$$

Where the sign + is for neutrinos, – for antineutrinos. In the relevant case of solar neutrinos,  $\nu_e$  are produced in the core. The propagating system is effectively a two-state one,  $\nu_e - \nu_X$  ( $X$  is a superposition of  $\nu_\mu$  and  $\nu_\tau$ , which is arbitrary because  $\nu_\mu$  and  $\nu_\tau$  have only NC that are equal). If  $\theta$  is the mixing angle (in vacuum) and  $\Delta m^2$  the square mass difference, the instantaneous mixing angle in matter  $\theta_m(x)$  is given by

$$\tan 2\theta_m(x) = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - 2EG_F n_e(x)}. \quad (14.61)$$

Depending on neutrino energy and mixing angle in vacuum, the denominator can cross zero at a certain  $x$ . This “resonance” condition may result in an adiabatic flavour conversion in matter (Mikheev-Smirnov-Wolfenstein Effect). The mixing parameters are obtained from global fits to the neutrino data, relative to both phenomena. Fits are performed by three different groups (NUFIT, BARI and VALENCIA), separately for NO and IO. The following is a summary of Table 14.7 of the main review (NUFIT without the SuperKamiokande analysis of matter effects in atmospheric neutrinos)

**Table 14.7:** Global fit results

Parameter	NUFIT w/o SK-atm	BARI	VALENCIA
NO			
$\sin^2 \theta_{12}/10^{-1}$	$3.03^{+0.12}_{-0.11}$	$3.03^{+0.13}_{-0.13}$	$3.18^{+0.16}_{-0.16}$
$\sin^2 \theta_{23}/10^{-1}$	$5.72^{+0.18}_{-0.23}$	$4.55^{+0.18}_{-0.15}$	$5.74^{+0.14}_{-0.14}$
$\sin^2 \theta_{13}/10^{-2}$	$2.203^{+0.056}_{-0.059}$	$2.23^{+0.07}_{-0.06}$	$2.200^{+0.069}_{-0.062}$
$\delta_{CP}/^\circ$	$197^{+42}_{-25}$	$223^{+32}_{-23}$	$194^{+24}_{-22}$
$\Delta m_{21}^2/\text{meV}^2$	$74.1^{+2.1}_{-2.0}$	$73.6^{+1.6}_{-1.5}$	$75.0^{+2.2}_{-2.0}$
$\Delta m_{32}^2/\text{meV}^2$	$2437^{+28}_{-27}$	$2448^{+23}_{-31}$	$2470^{+20}_{-30}$
IO			
	$\Delta\chi^2 = 2.3$	$\Delta\chi^2 = 6.5$	$\Delta\chi^2 = 6.4$
$\sin^2 \theta_{12}/10^{-1}$	$3.03^{+0.12}_{-0.11}$	$3.03^{+0.13}_{-0.13}$	$3.18^{+0.16}_{-0.16}$
$\sin^2 \theta_{23}/10^{-1}$	$5.78^{+0.16}_{-0.21}$	$5.69^{+0.13}_{-0.21}$	$5.78^{+0.10}_{-0.17}$
$\sin^2 \theta_{13}/10^{-2}$	$2.219^{+0.060}_{-0.057}$	$2.23^{+0.06}_{-0.06}$	$2.225^{+0.064}_{-0.070}$
$\delta_{CP}/^\circ$	$286^{+27}_{-32}$	$274^{+25}_{-27}$	$284^{+26}_{-28}$
$\Delta m_{21}^2/\text{meV}^2$	$74.1^{+2.1}_{-2.0}$	$73.6^{+1.6}_{-1.5}$	$75.0^{+2.2}_{-2.0}$
$\Delta m_{32}^2/\text{meV}^2$	$-2498^{+32}_{-25}$	$-2492^{+25}_{-30}$	$-2520^{+30}_{-20}$

Fig. 14.9 shows the allowed regions of the NUFIT analysis in terms, as an example, of one of the six leptonic unitary triangles (taking  $U$  as unitary by definition)

Information on the absolute scale of neutrino masses comes from three different sources.

- 1 Cosmology provides indirect limits on the sum of neutrino masses

$$\sum_{i=1}^3 m_i \quad (\text{see Sec. 25. Neutrinos in cosmology}).$$

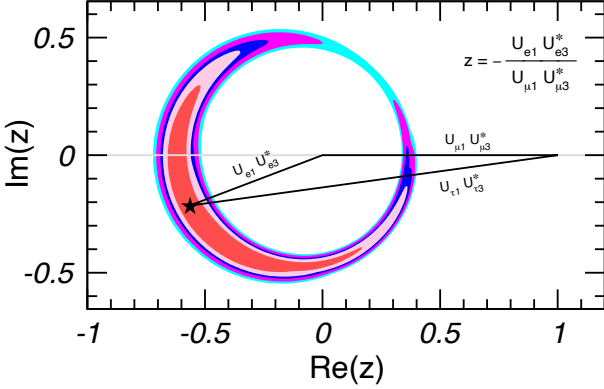
- 2 Measurements, with sub-eV energy resolution, of the end-point of the electron energy spectrum in the decay  ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$  gives

$$\text{direct information on } (m_{\nu_e}^{\text{eff}})^2 = \sum_{i=1}^3 m_i^2 |U_{ei}|^2. \quad \text{The most recent}$$

result from KATRIN experiment provides  $m_{\nu_e}^{\text{eff}} < 0.8\text{eV}$  at 90% CL.

- 3 Neutrino-less double beta decay  $(A, Z) \rightarrow (A, Z + 2) + 2e^-$  is forbidden in the SM as it violates lepton number conservation (by 2 units). However, if neutrino is a Majorana particle measurements of the half-lives  $T_{1/2}^{0\nu}$  of different isotopes give information

on  $m_{ee} = \left| \sum_{i=1}^3 m_i U_{ei}^2 \right|$ . The sensitivity reached by experiments on  $^{136}\text{Xe}$  and  $^{76}\text{Ge}$ ,  $T_{1/2}^{0\nu} > 2.3 \times 10^{26}$  yr, and  $T_{1/2}^{0\nu} > 1.8 \times 10^{26}$  yr, give bounds of  $m_{ee} < 36 - 156$  meV and  $m_{ee} < 79 - 180$  meV, respectively.



**Figure 14.9:** Leptonic unitarity triangle for the first and third columns of the mixing matrix. After scaling and rotating the triangle so that two of its vertices always coincide with  $(0, 0)$  and  $(1, 0)$  the figure shows the  $1\sigma$ ,  $90\%$ ,  $2\sigma$ ,  $99\%$ ,  $3\sigma$  CL (2 dof) allowed regions of the third vertex for the NO from the analysis in Ref. [180, 181].

## 15. Quark Model

Revised August 2023 by C. Amsler (Stefan Meyer Inst.), V. Crede (Florida State U.) and T. DeGrand (Colorado U., Boulder).

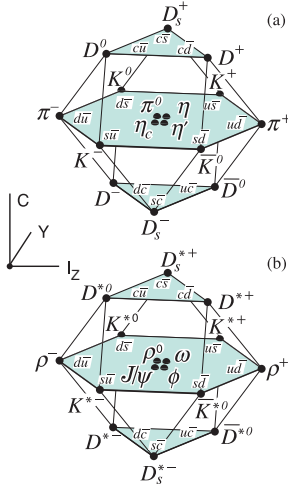
Quarks ( $q$ ) are strongly interacting fermions with spin  $\frac{1}{2}$  and, by convention, positive parity. Antiquarks ( $\bar{q}$ ) have negative parity. Quarks have the additive baryon number  $\mathcal{B} = \frac{1}{3}$ , while antiquarks have  $\mathcal{B} = -\frac{1}{3}$ . Table 15.1 gives the other additive quantum numbers for the three generations of quarks. They are related to the charge  $Q$  (in units of the elementary charge  $e$ ) through the generalized Gell-Mann-Nishijima formula

$$Q = I_z + \frac{\mathcal{B} + S + C + B + T}{2}. \quad (15.1)$$

By convention the quark *flavor* ( $I_z$ ,  $S$ ,  $C$ ,  $B$ , or  $T$ ) has the same sign as its *charge*  $Q$ .

**Table 15.1:** Quark quantum numbers.

	$d$	$u$	$s$	$c$	$b$	$t$
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
$I_z$ – isospin $z$ -component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	+1



**Figure 15.1:**  $SU(4)_f$  weight diagram showing the 16-plets for the pseudoscalar (a) and vector mesons (b) made of the  $u$ ,  $d$ ,  $s$ , and  $c$  quarks as a function of isospin  $I_z$ , charm  $C$ , and hypercharge  $Y = \mathcal{B} + S - \frac{C}{3}$ . The nonets of light mesons occupy the central planes to which the  $c\bar{c}$  states have been added.

The mesons, which are pairs of quarks and antiquarks, have  $\mathcal{B} = 0$  and can be characterized by their intrinsic spin  $s$ , orbital angular momentum  $\ell$ , and total spin  $J$ , lying between  $|\ell - s|$  and  $\ell + s$ . The



charge conjugation, or  $C$ , of meson is  $(-1)^{\ell+s}$  while its parity is  $(-1)^{\ell+1}$ . Mesons made of a quark and its antiquark are  $G$ -parity eigenstates with  $G = (-1)^{I+\ell+s}$ .

Following *flavor*  $SU(3)_f$ , the nine possible  $q\bar{q}'$  combinations containing the light  $u$ ,  $d$ , and  $s$  quarks are grouped into an octet and a singlet of light quark mesons:

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1} . \tag{15.2}$$

A fourth quark such as charm  $c$  can be included by extending  $SU(3)_f$  to  $SU(4)_f$ . However,  $SU(4)_f$  is badly broken owing to the much heavier  $c$  quark. Nevertheless, in an  $SU(4)_f$  classification, the sixteen mesons are grouped into a 15-plet and a singlet:

$$\mathbf{4} \otimes \bar{\mathbf{4}} = \mathbf{15} \oplus \mathbf{1} . \tag{15.3}$$

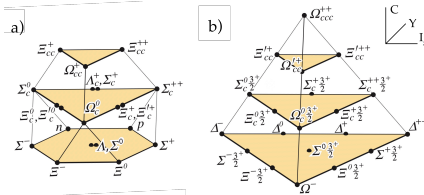
The *weight diagrams* for the ground state ( $\ell = 0$ ) pseudoscalar ( $J^{PC} = 0^{-+}$ ) and vector ( $1^{-}$ ) mesons are depicted in Fig. 15.1.

Baryons are made of three quarks. The  $SU(3)_f$  content of baryons made of  $u$ ,  $d$ , and  $s$  is governed by

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} . \tag{15.34}$$

The intrinsic spin of the three quarks yields either  $s = \frac{1}{2}$  or  $s = \frac{3}{2}$ . The proton and neutron are members of a combination of the two octets, while the spin- $\frac{3}{2}$   $\Delta^{++}$  is a member of a decuplet. The singlet is not realized for the ground state mesons.

The strong interactions are described by the *color*  $SU(3)$  gauge theory, with each quark coming in three ‘colors’. The quarks interact through a color octet of gluons, gauge vector bosons which are responsible for the formation of the bound states, mesons and baryons.



**Figure 15.5:**  $SU(4)_f$  multiplets of ground state baryons made of  $u$ ,  $d$ ,  $s$ , and  $c$  quarks. (a) The spin  $\frac{1}{2}$  20-plet extends the charmless  $SU(3)_f$  octet to  $C = 1, 2$ ; (b) the spin  $\frac{3}{2}$  20-plet extends the  $SU(3)_f$  decuplet to  $C = 1, 2, 3$ .

The existence of baryons with  $t$  quarks is very unlikely due to the short lifetime of the  $t$  quark. Meson candidates which cannot be (or are hard to be) described as  $q\bar{q}'$  pairs have been reported (e.g. with the non- $q\bar{q}$  quantum number  $J^{PC} = 1^{-+}$ ). Given the successes of the quark model, these are classified as ‘tetraquarks’ ( $qq\bar{q}\bar{q}$ ), hybrids ( $q\bar{q}$  pairs with an additional gluon) or ‘glueballs’ (bound states of the gluons). Candidate baryons for ‘pentaquarks’ ( $qqq\bar{q}q$ ) have also been reported.

## 22. Big-Bang Cosmology

Revised August 2023 by K.A. Olive (Minnesota U.) and J.A. Peacock (Edinburgh U.).

### 22.1.1 The Robertson-Walker Universe

The observed homogeneity and isotropy enable us to write the most general expression for a space-time metric which has a (3D) maximally symmetric subspace of a 4D space-time, known as the Robertson-Walker metric:

$$ds^2 = dt^2 - R^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right]. \quad (22.1)$$

Note that we adopt  $c = 1$  throughout. By rescaling the radial coordinate, we can choose the curvature constant  $k$  to take only the discrete values  $+1$ ,  $-1$ , or  $0$  corresponding to closed, open, or spatially flat geometries.

### 22.1.3 The Friedmann equations of motion

The cosmological equations of motion are derived from Einstein's equations:

$$\mathcal{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathcal{R} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}. \quad (22.6)$$

It is common to assume that the matter content of the Universe is a perfect fluid, for which

$$T_{\mu\nu} = -pg_{\mu\nu} + (p + \rho) u_\mu u_\nu, \quad (22.7)$$

where  $g_{\mu\nu}$  is the space-time metric described by Eq. (22.1),  $p$  is the isotropic pressure,  $\rho$  is the energy density and  $u = (1, 0, 0, 0)$  is the velocity vector for the isotropic fluid in co-moving coordinates. With the perfect fluid source, Einstein's equations lead to the Friedmann equations:

$$H^2 \equiv \left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}, \quad (22.8)$$

and

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3} (\rho + 3p), \quad (22.9)$$

where  $H(t)$  is the Hubble parameter and  $\Lambda$  is the cosmological constant. The first of these is sometimes called *the* Friedmann equation. Energy conservation via  $T^{\mu\nu}_{;\mu} = 0$ , leads to a third useful equation:

$$\dot{\rho} = -3H(\rho + p). \quad (22.10)$$

Equation (22.8) can also be simply derived as a consequence of the first law of thermodynamics.

### 22.1.5 Standard Model solutions

#### 22.1.5.1 Solutions for a general equation of state

Let us first assume a general equation of state parameter for a single component,  $w = p/\rho$  which is constant. In this case, Eq. (22.10) can be written as  $\dot{\rho} = -3(1+w)\rho\dot{R}/R$  and is easily integrated to yield

$$\rho \propto R^{-3(1+w)}. \quad (22.16)$$

Curvature domination occurs at rather late times (if a cosmological constant term does not dominate sooner). For  $w \neq -1$ ,

$$R(t) \propto t^{2/[3(1+w)]}. \quad (22.17)$$

### 22.1.5.2 A Radiation-dominated Universe

In the early hot and dense Universe, it is appropriate to assume an equation of state corresponding to a gas of radiation (or relativistic particles) for which  $w = 1/3$ . In this case, Eq. (22.16) becomes  $\rho \propto R^{-4}$ . Similarly, one can substitute  $w = 1/3$  into Eq. (22.17) to obtain

$$R(t) \propto t^{1/2}; \quad H = 1/2t. \quad (22.18)$$

### 22.1.5.3 A Matter-dominated Universe

Non-relativistic matter eventually dominates the energy density over radiation. A pressureless gas ( $w = 0$ ) leads to the expected dependence  $\rho \propto R^{-3}$ , and, if  $k = 0$ , we obtain

$$R(t) \propto t^{2/3}; \quad H = 2/3t. \quad (22.19)$$

### 22.1.5.4 A Universe dominated by vacuum energy

If there is a dominant source of vacuum energy, acting as a cosmological constant with equation of state  $w = -1$ . This leads to an exponential expansion of the Universe:

$$R(t) \propto e^{\sqrt{\Lambda/3}t}. \quad (22.20)$$

## 22.3 The Hot Thermal Universe

### 22.3.2 Radiation content of the Early Universe

At the very high temperatures associated with the early Universe, massive particles are pair produced, and are part of the thermal bath. If for a given particle species  $i$  we have  $T \gg m_i$ , then we can neglect the mass and the thermodynamic quantities are easily computed. In general, we can approximate the energy density (at high temperatures) by including only those particles with  $m_i \ll T$ . In this case, we have

$$\rho = \left( \sum_{\text{B}} g_{\text{B}} + \frac{7}{8} \sum_{\text{F}} g_{\text{F}} \right) \frac{\pi^2}{30} T^4 \equiv \frac{\pi^2}{30} N(T) T^4, \quad (22.42)$$

where  $g_{\text{B(F)}}$  is the number of degrees of freedom of each boson (fermion) and the sum runs over all boson and fermion states with  $m \ll T$ . Eq. (22.42) defines the effective number of degrees of freedom,  $N(T)$ , by taking into account new particle degrees of freedom as the temperature is raised.

The value of  $N(T)$  at any given temperature depends on the particle physics model. In the standard  $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$  model, we can specify  $N(T)$  up to temperatures of  $O(100)$  GeV. At higher temperatures,  $N(T)$  will be model-dependent.

In the radiation-dominated epoch, Eq. (22.10) can be integrated (neglecting the  $T$ -dependence of  $N$ ), giving us a relationship between the age of the Universe and its temperature:

$$t = \left( \frac{90}{32\pi^3 G_{\text{N}} N(T)} \right)^{1/2} T^{-2}. \quad (22.43)$$

This can be expressed more conveniently in the form

$$t T_{\text{MeV}}^2 = 2.4 [N(T)]^{-1/2}, \quad (22.44)$$

where  $t$  is measured in seconds and  $T_{\text{MeV}}$  in units of MeV.

## 27. Dark Matter

Revised August 2023 by L. Baudis (Zurich U.) and S. Profumo (UC Santa Cruz).

### 27.6 Laboratory detection of dark matter

Laboratory searches for DM particles can be roughly classified in direct detection experiments, axion searches, and searches at accelerators and colliders.

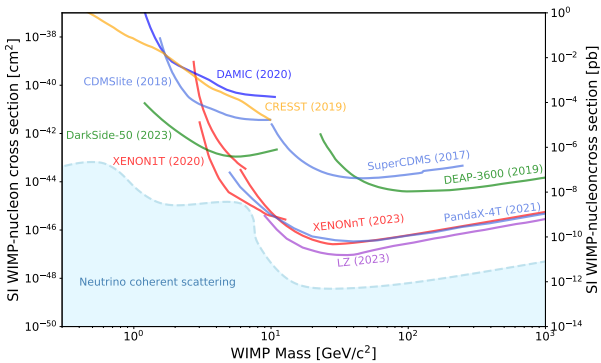
#### 27.6.1 Searches at Accelerators and Colliders

Various searches for dark matter have been carried out by the CMS and ATLAS collaborations at the LHC in  $pp$  collisions [98–102]. In general, these assume that dark matter particles escape the detector without interacting leading to significant amounts of missing energy and momentum.

#### 27.6.2 Direct detection formalism

Direct detection experiments mostly aim to observe elastic or inelastic scatters of Galactic DM particles with atomic nuclei, or with electrons in the detector material. Predicted event rates assume a certain mass and scattering cross section, as well as a set of astrophysical parameters: the local density  $\rho_0$ , the velocity distribution  $f(\vec{v})$ , and the escape velocity  $v_{esc}$  (see Sec. 27.4).

Figure 27.1 shows the best constraints for SI couplings in the cross-section versus DM mass parameter space, above masses of 0.3 GeV.



**Figure 27.1:** Upper limits on the SI DM-nucleon cross section as a function of DM mass.

### 27.7 Astrophysical detection of dark matter

DM as a microscopic constituent can have measurable, macroscopic effects on astrophysical systems. Indirect DM detection refers to the search for the annihilation or decay debris from DM particles, resulting in detectable species, including especially gamma rays, neutrinos, and antimatter particles. The production rate of such particles depends on (i) the annihilation (or decay) rate (ii) the density of pairs (respectively, of individual particles) in the region of interest, and (iii) the number of final-state particles produced in one annihilation (decay) event.

## 29. Cosmic Microwave Background

Revised August 2023 by D. Scott (U. of British Columbia) and G.F. Smoot (HKUST; UC Berkeley; LBNL; DIPC; Paris U.).

### 29.2 CMB Spectrum

It is well-known that the spectrum of the microwave background is very precisely that of blackbody radiation, whose temperature evolves with redshift as  $T(z) = T_0(1+z)$  in an expanding Universe.

### 29.3 Description of CMB Anisotropies

Observations show that the CMB contains temperature anisotropies at the  $10^{-5}$  level and polarization anisotropies at the  $10^{-6}$  (and lower) level, over a wide range of angular scales. These anisotropies are usually expressed using a spherical harmonic expansion of the CMB sky:

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi) \quad (29.1)$$

(with the linear polarization pattern written in a similar way using the so-called spin-2 spherical harmonics). Increasing angular resolution requires that the expansion goes to higher multipoles. Because only very weak phase correlations are observed in the CMB sky and no preferred direction is seen, the vast majority of the cosmological information is found in the temperature 2-point function, *i.e.*, the variance as a function only of angular separation. Equivalently, the anisotropy power per unit  $\ln \ell$  is  $\ell \sum_m |a_{\ell m}|^2 / 4\pi$ .

#### 29.3.1 The Monopole

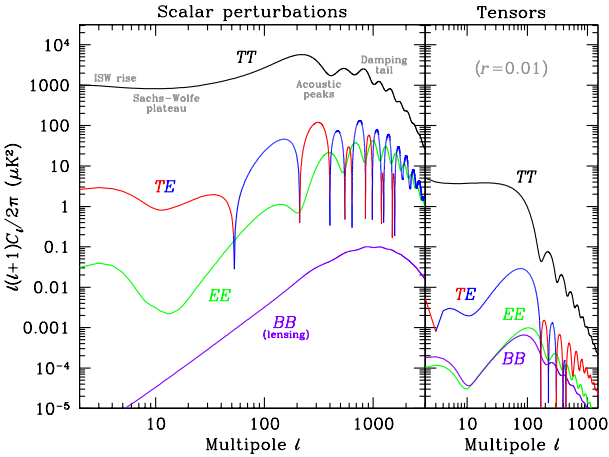
The CMB has a mean temperature of  $T_\gamma = 2.7255 \pm 0.0006 \text{ K}$  ( $1\sigma$ ) [19], which can be considered as the monopole component of CMB maps,  $a_{00}$ . Because all mapping experiments involve difference measurements, they are insensitive to this average level; monopole measurements can only be made with absolute temperature devices, such as the FIRAS instrument on the *COBE* satellite [20]. The measured  $kT_\gamma$  is equivalent to  $0.234 \text{ meV}$  or  $4.60 \times 10^{-10} m_e c^2$ . A blackbody of the measured temperature has a number density  $n_\gamma = (2\zeta(3)/\pi^2) T_\gamma^3 \simeq 411 \text{ cm}^{-3}$ , energy density  $\rho_\gamma = (\pi^2/15) T_\gamma^4 \simeq 4.64 \times 10^{-34} \text{ g cm}^{-3} \simeq 0.260 \text{ eV cm}^{-3}$ , and a fraction of the critical density  $\Omega_\gamma \simeq 5.38 \times 10^{-5}$ .

#### 29.3.2 The Dipole

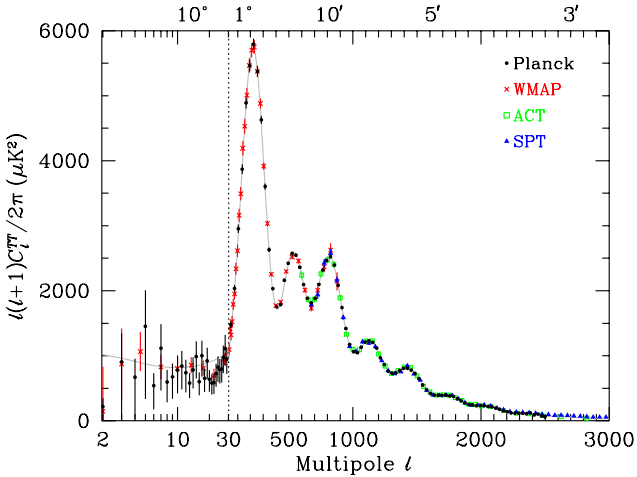
The largest anisotropy is in the  $\ell = 1$  (dipole) first spherical harmonic, with amplitude  $3.3621 \pm 0.0010 \text{ mK}$  [10]. The dipole is interpreted to be the result of the Doppler boosting of the monopole caused by the Solar System motion relative to the nearly isotropic blackbody field, as broadly confirmed by measurements of the radial velocities of local galaxies (*e.g.*, Ref. [21]).

#### 29.3.3 Higher-Order Multipoles

The variations in the CMB temperature maps at higher multipoles ( $\ell \geq 2$ ) are interpreted as being mostly the result of density perturbations in the early Universe, manifesting themselves at the epoch of the last scattering of the CMB photons.



**Figure 29.1:** Theoretical CMB anisotropy power spectra, using the best-fitting  $\Lambda$ CDM model from *Planck*, calculated using CAMB. The panel on the left shows the theoretical expectation for scalar perturbations, while the panel on the right is for tensor perturbations, with an amplitude set to  $r = 0.01$  for illustration.



**Figure 29.2:** CMB temperature anisotropy band-power estimates from the *Planck*, *WMAP*, ACT, and SPT experiments. The acoustic peaks and damping region are very clearly observed, with no need for a theoretical line to guide the eye; however, the curve plotted is the best-fit *Planck*  $\Lambda$ CDM model.

## 30. Cosmic Rays

Written October 2023 by J. Alvarez-Muñiz (Santiago de Compostela U.), Z. Cao (IHEP Beijing), U.F. Katz (Erlangen U.), P. Mertsch (TTK, RWTH) and C. Spiering (DESY, Zeuthen).

Cosmic rays (CRs) are a non-thermal population of particles that pervade the Universe. Their salient characteristics can be inferred from their major observational properties: spectrum, composition and arrival directions. For charged CRs, the energies extend from tens of MeV to close to 1 ZeV, the flux is  $\sim 10^4 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  above 1 GeV, but the differential spectrum falls steeply with energy  $E$ , following a power-law dependence  $E^{-\gamma}$ . The most striking spectral features are the “knee” at a few PeV where the spectral index  $\gamma$  changes from  $\sim 2.7$  to  $\sim 3$ , the “second knee” at  $\sim 100$  PeV with a change to  $\sim 3.3$  and the “ankle” at a few EeV where  $\gamma$  changes to  $\sim 2.5$ . The flux is largely suppressed above a few tens of EeV. Charged CRs are composed mostly of protons, helium, and other nuclei, as well as electrons, positrons and anti-protons. In the detection of CRs, two classes of techniques are distinguished: direct observations, making use of the interactions of CRs in particle physics detectors and indirect observations, detecting showers of secondary particles initiated by charged CR interactions in natural materials. The arrival directions are largely isotropic, but below and around the knee interesting  $\mathcal{O}(10^{-4} \dots 10^{-3})$  anisotropies due to the distribution of sources and properties of the Galactic magnetic fields have been observed, reaching  $\sim \mathcal{O}(10^{-1})$  at the highest energies. Gamma-rays and neutrinos are typically produced as secondary products of charged particle acceleration and interaction in astrophysical sources. Gamma-rays can be resolved into those from astrophysical sources ( $\sim 6660$  above 50 MeV,  $\sim 300$  at TeV energies), plus diffuse fluxes of galactic and extra-galactic origin, largely showing power-law dependence on energy. The observation of high-energy neutrinos has opened a new window; while the distribution is largely isotropic, evidence for two extra-galactic sources as well as for a contribution from the galactic plane has been found. Combined observations of charged CRs, gamma-rays and neutrinos as well as gravitational waves (see Sec. 21.2.3) allows for valuable insights into the most extreme astrophysical environments and is referred to as multi-messenger astrophysics. Measuring precisely the arrival times of neutral messengers also allows for studying transient phenomena.

Between hundreds of MeV and at least a few PeV, CRs are believed to be of galactic origin; above a few EeV, the sources are most likely extra-galactic. Sources of non-thermal electromagnetic radiation are routinely observed, yet the dominant source of locally measured CRs has not been unambiguously identified. Source candidates are typically associated with endpoints of stellar evolution or supermassive black holes that release large amounts of gravitational or rotational energy. In many astrophysical environments, the energy density of CRs constitutes a significant fraction of the total or is comparable to that of other ingredients. For instance, on galactic scales, the CR energy density is of the same order as that of magnetic fields, radiation fields or the turbulent gas. Due to their pressure, CRs can be dynamically important and shape their environments. CRs are also important probes of fundamental physics. If dark matter has interactions with the Standard Model, the products of self-annihilation or decay of DM particles can potentially be observed. Another target for exotic searches in CRs is anti-matter of primordial origin.

---

For details and references see the full *Review of Particle Physics*.

## 31. Accelerator Physics of Colliders

Revised July 2023 by V. Shiltsev (FNAL) and F. Zimmermann (CERN).

Collisions of two beams of particles accelerated to high energies  $E_{1,2}$  provide access to center-of-mass energies (c.m.e.)  $E_{\text{cme}} \approx 2\sqrt{E_1 E_2}$ , that is twice the beam energy  $E_{\text{cme}} = 2E_b$  for a typically small or zero crossing angle and equal energy beams. Particles with charge  $Ze$  gain energy  $\Delta E_b = ZeGl$  from high-frequency RF electric field with the average accelerating gradient  $G$  over distance  $l$ . The highest gradients achieved to date reach  $G \approx 100$  MV/m in 12 GHz normal-conducting RF cavities and  $\sim 30$  MV/m in 1.3 GHz superconducting (SC) ones, allow accessing high energies over reasonably long linacs. Repeated use of smaller RF system makes circular colliders cost-effective. In the rings, the ultra-relativistic particles' momentum is determined by the field of dipole magnets  $B$  and bending radius  $\rho$  inside them,  $p = ZeB\rho$  or  $E_b[\text{GeV}] = 0.3Z(B\rho)$  [Tm]. The maximum field of SC magnets with Nb-Ti wires cooled to liquid He temperatures can reach over 8 T, and up to 16 T with Nb<sub>3</sub>Sn conductor.

For the cross section of the process of interest,  $\sigma_{\text{exp}}$  and the instantaneous *luminosity*,  $\mathcal{L}$ , the event rate is  $dN_{\text{exp}}/dt = \sigma_{\text{exp}}\mathcal{L}$ . Today's colliders all employ bunched beams tightly focused at the interaction points to minimal rms transverse beam sizes  $\sigma_x^*$  and  $\sigma_y^*$ . If two of beams of  $n_b$  bunches, each containing  $N$  particles collide head-on with frequency  $f_{\text{coll}} = n_b f_0$ , a basic expression for the luminosity is

$$\mathcal{L} = f_{\text{coll}} \frac{N^2}{4\pi\sigma_x^*\sigma_y^*} \mathcal{F} = f_0 \gamma n_b \frac{N^2}{4\pi\sqrt{\varepsilon_{nx}\beta_x^*\varepsilon_{ny}\beta_y^*}} \mathcal{F}. \quad (31.15)$$

where  $f_0$  is the revolution frequency (or repetition rate in case of linear colliders),  $\gamma$  is the Lorentz factor, and  $\mathcal{F}$  is a factor of order 1, that takes into account geometric beam overlap effects. The second part in Eq. (31.3) recasts the rms sizes in terms of normalized transverse emittances (adiabatic invariants) and the amplitude (*beta*-) functions  $\beta^*$  at the IP as  $\sigma_{x,y}^{*2} = \beta_{x,y}^* \varepsilon_{nx,y}/\gamma$ .

Ultimate collider luminosity calls for high beam currents  $I_b = Ze f_0 n_b N$  resulting in growing RF demands to compensate the synchrotron-radiation (SR) power loss  $P = I_b \Delta E_{\text{SR}}$  in  $e^+/e^-$  beams, the advent of *coherent beam instabilities*, and the need to minimize radiation due to inevitable particle losses. Energy and luminosity limits of high-energy circular  $e^+e^-$  colliders are mostly defined by the SR energy loss per turn  $\Delta E_{\text{SR}} = 88.5$  [keV/turn]  $E_b^4[\text{GeV}]/\rho[\text{m}]$ , that needs to be replenished by ring's RF system. Critically important are disruptions due to electric and magnetic forces of the opposite bunch at the IPs, characterized by a dimensionless *beam-beam tuneshift parameter*

$$\xi_{x,y} = \frac{r_0 N \beta_{x,y}^*}{2\pi \gamma \sigma_{x,y}^* (\sigma_x^* + \sigma_y^*)}, \quad (31.16)$$

where  $r_0 = Z^2 e^2 / (4\pi \varepsilon_0 m c^2)$  is the classical radius of the colliding particle. Beam-beam limits of  $\xi_{x,y} \leq 0.01$  in circular hadron and  $\sim 0.1$  in circular  $e^+e^-$  colliders, directly affect the luminosity reach, as  $\mathcal{L} \propto \xi$ . The emission of beamstrahlung spreads up the c.m.e. spectra of linear  $e^+e^-$  colliders. In addition, for hadron colliders, fundamental luminosity limits are the beam lifetime due to inelastic  $pp$  interaction *burn-off*  $dN/dt = -\mathcal{L}\sigma_{\text{in}}$ , SR heat to be removed from inside SC magnets, and the radiation from the collision debris. Production, cooling and fast acceleration of muon beams are key challenges for future high-energy high-luminosity muon colliders.



**Table:** Tentative parameters of selected future high-energy colliders. Parameters associated with different beam energy scenarios are commensurated. Quantities are, where appropriate, r.m.s.;  $H$  and  $V$  indicate horizontal and vertical directions. See full *Review* for complete tables. Parameters for other proposed high-energy colliders, including the Compact Linear Collider (CLIC), can also be found in the full *Review*.

	EIC	FCC-ee	CEPC	ILC	$\mu\mu$ collider	FCC-hh
Species	$ep, e\text{-ion}$	$e^+e^-$	$e^+e^-$	$e^+e^-$	$\mu^+\mu^-$	$pp$
Beam energy (TeV)	0.01( $e$ ), 0.275( $p$ )	0.046, 0.120, 0.183	0.046, 0.120	0.125, 0.25	0.063, 5	40-58
Circumference / Length (km)	3.824	90.66	100	20.5, 31	0.3, 10	90.66
Interaction regions	1(2)	4	2	1	1, 2	4
Luminosity/IP ( $10^{34}/\text{cm}^2/\text{s}$ )	1.05	140 5.0, 1.3	115, 5.0	1.4, 1.8	0.008, 20	5-30
Rep.rate (Hz, $f_{rev}$ for rings)	$5.9 \cdot 10^5$	3307	3000	5	15, 5	3307
Time between collisions ( $\mu\text{s}$ )	0.009	0.025, 0.3, 2.5	0.025, 0.68	0.55	1, 33	0.025
Bunch length (rms, mm)	7( $e$ ), 60 ( $p$ )	15.5, 4.7, 2.2	8.7, 3.9	0.3	63, 1.5	80
IP beam size ( $\mu\text{m}$ )	H: 95, V: 8.5	H: 9, 13, 40 V: 0.04, 0.04, 0.05	H: 6, 14, V: 0.04, 0.04	H: 0.52, 0.47, V: 0.008, 0.006	75, 0.9	6.6-3.5 (init.)
$\beta^*$ , amplitude function at interaction point (cm)	H: 45( $e$ ), 80( $p$ ) V: 5.6( $e$ ), 7.2( $p$ )	H: 11, 24, 100 V: 0.07, 0.1, 0.16	H: 13, 33 V: 0.1, 0.1	H: 1.3, 2.2 V: 0.041, 0.048	1.7, 0.15	110-30
RF frequency (MHz)	591	400, 400, 800	650	1300	805/1300	400
Particles per bunch ( $10^{10}$ )	7.2( $e$ ), 6.9( $p$ )	21, 12, 16	14, 13	2	400, 180	10
Average beam current (mA)	2500( $e$ ), 1000( $p$ )	1270, 27, 4.9	804, 17	6 (in train)	640, 9	500
Total SR power loss (MW)	n/a	100	60	n/a	n/a	2.0-8.5

**Table:** Updated in March 2024 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved by December 2023. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy;  $H$  and  $V$  indicate horizontal and vertical directions; only selected colliders operating in 2022-2023 are included. See full *Review* for complete tables.

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC-II (China)	SuperKEKB (KEK)	LHC (CERN)
Physics start date	2010	1994	2008	2018	2009
Particles collided	$e^+e^-$	$e^+e^-$	$e^+e^-$	$e^+e^-$	$pp$
Maximum beam energy (GeV)	1.0	6	1.89 (2.474 max)	$e^-: 7, e^+: 4$	6800
Luminosity ( $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ )	50	20	1.096	$4.71 \times 10^4$	$2 \times 10^4$
Time between collisions (ns)	40	600	6	4.2	24.95
Energy spread (units $10^{-3}$ )	0.71	1	0.52	$e^-/e^+: 0.64/0.81$	0.11
Bunch length (cm)	4	5	1.35	$e^-/e^+: 0.6/0.6$	9.7
Beam radius ( $10^{-6} \text{ m}$ )	125 (round)	H:1000 V:30	H:347 V:4.5	$e^-: 16.6 (H), 0.22 (V)$ $e^+: 17.9 (H), 0.22 (V)$	9.3
Free space at interaction point (m)	$\pm 0.5$	$\pm 2$	$\pm 0.63$	$e^-: +1.20/-1.28, e^+: +0.78/-0.73$ (+300/-500) mrad cone	38
$\beta^*$ , amplitude function at interaction point (m)	H:0.05 - 0.11 V:0.05 - 0.11	H:0.75 V:0.05	H:1.0 V:0.0135	$e^-: 0.060 (H), 1 \times 10^{-3} (V)$ $e^+: 0.080 (H), 1 \times 10^{-3} (V)$	$1.2 \rightarrow 0.3$
Interaction regions	2	1	1	1	4 total, 2 high $\mathcal{L}$

## 34. Passage of Particles Through Matter

Revised August 2023 by D.E. Groom (LBNL) and S.R. Klein (NSD LBNL; UC Berkeley).

This review covers the interactions of photons and electrically charged particles in matter, concentrating on energies of interest for high-energy physics and astrophysics and processes of interest for particle detectors.

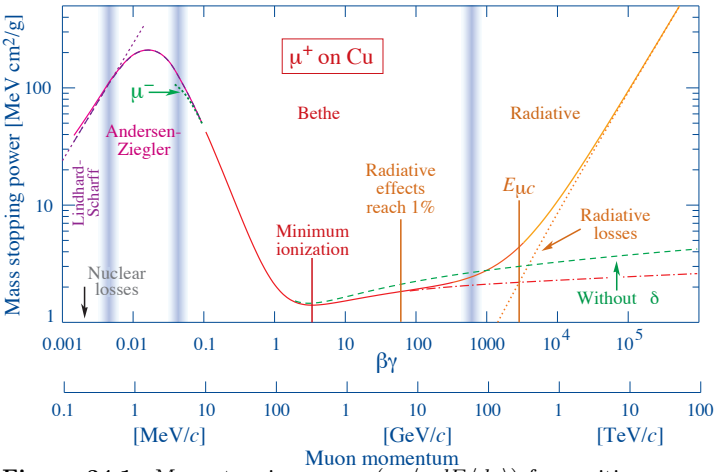
**Table 34.1:** Summary of variables used in this section. The kinematic variables  $\beta$  and  $\gamma$  have their usual relativistic meanings.

Symb.	Definition	Value or (usual) units
$m_e c^2$	electron mass $\times c^2$	0.510998 950 00(15) MeV
$r_e$	classical electron radius $e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 3227(19) fm
$\alpha$	fine structure constant $e^2/4\pi\epsilon_0 \hbar c$	1/137.035 999 139(31)
$N_A$	Avogadro's number	$6.022\,140\,76 \times 10^{23} \text{ mol}^{-1}$
$\rho$	density	$\text{g cm}^{-3}$
$x$	mass per unit area	$\text{g cm}^{-2}$
$M$	incident particle mass	$\text{MeV}/c^2$
$E$	incident part. energy $\gamma M c^2$	MeV
$T$	kinetic energy, $(\gamma - 1)M c^2$	MeV
$W$	energy transfer to an electron in a single collision	MeV
$W_{\max}$	Maximum possible energy transfer to an electron in a single collision	MeV
$k$	bremsstrahlung photon energy	MeV
$z$	charge number of incident particle	
$Z$	atomic number of absorber	
$A$	atomic mass of absorber	$\text{g mol}^{-1}$
$K$	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for $dE/dx$ )	$0.307\,075 \text{ MeV mol}^{-1} \text{ cm}^2$
$I$	mean excitation energy	eV ( <i>Nota bene!</i> )
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
$\hbar\omega_p$	plasma energy $\sqrt{4\pi N_e r_e^3 m_e c^2 / \alpha}$	$\sqrt{\rho \langle Z/A \rangle} \times 28.816 \text{ eV}$ $\hookrightarrow \rho$ in $\text{g cm}^{-3}$
$N_e$	electron density	(units of $r_e$ ) $^{-3}$
$w_j$	weight fraction of the $j$ th element in a compound or mixt.	
$n_j$	$\propto$ number of $j$ th kind of atoms in a compound or mixture	
$X_0$	radiation length	$\text{g cm}^{-2}$
$E_c$	critical energy for electrons	MeV
$E_{\mu c}$	critical energy for muons	GeV
$E_s$	scale energy $\sqrt{4\pi/\alpha} m_e c^2$	21.2052 MeV
$R_M$	Molière radius	$\text{g cm}^{-2}$

### 34.2.2 Maximum energy transfer in a single collision

For a particle with mass  $M$ ,

$$W_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} . \quad (34.4)$$



**Figure 34.1:** Mass stopping power ( $= \langle -dE/dx \rangle$ ) for positive muons in copper as a function of  $\beta\gamma = p/Mc$  over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Vertical bands indicate boundaries between different approximations discussed in the text.

### 34.2.3 Stopping power at intermediate energies

The mean rate of energy loss by moderately relativistic charged heavy particles is well-described by the “Bethe equation,”

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]. \quad (34.5)$$

This is the *mass stopping power*; with the symbol definitions and values given in Table 34.1, the units are  $\text{MeV g}^{-1} \text{cm}^2$ . As can be seen from Fig. 34.2,  $\langle -dE/dx \rangle$  defined in this way is about the same for most materials, decreasing slowly with  $Z$ . The *linear stopping power*, in  $\text{MeV/cm}$ , is  $\langle -dE/dx \rangle \rho$ , where  $\rho$  is the density in  $\text{g/cm}^3$ .

As the particle energy increases, its electric field flattens and extends, so that the distant-collision contribution to Eq. (34.5) increases as  $\ln \beta\gamma$ . However, real media become polarized, limiting the field extension and effectively truncating this part of the logarithmic rise. Parameterization of the density effect term  $\delta(\beta\gamma)$  in Eq. (34.5) is discussed in the full *Review*.

Few concepts in high-energy physics are as misused as  $\langle dE/dx \rangle$ . The mean is weighted by very rare events with large single-collision energy deposits. Even with samples of hundreds of events a dependable value for the mean energy loss cannot be obtained. Far better and more easily measured is the most probable energy loss, discussed below.

Although it must be used with cautions and caveats,  $\langle dE/dx \rangle$  as described in Eq. (34.5) still forms the basis of much of our understanding of energy loss by charged particles. Extensive tables are available [[pdg.lbl.gov/AtomicNuclearProperties/](http://pdg.lbl.gov/AtomicNuclearProperties/)].

Eq. (34.5) may be integrated to find the total (or partial) “continuous slowing-down approximation” (CSDA) range  $R$ . Since  $dE/dx$  depends (nearly) only on  $\beta$ ,  $R/M$  is a function of  $E/M$  or  $pc/M$ .

### 34.2.9 Fluctuations in energy loss

For detectors of moderate thickness  $x$  (e.g. scintillators or LAr cells), the energy loss probability distribution  $f(\Delta; \beta\gamma, x)$  is adequately described by the highly-skewed Landau (or Landau-Vavilov) distribution [30] [29]. The most probable energy loss

$$\Delta_p = \xi \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right], \quad (34.12)$$

where  $\xi = (K/2) \langle Z/A \rangle z^2 (x/\beta^2)$  MeV for a detector with a thickness  $x$  in  $\text{g cm}^{-2}$ , and  $j = 0.200$  [31]. While  $dE/dx$  is independent of thickness,  $\Delta_p/x$  scales as  $a \ln x + b$ . This most probable energy loss reaches a (Fermi) plateau rather than continuing  $\langle dE/dx \rangle$ 's logarithmic rise with increasing energy.

## 34.4 Photon and electron interactions in matter

At low energies electrons and positrons primarily lose energy by ionization, although other processes (Møller scattering, Bhabha scattering,  $e^+$  annihilation) contribute. While ionization loss rates rise logarithmically with energy, bremsstrahlung losses rise nearly linearly (fractional loss is nearly independent of energy), and dominates above the critical energy (Sec. 34.4.4 below), a few tens of MeV in most materials.

### 34.4.1 Collision energy losses by $e^\pm$

Stopping power differs somewhat for electrons and positrons, and both differ from stopping power for heavy particles because of the kinematics, spin, charge, and the identity of the incident electron with the electrons that it ionizes. Complete discussions and tables can be found in Refs. [12, 15], and [34] in the full *Review*.

### 34.4.2 Radiation length

High-energy electrons predominantly lose energy in matter by bremsstrahlung, and high-energy photons by  $e^+e^-$  pair production. The characteristic amount of matter traversed for these related interactions is called the radiation length  $X_0$ , usually measured in  $\text{g cm}^{-2}$ .  $X_0$  has been calculated and tabulated by Y.S. Tsai [42]:

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 [L_{\text{rad}} - f(Z)] + Z L'_{\text{rad}} \right\}. \quad (34.25)$$

For  $A = 1 \text{ g mol}^{-1}$ ,  $4\alpha r_e^2 N_A/A = (716.408 \text{ g cm}^{-2})^{-1}$ .  $L_{\text{rad}}$  and  $L'_{\text{rad}}$  are tabulated in the full *Review*, where a 4-place approximation for  $f(z)$  is also given.

### 34.4.3 Bremsstrahlung energy loss by $e^\pm$

At very high energies and except at the high-energy tip of the bremsstrahlung spectrum, the cross section can be approximated in the "complete screening case" as [42]

$$\begin{aligned} d\sigma/dk &= (1/k) 4\alpha r_e^2 \left\{ \left( \frac{4}{3} - \frac{4}{3}y + y^2 \right) [Z^2 (L_{\text{rad}} - f(Z)) + Z L'_{\text{rad}}] \right. \\ &\quad \left. + \frac{1}{9} (1-y)(Z^2 + Z) \right\}, \end{aligned} \quad (34.28)$$

where  $y = k/E$  is the fraction of the electron's energy transferred to the radiated photon. At small  $y$  (the "infrared limit") the term on the second line ranges from 1.7% (low  $Z$ ) to 2.5% (high  $Z$ ) of the total. If it

is ignored and the first line simplified with the definition of  $X_0$  given in Eq. (34.25), we have

$$\frac{d\sigma}{dk} = \frac{A}{X_0 N_A k} \left( \frac{4}{3} - \frac{4}{3}y + y^2 \right) . \quad (34.29)$$

#### 34.4.4 Critical energy

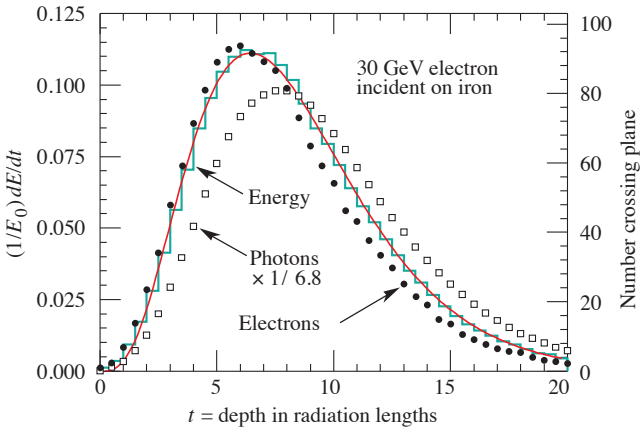
An electron loses energy by bremsstrahlung at a rate nearly proportional to its energy, while the ionization loss rate varies only logarithmically with the electron energy. The *critical energy*  $E_c$  is sometimes defined as the energy at which the two loss rates are equal [49]. Among alternate definitions is that of Rossi [2], who defines the critical energy as the energy at which the ionization loss per radiation length is equal to the electron energy. Equivalently, it is the same as the first definition with the approximation  $|dE/dx|_{\text{brems}} \approx E/X_0$ . This form has been found to describe transverse electromagnetic shower development more accurately.

Values of  $E_c$  for electrons can be reasonably well described by  $(610 \text{ MeV})/(Z + 1.24)$  for solids and  $(710 \text{ MeV})/(Z + 0.92)$  for gases.  $E_c$  for both electrons and positrons in more than 350 materials can be found at [pdg.lbl.gov/AtomicNuclearProperties](http://pdg.lbl.gov/AtomicNuclearProperties).

#### 34.4.5 Energy loss by photons

At low energies the photoelectric effect dominates, although Compton scattering, Rayleigh scattering, and photonuclear absorption also contribute. The photoelectric cross section is characterized by discontinuities (absorption edges) as thresholds for photoionization of various atomic levels are reached. Pair production dominates at high energies, but is suppressed at ultrahigh energies because of quantum mechanical interference between amplitudes from different scattering centers (LPM effect).

At still higher photon and electron energies, where the bremsstrahlung and pair production cross-sections are heavily suppressed by the LPM effect, photonuclear and electronuclear interactions predominate over electromagnetic interactions. At photon energies above about  $10^{20}$  eV, for example, photons usually interact hadronically.



**Figure 34.20:** An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution.

### 34.5 Electromagnetic cascades

When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energies.

The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and then dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is convenient to introduce the scale variables

$$t = x/X_0, \quad y = E/E_c, \quad (34.34)$$

so that distance is measured in units of radiation length and energy in units of critical energy.

The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution [61]:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \quad (34.35)$$

at energies from 1 GeV to 100 GeV.

### 34.6 Muon energy loss at high energy

At sufficiently high energies, radiative processes become more important than ionization for all charged particles. These contributions increase almost linearly with energy. It is convenient to write the average rate of muon energy loss as [74]

$$-dE/dx = a(E) + b(E)E. \quad (34.39)$$

Here  $a(E)$  is the ionization energy loss given by Eq. (34.5), and  $b(E)E$  is the sum of  $e^+e^-$  pair production, bremsstrahlung, and photonuclear contributions. These are subject large fluctuations, particularly at higher energies.

To the approximation that the slowly-varying functions  $a(E)$  and  $b(E)$  are constant, the mean range  $x_0$  of a muon with initial energy  $E_0$  is given by

$$x_0 \approx (1/b) \ln(1 + E_0/E_{\mu c}), \quad (34.40)$$

where  $E_{\mu c} = a/b$ .

The "muon critical energy"  $E_{\mu c}$  can be defined as the energy at which radiative and ionization losses are equal, and can be found by solving  $E_{\mu c} = a(E_{\mu c})/b(E_{\mu c})$ . This definition is different from the Rossi definition we used for electrons. It decreases with  $Z$ , and is several hundred GeV for iron. It is given for the elements and many other materials in [pdg.lbl.gov/AtomicNuclearProperties](http://pdg.lbl.gov/AtomicNuclearProperties).

### 34.7 Cherenkov and transition radiation

A charged particle radiates if its velocity is greater than the local phase velocity of light (Cherenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation). Neither process is important for energy loss, but both are used in high-energy and cosmic-ray physics detectors.

### 34.7.1 Optical Cherenkov radiation

The angle  $\theta_c$  of Cherenkov radiation, relative to the particle's direction, for a particle with velocity  $\beta c$  in a medium with index of refraction  $n$  is

$$\begin{aligned}\cos \theta_c &= (1/n\beta) \\ \text{or } \tan \theta_c &= \sqrt{\beta^2 n^2 - 1} \\ &\approx \sqrt{2(1 - 1/n\beta)} \quad \text{for small } \theta_c, \text{ e.g. in gases.}\end{aligned}\quad (34.41)$$

The threshold velocity  $\beta_t$  is  $1/n$ . Values of  $n - 1$  for various commonly used gases are given as a function of pressure and wavelength in Ref. [80]. Data for other commonly used materials are given in [81].

The number of photons produced per unit path length of a particle with charge  $ze$  and per unit energy interval of the photons is

$$\begin{aligned}\frac{d^2 N}{dE dx} &= \frac{\alpha z^2}{\hbar c} \sin^2 \theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2} \left(1 - \frac{1}{\beta^2 n^2(E)}\right) \\ &\approx 370 \sin^2 \theta_c(E) \text{ eV}^{-1} \text{ cm}^{-1} \quad (z = 1),\end{aligned}\quad (34.43)$$

or, equivalently,

$$\frac{d^2 N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right). \quad (34.44)$$

### 34.7.2 Coherent radio Cherenkov radiation

Coherent Cherenkov radiation is produced by many charged particles with a non-zero net charge moving through matter on an approximately common "wavefront"—for example, the electrons and positrons in a high-energy electromagnetic cascade. Near the end of a shower, when typical particle energies are below  $E_c$  (but still relativistic), a charge imbalance develops. Photons can Compton-scatter atomic electrons, and positrons can annihilate with atomic electrons to contribute even more photons which can in turn Compton scatter. These processes result in a roughly 20% excess of electrons over positrons in a shower. The net negative charge leads to coherent radio Cherenkov emission. The phenomenon is called the Askaryan effect [86]. The signals can be visible above backgrounds for shower energies as low as  $10^{17}$  eV; see Sec. 36.3.3 for more details.

### 34.7.3 Transition radiation

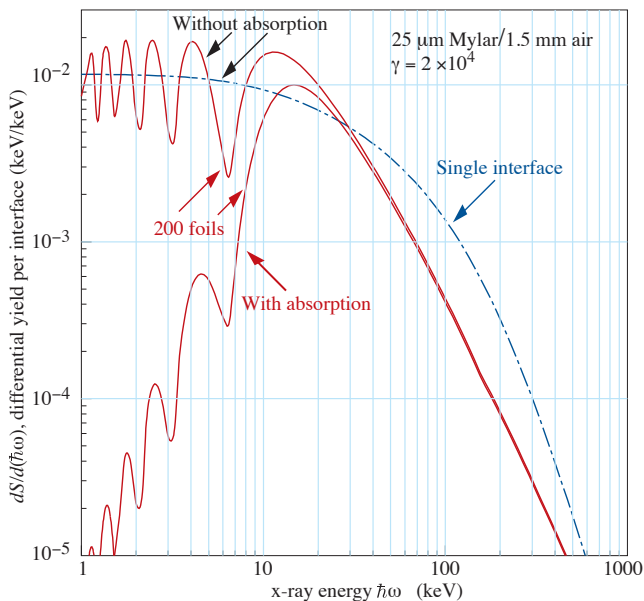
The energy radiated when a particle with charge  $ze$  crosses the boundary between vacuum and a medium with plasma frequency  $\omega_p$  is

$$I = \alpha z^2 \gamma \hbar \omega_p / 3, \quad (34.45)$$

The plasma energy  $\hbar \omega_p$  is defined in Table 34.1.

For styrene and similar materials,  $\hbar \omega_p \approx 20$  eV; for air it is 0.7 eV. The number spectrum  $dN_\gamma/d(\hbar \omega)$  diverges logarithmically at low energies and decreases rapidly for  $\hbar \omega/\gamma \hbar \omega_p > 1$ . Inevitable absorption in a practical detector removes the divergence. About half the energy is emitted in the range  $0.1 \leq \hbar \omega/\gamma \hbar \omega_p \leq 1$ . The  $\gamma$  dependence of the emitted energy thus comes from the hardening of the spectrum rather than from an increased quantum yield. For a particle with  $\gamma = 10^3$ , the radiated photons are in the soft x-ray range 2 to 40 keV.





**Figure 34.27:** X-ray photon energy spectra for a radiator consisting of 200 25  $\mu\text{m}$  thick foils of Mylar with 1.5 mm spacing in air (solid lines) and for a single surface (dashed line).

The number of photons with energy  $\hbar\omega > \hbar\omega_0$  is given by the answer to problem 13.15 in [3],

$$N_\gamma(\hbar\omega > \hbar\omega_0) = \frac{\alpha z^2}{\pi} \left[ \left( \ln \frac{\gamma \hbar\omega_p}{\hbar\omega_0} - 1 \right)^2 + \frac{\pi^2}{12} \right], \quad (34.47)$$

within corrections of order  $(\hbar\omega_0/\gamma\hbar\omega_p)^2$ . The number of photons above a fixed energy  $\hbar\omega_0 \ll \gamma\hbar\omega_p$  thus grows as  $(\ln \gamma)^2$ , but the number above a fixed fraction of  $\gamma\hbar\omega_p$  (as in the example above) is constant. For example, for  $\hbar\omega > \gamma\hbar\omega_p/10$ ,  $N_\gamma = 2.519 \alpha z^2/\pi = 0.0059 \times z^2$ .

The particle stays “in phase” with the x ray over a distance called the formation length,  $d(\omega) = (2c/\omega)(1/\gamma^2 + \theta^2 + \omega_p^2/\omega^2)^{-1}$ . Most of the radiation is produced in this distance. Here  $\theta$  is the x-ray emission angle, characteristically  $1/\gamma$ . For  $\theta = 1/\gamma$  the formation length has a maximum at  $d(\gamma\omega_p/\sqrt{2}) = \gamma c/\sqrt{2}\omega_p$ . In practical situations it is tens of  $\mu\text{m}$ .

Since the useful x-ray yield from a single interface is low, in practical detectors it is enhanced by using a stack of  $N$  foil radiators—foils  $L$  thick, where  $L$  is typically several formation lengths—separated by gas-filled gaps. The amplitudes at successive interfaces interfere to cause oscillations about the single-interface spectrum. At increasing frequencies above the position of the last interference maximum ( $L/d(\omega) = \pi/2$ ), the formation zones, which have opposite phase, overlap more and more and the spectrum saturates,  $dI/d\omega$  approaching zero as  $L/d(\omega) \rightarrow 0$ . This is illustrated in Fig. 34.27 for a realistic detector configuration.

Although one might expect the intensity of coherent radiation from the stack of foils to be proportional to  $N^2$ , the angular dependence of the formation length conspires to make the intensity  $\propto N$ .

## 35. Particle Detectors at Accelerators

Revised 2023. See the various sections for authors.

### 35.1 Introduction

This review summarizes the detector technologies employed at accelerator particle physics experiments. Several of these detectors are also used in a non-accelerator context and examples of such applications will be provided. The detector techniques which are specific to non-accelerator particle physics experiments are the subject of Chap. 36. More detailed discussions of detectors and their underlying physics can be found in books by Kolanoski & Wermes [1], Ferbel [2], Kleinknecht [3], Knoll [4], Green [5], Leroy & Rancoita [6], and Grupen [7].

In Table 35.1 are given typical resolutions and deadtimes of common charged particle detectors. The quoted numbers are usually based on typical devices, and should be regarded only as rough approximations for new designs. The spatial resolution refers to the intrinsic detector resolution, i.e. without multiple scattering. We note that analog detector readout can provide better spatial resolution than digital readout by measuring and averaging the deposited charge in neighboring channels. Quoted ranges attempt to be representative of both possibilities. The time resolution is defined by how accurately the time at which a particle crossed the detector can be determined. The deadtime is the minimum separation in time between two resolved hits on the same channel. Typical performance of calorimetry and particle identification are provided in the relevant sections below. Further discussion and all references may be found in the full *Review*.

**Table 35.1:** Typical resolutions and deadtimes of common charged particle detectors. Revised September 2023.

Detector Type	Intrinsic Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	50 $\mu\text{m}$	50–1000 ps*	10 ns <sup>†</sup>
Liquid argon TPC	0.5–1 mm <sup>‡</sup>	0.01–1 $\mu\text{s}$ <sup>§</sup>	— <sup>¶</sup>
Scintillation tracker	$\sim 100 \mu\text{m}$	100 ps/n <sup>  </sup>	10 ns
Bubble chamber	10–150 $\mu\text{m}$	1 ms	50 ms**
Wire chambers (proportional and drift chambers)	50–100 $\mu\text{m}$	5–10 ns <sup>††</sup>	20–200 ns <sup>‡‡</sup>
Micro-pattern gas detector	30–40 $\mu\text{m}$	5–10 ns <sup>††</sup>	20–200 ns <sup>‡‡</sup>
Silicon strips/pixels	$\lesssim 10 \mu\text{m}$ <sup>§§</sup>	few ns <sup>¶¶</sup> ‡‡	$\lesssim 50 \text{ ns}$ <sup>‡‡</sup>

\* LHC:  $\sim 2 \text{ mm}$  gap,  $\sim 1 \text{ ns}$ . HL-LHC:  $\sim 1 \text{ mm}$  gap,  $\sim 350 \text{ ps}$ . Timing RPC:  $\sim 50 \text{ ps}$ .

<sup>†</sup> Limited by amplifier and discriminator bandwidth, usually around 100 MHz.

<sup>‡</sup> Detector geometry dependent.

<sup>§</sup> Using the scintillation signal.

<sup>¶</sup> No deadtime for medium.

<sup>||</sup>  $n$  = index of refraction.

\*\* Multiple pulsing time.

<sup>††</sup> For fast particles.

<sup>‡‡</sup> Depending/limited by the amplifying electronics [8].

<sup>§§</sup> Depending on electrode pitch, best values around 2–4  $\mu\text{m}$  have been achieved.

<sup>¶¶</sup> Resolutions  $< 100 \text{ ps}$  are reached in dedicated pixel developments.

## 37. Radioactivity and Radiation Protection

Revised July 2023 by S. Roesler (CERN) and M. Silari ().

### 37.1 Definitions

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

- **Activity** (unit: Becquerel):

1 Bq = 1 disintegration per second (= 27 pCi).

- **Absorbed dose** (unit: gray): The absorbed dose is the energy imparted by ionizing radiation in a volume element of a specified material divided by the mass of this volume element.

1 Gy = 1 J/kg (=  $10^4$  erg/g = 100 rad)

=  $6.24 \times 10^{12}$  MeV/kg deposited energy.

- **Kerma** (unit: gray): Kerma is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a volume element of the specified material divided by the mass of this volume element.

- **Exposure** (unit: C/kg of air [= 3880 Roentgen\*]): The exposure is a measure of photon fluence at a certain point in space integrated over time, in terms of ion charge of either sign produced by secondary electrons in a small volume of air about the point. Implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving (so-called charged particle equilibrium).

**Table 37.1:** Radiation weighting factors,  $w_R$ .

Radiation type	$w_R$
Photons	1
Electrons and muons	1
Neutrons, $E_n < 1$ MeV	$2.5 + 18.2 \times \exp[-(\ln E_n)^2/6]$
1 MeV $\leq E_n \leq 50$ MeV	$5.0 + 17.0 \times \exp[-(\ln(2E_n))^2/6]$
$E_n > 50$ MeV	$2.5 + 3.25 \times \exp[-(\ln(0.04E_n))^2/6]$
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20

- **Equivalent dose** (unit: Sievert [= 100 rem (roentgen equivalent in man)]): The equivalent dose  $H_T$  in an organ or tissue  $T$  is equal to the sum of the absorbed doses  $D_{T,R}$  in the organ or tissue caused by different radiation types  $R$  weighted with so-called radiation weighting factors  $w_R$ :

$$H_T = \sum_R w_R \times D_{T,R} .$$

It expresses long-term risks (primarily cancer and leukemia) from low-level chronic exposure. The values for  $w_R$  recommended recently by ICRP [2] are given in Table 37.1.

- **Effective dose** (unit: Sievert): The sum of the equivalent doses, weighted by the tissue weighting factors  $w_T$  ( $\sum_T w_T = 1$ ) of several

\*This unit is somewhat historical, but appears on some measuring instruments. One R is the amount of radiation required to liberate positive and negative charges of one electrostatic unit of charge in  $1 \text{ cm}^3$  of air at standard temperature and pressure (STP)

organs and tissues  $T$  of the body that are considered to be most sensitive [2], is called “effective dose”  $E$ :

$$E = \sum_T w_T \times H_T .$$

### 37.2 Radiation levels [5]

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate  $\approx (1.0\text{--}13)$  mSv (0.1–1.3 rem). Can range up to 50 mSv (5 rem) in certain areas. U.S. average  $\approx 3.6$  mSv, including  $\approx 2$  mSv ( $\approx 200$  mrem) from inhaled natural radioactivity, mostly radon and radon daughters. (Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines. 0.1–0.2 mSv in open areas.)

• **Cosmic ray background** (sea level, mostly muons):  $\sim 1 \text{ min}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . For more accurate estimates and details, see the Cosmic Rays section (Sec. 30 of this *Review*).

• **Fluence** (per  $\text{cm}^2$ ) to deposit one Gy, assuming uniform irradiation:  $\approx$  (**charged particles**)  $6.24 \times 10^9 / (dE/dx)$ , where  $dE/dx$  ( $\text{MeV g}^{-1} \text{ cm}^2$ ), the energy loss per unit length, may be obtained from Figs. 34.2 and 34.4 in Sec. 34 of this *Review*.

$\approx 3.5 \times 10^9 \text{ cm}^{-2}$  minimum-ionizing singly-charged particles in carbon.

$\approx$  (**photons**)  $6.24 \times 10^9 / [Ef/\ell]$ , for photons of energy  $E$  (MeV), attenuation length  $\ell$  ( $\text{g cm}^{-2}$ ), and fraction  $f \leq 1$  expressing the fraction of the photon’s energy deposited in a small volume of thickness  $\ll \ell$  but large enough to contain the secondary electrons.

$\approx 2 \times 10^{11}$  photons  $\text{cm}^{-2}$  for 1 MeV photons on carbon ( $f \approx 1/2$ ).

### 37.3 Health effects of ionizing radiation

• **Recommended limits of effective dose to radiation workers (whole-body dose):**<sup>†</sup>

EU/Switzerland: 20 mSv  $\text{yr}^{-1}$

U.S.: 50 mSv  $\text{yr}^{-1}$  (5 rem  $\text{yr}^{-1}$ )<sup>‡</sup>

• **Lethal dose:** The whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) is 2.5–4.5 Gy (250–450 rad), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

• **Cancer induction by low LET radiation:** The cancer induction probability is about 5% per Sv on average for the entire population [3].

See full *Review* for references and further details.

<sup>†</sup>The ICRP recommendation [3] is 20 mSv  $\text{yr}^{-1}$  averaged over 5 years, with the dose in any one year  $\leq 50$  mSv.

<sup>‡</sup>Many laboratories in the U.S. and elsewhere set lower limits.

## 38. Commonly Used Radioactive Sources

Table 38.1: Radioactive sources

Nuclide	Half-life	Type of Decay	Particle		Photon	
			Energy (MeV)	Emission prob.	Energy (MeV)	Emission prob.
$^{22}_{11}\text{Na}$	2.603 y	$\beta^+$ ,	0.546	90%	0.511	Annih.
		EC			1.275	100%
$^{51}_{24}\text{Cr}$	27.70 d	EC			0.320	10%
					V K x rays	100%
Neutrino calibration source						
$^{54}_{25}\text{Mn}$	0.855 y	EC			0.835	100%
					Cr K x rays	26%
$^{55}_{26}\text{Fe}$	2.747 y	EC			Mn K x rays:	
					0.00590	24.4%
$^{57}_{27}\text{Co}$	271.8 d	EC			0.00649	2.86%
					0.014	9%
$^{60}_{27}\text{Co}$	5.271 y	$\beta^-$	0.317	99.9%	0.122	86%
					0.136	11%
$^{68}_{32}\text{Ge}$	271.0 d	EC			Fe K x rays	58%
					1.173	99.9%
$\rightarrow ^{68}_{31}\text{Ga}$	67.8 m	$\beta^+$ , EC	1.899	90%	1.333	99.9%
					0.511	Annih.
$^{90}_{38}\text{Sr}$	28.8 y	$\beta^-$	0.546	100%	1.077	3%
					2.279	100%
$\rightarrow ^{90}_{39}\text{Y}$	2.67 d	$\beta^-$	2.279	100%		
					0.039	100%
$^{106}_{44}\text{Ru}$	371.5 d	$\beta^-$	0.039	100%		
$\rightarrow ^{106}_{45}\text{Rh}$	30.1 s	$\beta^-$	3.546	79%	0.512	21%
					0.622	10%
$^{109}_{48}\text{Cd}$	1.265 y	EC	0.063 $e^-$	42%	0.088	3.7%
			0.084 $e^-$	44%	Ag K x rays	100%
$^{113}_{50}\text{Sn}$	115.1 d	EC	0.364 $e^-$	28%	0.392	65%
			0.388 $e^-$	6%	In K x rays	97
$^{137}_{55}\text{Cs}$	30.0 y	$\beta^-$	0.514	94%	0.662	85%
			1.176	6%		
$^{133}_{56}\text{Ba}$	10.55 y	EC	0.045 $e^-$	50%	0.081	33%
			0.075 $e^-$	6%	0.356	62%
					Cs K x rays	121%
$^{152}_{63}\text{Eu}$	13.537 y	EC		72.1%	Many $\gamma$ 's	
		$\beta^-$		27.9%	0.1218–1.408 MeV	
$^{207}_{83}\text{Bi}$	32.9 y	EC	0.481 $e^-$	2%	0.569	98%
			0.975 $e^-$	7%	1.063	75%
			1.047 $e^-$	2%	1.770	7%
					Pb K x rays	78%
$^{228}_{90}\text{Th}$	1.912 y	6 $\alpha$ :	5.341 – 8.785		0.239	44%
		3 $\beta^-$ :	0.334 – 2.246		0.583	31%
					2.614	36%
$\left( \begin{array}{cccccc} \rightarrow ^{224}_{88}\text{Ra} & \rightarrow ^{220}_{86}\text{Rn} & \rightarrow ^{216}_{84}\text{Po} & \rightarrow ^{212}_{82}\text{Pb} & \rightarrow ^{212}_{83}\text{Bi} & \rightarrow ^{212}_{84}\text{Po} \\ & 361 \text{ d} & 55.8 \text{ s} & 0.148 \text{ s} & 10.64 \text{ h} & 60.54 \text{ m} & 300 \text{ ns} \end{array} \right)$						
$^{241}_{95}\text{Am}$	432.6 y	$\alpha$	5.433	13%	0.0595409	36%
			5.486	85%	Np L x rays	38%
$^{241}\text{Am/Be}$	432.6 y	neutrons ( $E = 4 \text{ MeV}$ ) and $\gamma$ 's (4.43 MeV from $^9\text{Be}(\alpha, n)$ )				
$^{244}_{96}\text{Cm}$	18.11 y	$\alpha$	5.763	24%	Pu L x rays	$\sim 9\%$
			5.805	76%		
$^{252}_{98}\text{Cf}$	2.645 y	$\alpha$	6.076	15%		
		(97%)	6.118	82%		
Fission (3.1%): Average 7.8 $\gamma$ 's/fission; ( $E_\gamma$ ) = 0.88 MeV $\approx 4$ neutrons/fission; ( $E_n$ ) = 2.14 MeV						

## 39. Probability

Revised November 2021 by G. Cowan (RHUL).

The following is a much-shortened version of Sec. 39 of the full *Review*. Equation, section, and figure numbers follow the *Review*.

### 39.2 Random variables

- *Probability density function* (p.d.f.):  $x$  is a *random variable*.

Continuous:  $f(x; \theta)dx$  = probability  $x$  is between  $x$  to  $x + dx$ , given parameter(s)  $\theta$ ;

Discrete:  $f(x; \theta)$  = probability of  $x$  given  $\theta$ .

- *Cumulative distribution function*:

$$F(a) = \int_{-\infty}^a f(x) dx. \quad (39.6)$$

Here and below, if  $x$  is discrete-valued, the integral is replaced by a sum. The endpoint  $a$  is included in the integral or sum.

- *Expectation values*: Given a function  $u$ :

$$E[u(x)] = \int_{-\infty}^{\infty} u(x) f(x) dx. \quad (39.7)$$

- *Moments*:

$$n^{th} \text{ moment of a random variable: } \alpha_n = E[x^n], \quad (39.8a)$$

$$n^{th} \text{ central moment: } m_n = E[(x - \alpha_1)^n]. \quad (39.8b)$$

$$\text{Mean: } \mu \equiv \alpha_1, \quad (39.9a)$$

$$\text{Variance: } \sigma^2 \equiv V[x] \equiv m_2 = \alpha_2 - \mu^2. \quad (39.9b)$$

Coefficient of skewness:  $\gamma_1 \equiv m_3/\sigma^3$ .

Kurtosis:  $\gamma_2 = m_4/\sigma^4 - 3$ .

Median:  $F(x_{\text{med}}) = 1/2$ .

- *Marginal* p.d.f.: Let  $x, y$  be two random variables with joint p.d.f.  $f(x, y)$ .

$$f_1(x) = \int_{-\infty}^{\infty} f(x, y) dy; \quad f_2(y) = \int_{-\infty}^{\infty} f(x, y) dx. \quad (39.10)$$

- *Conditional* p.d.f.:

$$f_4(x|y) = f(x, y)/f_2(y); \quad f_3(y|x) = f(x, y)/f_1(x).$$

- *Bayes' theorem*:

$$f_4(x|y) = \frac{f_3(y|x)f_1(x)}{f_2(y)} = \frac{f_3(y|x)f_1(x)}{\int f_3(y|x')f_1(x') dx'}. \quad (39.11)$$

- *Correlation coefficient and covariance:*

$$\mu_x = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xf(x, y) dx dy, \quad (39.12)$$

$$\rho_{xy} = E[(x - \mu_x)(y - \mu_y)] / \sigma_x \sigma_y \equiv \text{cov}[x, y] / \sigma_x \sigma_y,$$

$$\sigma_x = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (x - \mu_x)^2 f(x, y) dx dy. \text{ Note } \rho_{xy}^2 \leq 1.$$

- *Independence:*  $x, y$  are independent if and only if  $f(x, y) = f_1(x) \cdot f_2(y)$ ; then  $\rho_{xy} = 0$ ,  $E[u(x)v(y)] = E[u(x)]E[v(y)]$  and  $V[x+y] = V[x] + V[y]$ .

- *Change of variables:* From  $\mathbf{x} = (x_1, \dots, x_n)$  to  $\mathbf{y} = (y_1, \dots, y_n)$ :  $g(\mathbf{y}) = f(\mathbf{x}(\mathbf{y})) \cdot |J|$  where  $|J|$  is the absolute value of the determinant of the Jacobian  $J_{ij} = \partial x_i / \partial y_j$ . For discrete variables, use  $|J| = 1$ .

### 39.3 Characteristic functions

Given a pdf  $f(x)$  for a continuous random variable  $x$ , the characteristic function  $\phi(u)$  is given by (31.6). Its derivatives are related to the algebraic moments of  $x$  by (31.7).

$$\phi(u) = E[e^{iux}] = \int_{-\infty}^{\infty} e^{iux} f(x) dx. \quad (39.19)$$

$$i^{-n} \left. \frac{d^n \phi}{du^n} \right|_{u=0} = \int_{-\infty}^{\infty} x^n f(x) dx = \alpha_n. \quad (39.20)$$

If the p.d.f.s  $f_1(x)$  and  $f_2(y)$  for independent random variables  $x$  and  $y$  have characteristic functions  $\phi_1(u)$  and  $\phi_2(u)$ , then the characteristic function of the weighted sum  $ax + by$  is  $\phi_1(au)\phi_2(bu)$ . The additional rules for several important distributions (e.g., that the sum of two Gaussian distributed variables also follows a Gaussian distribution) easily follow from this observation.

### 39.4 Some probability distributions

See Table 39.1.

#### 39.4.2 Poisson distribution

The Poisson distribution  $f(n; \nu)$  gives the probability of finding exactly  $n$  events in a given interval of  $x$  (e.g., space or time) when the events occur independently of one another and of  $x$  at an average rate of  $\nu$  per the given interval. The variance  $\sigma^2$  equals  $\nu$ . It is the limiting case  $p \rightarrow 0$ ,  $N \rightarrow \infty$ ,  $Np = \nu$  of the binomial distribution. The Poisson distribution approaches the Gaussian distribution for large  $\nu$ .

#### 39.4.3 Normal or Gaussian distribution

Its cumulative distribution, for mean 0 and variance 1, is often tabulated as the *error function*

$$F(x; 0, 1) = \frac{1}{2} \left[ 1 + \text{erf}(x/\sqrt{2}) \right]. \quad (39.26)$$

For mean  $\mu$  and variance  $\sigma^2$ , replace  $x$  by  $(x - \mu)/\sigma$ .

$$P(x \text{ in range } \mu \pm \sigma) = 0.6827,$$

$$P(x \text{ in range } \mu \pm 0.6745\sigma) = 0.5,$$

$$E[|x - \mu|] = \sqrt{2/\pi}\sigma = 0.7979\sigma,$$

half-width at half maximum =  $\sqrt{2 \ln 2} \cdot \sigma = 1.177\sigma$ .

For  $n$  Gaussian random variables  $x_i$ , the joint p.d.f. is the multivariate Gaussian:

$$f(\mathbf{x}; \boldsymbol{\mu}, V) = \frac{1}{(2\pi)^{n/2} \sqrt{|V|}} \exp \left[ -\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^T V^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right], \quad |V| > 0. \quad (39.27)$$

$V$  is the  $n \times n$  covariance matrix;  $V_{ij} \equiv E[(x_i - \mu_i)(x_j - \mu_j)] \equiv \rho_{ij} \sigma_i \sigma_j$ , and  $V_{ii} = V[x_i]$ ;  $|V|$  is the determinant of  $V$ . For  $n = 2$ ,  $f(\mathbf{x}; \boldsymbol{\mu}, V)$  is

$$f(x_1, x_2; \mu_1, \mu_2, \sigma_1, \sigma_2, \rho) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}} \times \exp \left\{ \frac{-1}{2(1-\rho^2)} \left[ \frac{(x_1 - \mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1 - \mu_1)(x_2 - \mu_2)}{\sigma_1\sigma_2} + \frac{(x_2 - \mu_2)^2}{\sigma_2^2} \right] \right\}. \quad (39.28)$$

The marginal distribution of any  $x_i$  is a Gaussian with mean  $\mu_i$  and variance  $V_{ii}$ .  $V$  is  $n \times n$ , symmetric, and positive definite. Therefore for any vector  $\mathbf{X}$ , the quadratic form  $\mathbf{X}^T V^{-1} \mathbf{X} = C$ , where  $C$  is any positive number, traces an  $n$ -dimensional ellipsoid as  $\mathbf{X}$  varies. If  $X_i = x_i - \mu_i$ , then  $C$  is a random variable obeying the  $\chi^2$  distribution with  $n$  degrees of freedom, discussed in the following section. The probability that  $\mathbf{X}$  corresponding to a set of Gaussian random variables  $x_i$  lies outside the ellipsoid characterized by a given value of  $C$  ( $= \chi^2$ ) is given by  $1 - F_{\chi^2}(C; n)$ , where  $F_{\chi^2}$  is the cumulative  $\chi^2$  distribution. This may be read from Fig. 40.1. For example, the “ $s$ -standard-deviation ellipsoid” occurs at  $C = s^2$ . For the two-variable case ( $n = 2$ ), the point  $\mathbf{X}$  lies outside the one-standard-deviation ellipsoid with 61% probability. The use of these ellipsoids as indicators of probable error is described in Sec. 40.4.2.2; the validity of those indicators assumes that  $\boldsymbol{\mu}$  and  $V$  are correct.

#### 39.4.5 $\chi^2$ distribution

If  $x_1, \dots, x_n$  are independent Gaussian random variables, the sum  $z = \sum_{i=1}^n (x_i - \mu_i)^2 / \sigma_i^2$  follows the  $\chi^2$  p.d.f. with  $n$  degrees of freedom, which we denote by  $\chi^2(n)$ . More generally, for  $n$  correlated Gaussian variables as components of a vector  $\mathbf{X}$  with covariance matrix  $V$ ,  $z = \mathbf{X}^T V^{-1} \mathbf{X}$  follows  $\chi^2(n)$  as in the previous section. For a set of  $z_i$ , each of which follows  $\chi^2(n_i)$ ,  $\sum z_i$  follows  $\chi^2(\sum n_i)$ . For large  $n$ , the  $\chi^2$  p.d.f. approaches a Gaussian with mean  $\mu = n$  and variance  $\sigma^2 = 2n$ .

The  $\chi^2$  p.d.f. is often used in evaluating the level of compatibility between observed data and a hypothesis for the p.d.f. that the data might follow. This is discussed further in Sec. 40.3.2 on tests of goodness-of-fit.

#### 39.4.7 Gamma distribution

For a process that generates events as a function of  $x$  (e.g., space or time) according to a Poisson distribution, the distance in  $x$  from an arbitrary starting point (which may be some particular event) to the  $k^{\text{th}}$  event follows a gamma distribution,  $f(x; \lambda, k)$ . The Poisson parameter  $\mu$  is  $\lambda$  per unit  $x$ . The special case  $k = 1$  (i.e.,  $f(x; \lambda, 1) = \lambda e^{-\lambda x}$ ) is called the exponential distribution. A sum of  $k'$  exponential random variables  $x_i$  is distributed as  $f(\sum x_i; \lambda, k')$ .

The parameter  $k$  is not required to be an integer. For  $\lambda = 1/2$  and  $k = n/2$ , the gamma distribution reduces to the  $\chi^2(n)$  distribution.

See the full *Review* for further discussion and all references.



**Table 39.1:** Some common probability density functions, with corresponding characteristic functions and means and variances. In the Table,  $\Gamma(k)$  is the gamma function, equal to  $(k-1)!$  when  $k$  is an integer.

Distribution	Probability density function $f$ (variable; parameters)	Characteristic function $\phi(u)$	Mean	Variance
Uniform	$f(x; a, b) = \begin{cases} 1/(b-a) & a \leq x \leq b \\ 0 & \text{otherwise} \end{cases}$	$\frac{e^{ibu} - e^{iau}}{(b-a)iu}$	$\frac{a+b}{2}$	$\frac{(b-a)^2}{12}$
Binomial	$f(r; N, p) = \frac{N!}{r!(N-r)!} p^r q^{N-r}$ $r = 0, 1, 2, \dots, N; 0 \leq p \leq 1; q = 1 - p$	$(q + pe^{iu})^N$	$Np$	$Npq$
Poisson	$f(n; \nu) = \frac{\nu^n e^{-\nu}}{n!}; n = 0, 1, 2, \dots; \nu > 0$	$\exp[\nu(e^{iu} - 1)]$	$\nu$	$\nu$
Normal (Gaussian)	$f(x; \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-(x-\mu)^2/2\sigma^2)$	$\exp(i\mu u - \frac{1}{2}\sigma^2 u^2)$	$\mu$	$\sigma^2$
Multivariate Gaussian	$f(\mathbf{x}; \boldsymbol{\mu}, \mathbf{V}) = \frac{1}{(2\pi)^{n/2} \sqrt{ \mathbf{V} }} \times \exp[-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^T \mathbf{V}^{-1}(\mathbf{x} - \boldsymbol{\mu})]$ $-\infty < x_j < \infty; -\infty < \mu_j < \infty;  \mathbf{V}  > 0$	$\exp[i\boldsymbol{\mu} \cdot \mathbf{u} - \frac{1}{2}\mathbf{u}^T \mathbf{V} \mathbf{u}]$	$\mathbf{u}$	$V_{jk}$
$\chi^2$	$f(z; n) = \frac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)}; z \geq 0$	$(1 - 2iu)^{-n/2}$	$n$	$2n$
Student's $t$	$f(t; n) = \frac{1}{\sqrt{n\pi}} \frac{\Gamma[(n+1)/2]}{\Gamma(n/2)} \left(1 + \frac{t^2}{n}\right)^{-(n+1)/2}$ $-\infty < t < \infty; n$ not required to be integer	—	0 for $n > 1$	$n/(n-2)$ for $n > 2$
Gamma	$f(x; \lambda, k) = \frac{x^{k-1} \lambda^k e^{-\lambda x}}{\Gamma(k)}; 0 \leq x < \infty; k$ not required to be integer	$(1 - iu/\lambda)^{-k}$	$k/\lambda$	$k/\lambda^2$

## 40. Statistics

Revised March 2024 by G. Cowan (RHUL).

This chapter gives an overview of statistical methods used in high-energy physics. In statistics, we are interested in using a given sample of data to make inferences about a probabilistic model, *e.g.*, to assess the model's validity or to determine the values of its parameters. There are two main approaches to statistical inference, which we may call frequentist and Bayesian.

### 40.2 Parameter estimation

An *estimator*  $\hat{\theta}$  (written with a hat) is a function of the data used to estimate the value of the parameter  $\theta$ .

#### 40.2.1 Estimators for mean, variance, and median

Suppose we have a set of  $n$  independent measurements,  $x_1, \dots, x_n$ , each assumed to follow a p.d.f. with unknown mean  $\mu$  and unknown variance  $\sigma^2$  (the measurements do not necessarily have to follow a Gaussian distribution). Then

$$\hat{\mu} = \frac{1}{n} \sum_{i=1}^n x_i \quad (40.5)$$

$$\hat{\sigma}^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \hat{\mu})^2 \quad (40.6)$$

are unbiased estimators of  $\mu$  and  $\sigma^2$ . The variance of  $\hat{\mu}$  is  $\sigma^2/n$  and the variance of  $\hat{\sigma}^2$  is

$$V \left[ \hat{\sigma}^2 \right] = \frac{1}{n} \left( m_4 - \frac{n-3}{n-1} \sigma^4 \right), \quad (40.7)$$

where  $m_4$  is the 4<sup>th</sup> central moment of  $x$  (see Eq. (39.8)). For Gaussian distributed  $x_i$ , this becomes  $2\sigma^4/(n-1)$  for any  $n \geq 2$ , and for large  $n$  the standard deviation of  $\hat{\sigma}$  is  $\sigma/\sqrt{2n}$ .

If the  $x_i$  have different, known variances  $\sigma_i^2$ , then the weighted average

$$\hat{\mu} = \frac{1}{w} \sum_{i=1}^n w_i x_i, \quad (40.8)$$

where  $w_i = 1/\sigma_i^2$  and  $w = \sum_i w_i$ , is an unbiased estimator for  $\mu$  with a smaller variance than an unweighted average. The standard deviation of  $\hat{\mu}$  is  $1/\sqrt{w}$ .

#### 40.2.2 The method of maximum likelihood

Suppose we have a set of measured quantities  $\mathbf{x}$  and the likelihood  $L(\boldsymbol{\theta}) = P(\mathbf{x}|\boldsymbol{\theta})$  for a set of parameters  $\boldsymbol{\theta} = (\theta_1, \dots, \theta_N)$ . The *maximum likelihood estimators* (MLEs) for  $\boldsymbol{\theta}$  can be found by solving the *likelihood equations*,

$$\frac{\partial \ln L}{\partial \theta_i} = 0, \quad i = 1, \dots, N. \quad (40.9)$$

The inverse  $V^{-1}$  of the covariance matrix  $V_{ij} = \text{cov}[\hat{\theta}_i, \hat{\theta}_j]$  for a set of MLEs can be estimated by using

$$(\hat{V}^{-1})_{ij} = - \left. \frac{\partial^2 \ln L}{\partial \theta_i \partial \theta_j} \right|_{\hat{\theta}}. \quad (40.12)$$

In the large sample limit,  $s$  times the standard deviations  $\sigma_i$  of the MLEs can be obtained from the distances in  $\theta_i$  to the planes tangent to the surface defined by

$$\ln L(\theta) = \ln L_{\max} - s^2/2. \quad (40.13)$$

### 40.2.3 The method of least squares

For Gaussian distributed measurements  $y_i$  with mean  $\mu(x_i; \theta)$  and known variance  $\sigma_i^2$ , the log-likelihood function contains the sum of squares

$$\chi^2(\theta) = -2 \ln L(\theta) + \text{constant} = \sum_{i=1}^N \frac{(y_i - \mu(x_i; \theta))^2}{\sigma_i^2}. \quad (40.19)$$

If the  $y_i$  have a covariance matrix  $V_{ij} = \text{cov}[y_i, y_j]$ , then the estimators are determined by the minimum of

$$\chi^2(\theta) = (\mathbf{y} - \boldsymbol{\mu}(\theta))^T V^{-1} (\mathbf{y} - \boldsymbol{\mu}(\theta)), \quad (40.20)$$

## 40.3 Statistical tests

### 40.3.1 Hypothesis tests

In a frequentist *test* of a hypothesis (often called the null hypothesis,  $H_0$ ) one specifies a subset of the data space  $w$  called the critical region such that there is no more than a given probability  $\alpha$ , called the *size* of the test, to find  $\mathbf{x} \in w$ . If the data are discrete, we require  $P(\mathbf{x} \in w | H_0) \leq \alpha$ . If the data are observed in the critical region,  $H_0$  is rejected.

The critical region is not unique, and generally defined relative to some alternative hypothesis  $H_1$ . To maximize the power of the test of  $H_0$  with respect to the alternative  $H_1$ , the *Neyman-Pearson lemma* states that the critical region  $w$  should be chosen such that for all data values  $\mathbf{x}$  inside  $w$ , the likelihood ratio

$$\lambda(\mathbf{x}) = \frac{f(\mathbf{x}|H_1)}{f(\mathbf{x}|H_0)} \quad (40.44)$$

is greater than or equal to a given constant  $c_\alpha$ , and everywhere outside the critical region one has  $\lambda(\mathbf{x}) < c_\alpha$ , where the value of  $c_\alpha$  is determined by the size of the test  $\alpha$ . Here  $H_0$  and  $H_1$  must not contain undetermined parameters.

### 40.3.2 Tests of significance, $p$ -values

A frequentist *significance test* provides a  $p$ -value, which reflects the level of agreement between a hypothesis  $H_0$  and the observed data  $\mathbf{x}$ . One specifies a subset of the data space, whose boundary includes the observed data point  $\mathbf{x}_{\text{obs}}$ , that is deemed to have equal or lesser compatibility with  $H_0$  relative to  $\mathbf{x}_{\text{obs}}$ . Surfaces of equal compatibility can be determined by constant values of a scalar statistic  $t(\mathbf{x})$ . For example, if large values of  $t$  correspond to poor agreement with the hypothesis, then the  $p$ -value is  $p = P(t \geq t_{\text{obs}} | H_0)$ , where  $t_{\text{obs}} = t(\mathbf{x}_{\text{obs}})$  is the observed value of the statistic. A *goodness-of-fit test* quantifies the level of agreement between the data and a hypothesis without explicit reference to alternative hypotheses.

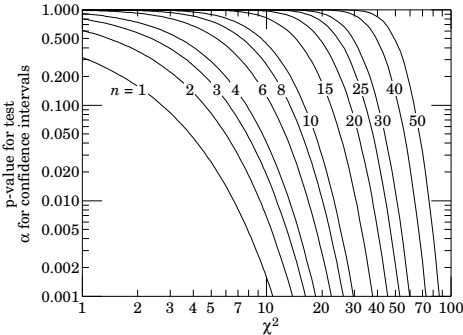
## 40.3.3.1 Goodness-of-fit with chi-square or likelihood ratio

When carrying out a fit with the method of least squares, one can quantify the level of agreement between the data and hypothesized fit function by using the minimized value of the  $\chi^2$  (40.19) as a goodness-of-fit statistic, i.e.,  $t = \chi_{\min}^2$ . If the fit function is correct, then for  $N$  Gaussian distributed data values and  $M$  fitted parameters, this statistic will follow a  $\chi^2$  p.d.f. for  $n_d = N - M$  degrees of freedom. This remains approximately true if the data are approximately Gaussian, e.g., for fitting a histogram with Poisson distributed data provided one has a sufficient number of entries in each bin.

Assuming the goodness-of-fit statistic follows a  $\chi^2$  p.d.f. under the hypothesis in question, the  $p$ -value is

$$p = \int_{\chi_{\min}^2}^{\infty} f(t; n_d) dt, \quad (40.55)$$

where  $f(t; n_d)$  is the  $\chi^2$  p.d.f. for  $n_d$  degrees of freedom. Values are shown in Fig. 40.1. The  $p$ -values obtained for different values of  $\chi^2/n_d$  are shown in Fig. 40.2.



**Figure 40.1:** One minus the  $\chi^2$  cumulative distribution,  $1 - F(\chi^2; n)$ , for  $n$  degrees of freedom. This gives the  $p$ -value for the  $\chi^2$  goodness-of-fit test as well as one minus the coverage probability for confidence regions (see Sec. 40.4.2.2).

## 40.3.4 Bayes factors

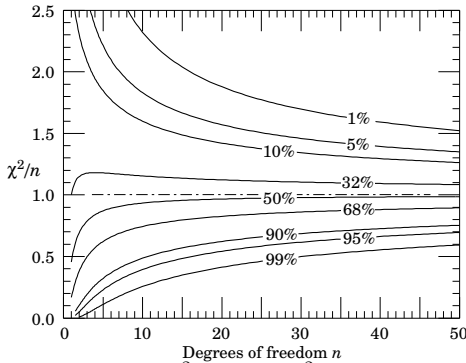
In Bayesian statistics, one could reject a hypothesis  $H$  if its posterior probability  $P(H|\mathbf{x})$  is sufficiently small. The full prior probability for two models (hypotheses)  $H_i$  and  $H_j$  can be written in the form

$$\pi(H_i, \boldsymbol{\theta}_i) = P(H_i)\pi(\boldsymbol{\theta}_i|H_i). \quad (40.61)$$

The *Bayes factor* is defined as

$$B_{ij} = \frac{\int P(\mathbf{x}|\boldsymbol{\theta}_i, H_i)\pi(\boldsymbol{\theta}_i|H_i) d\boldsymbol{\theta}_i}{\int P(\mathbf{x}|\boldsymbol{\theta}_j, H_j)\pi(\boldsymbol{\theta}_j|H_j) d\boldsymbol{\theta}_j}. \quad (40.64)$$

This gives what the ratio of posterior probabilities for models  $i$  and  $j$  would be if the overall prior probabilities for the two models were equal.



**Figure 40.2:** The ‘reduced’  $\chi^2$ , equal to  $\chi^2/n$ , for  $n$  degrees of freedom. The curves show as a function of  $n$  the  $\chi^2/n$  that corresponds to a given  $p$ -value.

## 40.4 Intervals and limits

### 40.4.1 Bayesian intervals

A Bayesian or credible interval  $[\theta_{\text{lo}}, \theta_{\text{up}}]$  can be determined which contains a given fraction  $1 - \alpha$  of the posterior probability, *i.e.*,

$$1 - \alpha = \int_{\theta_{\text{lo}}}^{\theta_{\text{up}}} p(\theta|\mathbf{x}) d\theta. \quad (40.66)$$

### 40.4.2 Frequentist confidence intervals

#### 40.4.2.1 The Neyman construction for confidence intervals

Given a p.d.f.  $f(x; \theta)$ , we can find using a pre-defined rule and probability  $1 - \alpha$  for every value of  $\theta$ , a set of values  $x_1(\theta, \alpha)$  and  $x_2(\theta, \alpha)$  such that

$$P(x_1 < x < x_2; \theta) = \int_{x_1}^{x_2} f(x; \theta) dx \geq 1 - \alpha. \quad (40.73)$$

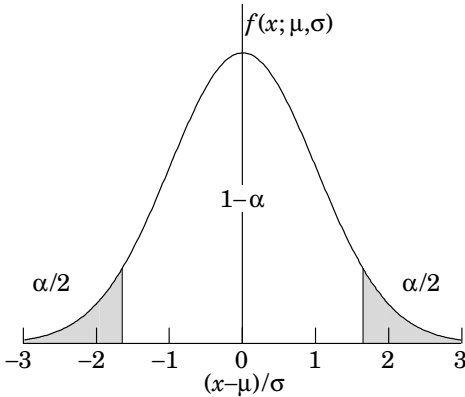
#### 40.4.2.2 Gaussian distributed measurements

When the data consists of a single random variable  $x$  that follows a Gaussian distribution with known  $\sigma$ , the probability that the measured value  $x$  will fall within  $\pm\delta$  of the true value  $\mu$  is

$$\begin{aligned} 1 - \alpha &= \frac{1}{\sqrt{2\pi}\sigma} \int_{\mu-\delta}^{\mu+\delta} e^{-(x-\mu)^2/2\sigma^2} dx \\ &= \text{erf}\left(\frac{\delta}{\sqrt{2}\sigma}\right) = 2\Phi\left(\frac{\delta}{\sigma}\right) - 1, \end{aligned} \quad (40.76)$$

Fig. 40.4 shows a  $\delta = 1.64\sigma$  confidence interval unshaded. Values of  $\alpha$  for other frequently used choices of  $\delta$  are given in Table 40.1.

We can set a one-sided (upper or lower) limit by excluding above  $x + \delta$  (or below  $x - \delta$ ). The values of  $\alpha$  for such limits are half the values in Table 40.1. Values of  $\Delta\chi^2$  or  $2\Delta\ln L$  are given in Table 40.2 for several values of the coverage probability  $1 - \alpha$  and number of fitted parameters  $m$ .



**Figure 40.4:** Illustration of a symmetric 90% confidence interval (unshaded) for a Gaussian-distributed measurement of a single quantity. Integrated probabilities, defined by  $\alpha = 0.1$ , are as shown.

**Table 40.1:** Area of the tails  $\alpha$  outside  $\pm\delta$  from the mean of a Gaussian distribution.

$\alpha$	$\delta$	$\alpha$	$\delta$
0.3173	$1\sigma$	0.2	$1.28\sigma$
$4.55 \times 10^{-2}$	$2\sigma$	0.1	$1.64\sigma$
$2.7 \times 10^{-3}$	$3\sigma$	0.05	$1.96\sigma$
$6.3 \times 10^{-5}$	$4\sigma$	0.01	$2.58\sigma$
$5.7 \times 10^{-7}$	$5\sigma$	0.001	$3.29\sigma$
$2.0 \times 10^{-9}$	$6\sigma$	$10^{-4}$	$3.89\sigma$

**Table 40.2:** Values of  $\Delta\chi^2$  or  $2\Delta \ln L$  corresponding to a coverage probability  $1 - \alpha$  in the large data sample limit, for joint estimation of  $m$  parameters.

$(1 - \alpha)$ (%)	$m = 1$	$m = 2$	$m = 3$
68.27	1.00	2.30	3.53
90.	2.71	4.61	6.25
95.	3.84	5.99	7.82
95.45	4.00	6.18	8.03
99.	6.63	9.21	11.34
99.73	9.00	11.83	14.16

#### 40.4.2.3 Poisson or binomial data

For Poisson distributed  $n$ , the upper and lower limits on the mean value  $\mu$  from the Neyman procedure are

$$\mu_{\text{lo}} = \frac{1}{2} F_{\chi^2}^{-1}(\alpha_{\text{lo}}; 2n), \quad (40.82a)$$

$$\mu_{\text{up}} = \frac{1}{2} F_{\chi^2}^{-1}(1 - \alpha_{\text{up}}; 2(n + 1)), \quad (40.82b)$$

For the case of binomially distributed  $n$  successes out of  $N$  trials with

**Table 40.3:** Lower and upper (one-sided) limits for the mean  $\mu$  of a Poisson variable given  $n$  observed events in the absence of background, for confidence levels of 90% and 95%.

$n$	$1 - \alpha = 90\%$		$1 - \alpha = 95\%$	
	$\mu_{lo}$	$\mu_{up}$	$\mu_{lo}$	$\mu_{up}$
0	–	2.30	–	3.00
1	0.105	3.89	0.051	4.74
2	0.532	5.32	0.355	6.30
3	1.10	6.68	0.818	7.75
4	1.74	7.99	1.37	9.15
5	2.43	9.27	1.97	10.51
6	3.15	10.53	2.61	11.84
7	3.89	11.77	3.29	13.15
8	4.66	12.99	3.98	14.43
9	5.43	14.21	4.70	15.71
10	6.22	15.41	5.43	16.96

probability of success  $p$ , the upper and lower limits on  $p$  are found to be

$$p_{lo} = \frac{nF_F^{-1}[\alpha_{lo}; 2n, 2(N - n + 1)]}{N - n + 1 + nF_F^{-1}[\alpha_{lo}; 2n, 2(N - n + 1)]}, \quad (40.83a)$$

$$p_{up} = \frac{(n + 1)F_F^{-1}[1 - \alpha_{up}; 2(n + 1), 2(N - n)]}{(N - n) + (n + 1)F_F^{-1}[1 - \alpha_{up}; 2(n + 1), 2(N - n)]}. \quad (40.83b)$$

Here  $F_F^{-1}$  is the quantile of the  $F$  distribution (also called the Fisher-Snedecor distribution; see Ref. [4]).

Several problems with such intervals are overcome by using the unified approach of Feldman and Cousins [42], as described further in the *Review*. Table 40.4 gives the unified confidence intervals  $[\mu_1, \mu_2]$  for the mean of a Poisson variable given  $n$  observed events in the absence of background, for confidence levels of 90% and 95%.

**Table 40.4:** Unified confidence intervals  $[\mu_1, \mu_2]$  for a the mean of a Poisson variable given  $n$  observed events in the absence of background, for confidence levels of 90% and 95%.

$n$	$1 - \alpha = 90\%$		$1 - \alpha = 95\%$	
	$\mu_1$	$\mu_2$	$\mu_1$	$\mu_2$
0	0.00	2.44	0.00	3.09
1	0.11	4.36	0.05	5.14
2	0.53	5.91	0.36	6.72
3	1.10	7.42	0.82	8.25
4	1.47	8.60	1.37	9.76
5	1.84	9.99	1.84	11.26
6	2.21	11.47	2.21	12.75
7	3.56	12.53	2.58	13.81
8	3.96	13.99	2.94	15.29
9	4.36	15.30	4.36	16.77
10	5.50	16.50	4.75	17.82

Further discussion and all references may be found in the full *Review of Particle Physics*.

## 45. Monte Carlo Particle Numbering Scheme

Revised August 2023 by A. Buckley (Glasgow U.), F. Krauss (Durham U.), S. Navas (Granada U.) and P. Richardson (Durham U.).

The Monte Carlo particle numbering scheme presented here is intended to facilitate interfacing between matrix-element generators, event generators, detector simulators, and analysis packages used in particle physics, and is widely accepted as the “industry standard”. The general form is a 7-digit number:

$$\pm n n_r n_L n_{q_1} n_{q_2} n_{q_3} n_J .$$

Tetra- and penta-quark state are signified by a 9-digit code, and nuclear codes are 10-digit numbers. This encodes information about the particle’s spin, flavor content, and internal quantum numbers: See the full review for details. An *abbreviated* list of common or well-measured particles follows below.<sup>1</sup>

QUARKS		SPECIAL PARTICLES		$\tilde{\tau}_2^-$	2000015
$d$	1	$G$ (graviton)	39	$\tilde{g}$	1000021
$u$	2	$R^0$	41	$\tilde{\chi}_1^0$	1000022
$s$	3	$LQ^c$	42	$\tilde{\chi}_2^0$	1000023
$c$	4	DM ( $S=0$ )	51	$\tilde{\chi}_1^+$	1000024
$b$	5	DM ( $S=\frac{1}{2}$ )	52	$\tilde{\chi}_3^0$	1000025
$t$	6	DM ( $S=1$ )	53	$\tilde{\chi}_4^0$	1000035
$b'$	7	<i>reggeon</i>	110	$\tilde{\chi}_2^+$	1000037
$t'$	8	<i>pomeron</i>	990	$G$	1000039
$odderon$	9990				
LEPTONS		for MC internal use			
$e^-$	11	81–100, 901–930,			
$\nu_e$	12	998–999,			
$\mu^-$	13	1901–1930,			
$\nu_\mu$	14	2901–2930, and			
$\tau^-$	15	3901–3930			
$\nu_\tau$	16				
$\tau'^-$	17				
$\nu_{\tau'}$	18				
GAUGE AND HIGGS BOSONS		SUSY PARTICLES		DIQUARKS	
$g$	(9) 21	$\tilde{d}_L$	1000001	$(dd)_1$	1103
$\gamma$	22	$\tilde{u}_L$	1000002	$(ud)_0$	2101
$Z^0$	23	$\tilde{s}_L$	1000003	$(ud)_1$	2103
$W^+$	24	$\tilde{c}_L$	1000004	$(uu)_1$	2203
$h^0/H_1^0$	25	$\tilde{b}_1$	1000005	$(sd)_0$	3101
$Z'/Z_2^0$	32	$\tilde{t}_1$	1000006	$(sd)_1$	3103
$Z''/Z_3^0$	33	$\tilde{e}_L$	1000011	$(su)_0$	3201
$W'/W_2^+$	34	$\tilde{\nu}_{eL}$	1000012	$(su)_1$	3203
$H^0/H_2^0$	35	$\tilde{\mu}_L$	1000013	$(ss)_1$	3303
$A^0/H_3^0$	36	$\tilde{\nu}_{\mu L}$	1000014		
$H^+$	37	$\tilde{\tau}_1$	1000015	LIGHT $I = 1$ MESONS	
$H^{++}$	38	$\tilde{\nu}_{\tau L}$	1000016	$\pi^0$	111
$a^0/H_4^0$	40	$\tilde{d}_R$	2000001	$\pi^+$	211
		$\tilde{u}_R$	2000002	$a_0(980)^0$	9000111
		$\tilde{s}_R$	2000003	$a_0(980)^+$	9000211
		$\tilde{c}_R$	2000004	$a_0(1450)^0$	10111
		$\tilde{b}_2$	2000005	$a_0(1450)^+$	10211
		$\tilde{t}_2$	2000006	$\rho(770)^0$	113
		$\tilde{e}_R$	2000011	$\rho(770)^+$	213
		$\tilde{\mu}_R$	2000013	$b_1(1235)^0$	10113
				$b_1(1235)^+$	10213
				$a_2(1320)^0$	115
				$a_2(1320)^+$	215
				$\rho_3(1690)^0$	117
				$\rho_3(1690)^+$	217
				$a_4(2040)^0$	119
				$a_4(2040)^+$	219



LIGHT $I = 0$ MESONS ( $u\bar{u}$ , $d\bar{d}$ , $s\bar{s}$ admixture)	
$\eta$	221
$\eta'$ (958)	331
$f_0$ (500)	9000221
$f_0$ (980)	9010221
$\omega$ (782)	223
$\phi$ (1020)	333
$f_1$ (1285)	20223
$f_2$ (1270)	225
$f_2'$ (1525)	335
$\omega_3$ (1670)	227
$\phi_3$ (1850)	337
$f_4$ (2050)	229

STRANGE MESONS	
$K^0$	130
$K^0_{\bar{0}}$	310
$K^0_{\bar{0}}$	311
$K^+$	321
$K^*_0$ (1430) <sup>0</sup>	10311
$K^*_0$ (1430) <sup>+</sup>	10321
$K^*$ (892) <sup>0</sup>	313
$K^*$ (892) <sup>+</sup>	323
$K_1$ (1270) <sup>0</sup>	10313
$K_1$ (1270) <sup>+</sup>	10323
$K^*$ (1680) <sup>0</sup>	30313
$K^*$ (1680) <sup>+</sup>	30323
$K^*_2$ (1430) <sup>0</sup>	315
$K^*_2$ (1430) <sup>+</sup>	325
$K_2$ (1770) <sup>0</sup>	10315
$K_2$ (1770) <sup>+</sup>	10325
$K^*_3$ (1780) <sup>0</sup>	317
$K^*_3$ (1780) <sup>+</sup>	327
$K^*_4$ (2045) <sup>0</sup>	319
$K^*_4$ (2045) <sup>+</sup>	329

CHARMED MESONS	
$D^+$	411
$D^0$	421
$D^*_0$ (2400) <sup>+</sup>	10411
$D^*_0$ (2400) <sup>0</sup>	10421
$D^*$ (2010) <sup>+</sup>	413
$D^*$ (2007) <sup>0</sup>	423
$D_1$ (2420) <sup>+</sup>	10413
$D_1$ (2420) <sup>0</sup>	10423
$D_1$ (H) <sup>+</sup>	20413
$D_1$ (2430) <sup>0</sup>	20423
$D^*_2$ (2460) <sup>+</sup>	415
$D^*_2$ (2460) <sup>0</sup>	425
$D^+_s$	431
$D^*_{s0}$ (2317) <sup>+</sup>	10431
$D^*_{s^+}$	433
$D_{s1}$ (2536) <sup>+</sup>	10433
$D_{s1}$ (2460) <sup>+</sup>	20433
$D^*_{s2}$ (2573) <sup>+</sup>	435

BOTTOM MESONS	
$B^0$	511
$B^+$	521
$B^{*0}$	10511
$B^{*+}$	10521
$B^*_0$	513
$B^{*+}$	523
$B_1(L)^0$	10513
$B_1(L)^+$	10523
$B_1(H)^0$	20513
$B_1(H)^+$	20523
$B^{*0}_2$	515
$B^{*+}_2$	525
$\bar{B}^0_s$	531
$B^{*0}_s$	533
$B^{*0}_{s2}$	535
$B^+_c$	541
$B^{*+}_c$	543
$B^{*+}_{c2}$	545

$c\bar{c}$ MESONS	
$\eta_c(1S)$	441
$\chi_{c0}(1P)$	10441
$\eta_c(2S)$	100441
$J/\psi(1S)$	443
$h_c(1P)$	10443
$\chi_{c1}(1P)$	20443
$\psi(2S)$	100443
$\psi(3770)$	30443
$\chi_{c2}(1P)$	445

$b\bar{b}$ MESONS	
$\eta_b(1S)$	551
$\chi_{b0}(1P)$	10551
$\chi_{b0}(2P)$	110551
$\Upsilon(1S)$	553
$h_b(1P)$	10553
$\chi_{b1}(1P)$	20553
$\Upsilon_1(1D)$	30553
$\Upsilon(2S)$	100553
$h_b(2P)$	110553
$\chi_{b1}(2P)$	120553
$\Upsilon(3S)$	200553
$\Upsilon(4S)$	300553
$\Upsilon(10860)$	9000553
$\Upsilon(11020)$	9010553
$\chi_{b2}(1P)$	555
$\Upsilon_2(1D)$	20555
$\chi_{b2}(2P)$	100555

LIGHT BARYONS	
$p$	2212
$n$	2112
$\Delta^{++}$	2224
$\Delta^+$	2214
$\Delta^0$	2114
$\Delta^-$	1114

STRANGE BARYONS	
$\Lambda$	3122
$\Sigma^+$	3222
$\Sigma^0$	3212
$\Sigma^-$	3112
$\Sigma^{*+}$	3224
$\Sigma^{*0}$	3214
$\Sigma^{*-}$	3114
$\Xi^0$	3322
$\Xi^-$	3312
$\Xi^{*0}$	3324
$\Xi^{*-}$	3314
$\Omega^-$	3334

CHARMED BARYONS	
$\Lambda^+_c$	4122
$\Sigma^{++}_c$	4222
$\Sigma^+_c$	4212
$\Sigma^0_c$	4112
$\Sigma^{*++}_c$	4224
$\Sigma^{*+}_c$	4214
$\Sigma^{*0}_c$	4114
$\Xi^+_c$	4232
$\Xi^0_c$	4132
$\Xi^{*+}_c$	4322
$\Xi^{*0}_c$	4312
$\Xi^{*+}_c$	4324
$\Xi^{*0}_c$	4314
$\Omega^0_c$	4332
$\Omega^{*0}_c$	4334
$\Xi^{++}_c$	4422

BOTTOM BARYONS	
$\Lambda^0_b$	5122
$\Sigma^-_b$	5112
$\Sigma^0_b$	5212
$\Sigma^+_b$	5222
$\Sigma^{*-}_b$	5114
$\Sigma^{*0}_b$	5214
$\Sigma^{*+}_b$	5224
$\Xi^-_b$	5132
$\Xi^0_b$	5232
$\Xi^{*-}_b$	5312
$\Xi^{*0}_b$	5322
$\Xi^{*-}_b$	5314
$\Xi^{*0}_b$	5324
$\Omega^-_b$	5332
$\Omega^{*-}_b$	5334

PENTA- QUARKS	
$\Theta^+$	100221132
$\Phi^{--}$	100331122

<sup>1</sup>The scheme was substantially updated and extended in 2012. Certain excited baryons follow the pre-2012 scheme. A further revision and/or extension of the numbering scheme is anticipated in the near future.



$$d_{m,m}^j = (-1)^{m-m'} d_{m,m'}^j$$

$$d_{m,0}^\ell = \sqrt{\frac{4\pi}{2\ell+1}} Y_\ell^m e^{-im\phi}$$

$$d_{1,1}^1 = \frac{1+\cos\theta}{2}$$

$$d_{1,0}^1 = -\frac{\sin\theta}{\sqrt{2}}$$

$$d_{1,-1}^1 = \frac{1-\cos\theta}{2}$$

$$d_{1/2,1/2}^1 = \cos\frac{\theta}{2}$$

$$d_{1/2,-1/2}^1 = -\sin\frac{\theta}{2}$$

$$d_{1,0}^2 = \cos\theta$$

$$d_{1/2,1/2}^2 = \frac{3}{2} \times \frac{3}{2} \times \frac{3}{2}$$

$$d_{1/2,-1/2}^2 = \frac{3}{2} \times \frac{3}{2} \times \frac{3}{2}$$

$$d_{1,1}^3 = \frac{1+\cos\theta}{2}$$

$$d_{1,0}^3 = -\sqrt{\frac{3}{2}} \sin\theta \cos\theta$$

$$d_{1,-1}^3 = \frac{1-\cos\theta}{2}$$

$$d_{3/2,3/2}^3 = \frac{1+\cos\theta}{2} \cos\frac{\theta}{2}$$

$$d_{3/2,1/2}^3 = -\sqrt{\frac{3}{2}} \frac{1+\cos\theta}{2} \sin\frac{\theta}{2}$$

$$d_{3/2,-1/2}^3 = \sqrt{\frac{3}{2}} \frac{1-\cos\theta}{2} \cos\frac{\theta}{2}$$

$$d_{3/2,-3/2}^3 = -\frac{1-\cos\theta}{2} \sin\frac{\theta}{2}$$

$$d_{1/2,1/2}^3 = \frac{3\cos\theta - 1}{2} \cos\frac{\theta}{2}$$

$$d_{1/2,-1/2}^3 = -\frac{3\cos\theta + 1}{2} \sin\frac{\theta}{2}$$

$$d_{0,0}^2 = (2\cos\theta + 1)$$

$$d_{0,0}^3 = \left(\frac{3}{2} \cos^2\theta - \frac{1}{2}\right)$$

## 49. Kinematics

Revised August 2021 by D.J. Miller (Glasgow U.) and D.R. Tovey (Sheffield U.).

Throughout this section units are used in which  $\hbar = c = 1$ . The following conversions are useful:  $\hbar c = 197.3 \text{ MeV fm}$ ,  $(\hbar c)^2 = 0.3894 \text{ (GeV)}^2 \text{ mb}$ .

### 49.1 Lorentz transformations

The energy  $E$  and 3-momentum  $\mathbf{p}$  of a particle of mass  $m$  form a 4-vector  $p = (E, \mathbf{p})$  whose square  $p^2 \equiv E^2 - |\mathbf{p}|^2 = m^2$ . The velocity of the particle is  $\boldsymbol{\beta} = \mathbf{p}/E$ . The energy and momentum  $(E^*, \mathbf{p}^*)$  viewed from a frame moving with velocity  $\boldsymbol{\beta}_f$  are given by

$$\begin{pmatrix} E^* \\ \mathbf{p}_{\parallel}^* \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f \boldsymbol{\beta}_f \\ -\gamma_f \boldsymbol{\beta}_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_{\parallel} \end{pmatrix}, \quad p_T^* = p_T, \quad (49.1)$$

where  $\gamma_f = (1 - \boldsymbol{\beta}_f^2)^{-1/2}$  and  $p_T$  ( $p_{\parallel}$ ) are the components of  $\mathbf{p}$  perpendicular (parallel) to  $\boldsymbol{\beta}_f$ . Other 4-vectors, such as the space-time coordinates of events, of course transform in the same way. The scalar product of two 4-momenta  $p_1 \cdot p_2 = E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2$  is invariant (frame independent).

### 49.2 Center-of-mass energy and momentum

In the collision of two particles of masses  $m_1$  and  $m_2$  the total center-of-mass energy can be expressed in the Lorentz-invariant form

$$\begin{aligned} E_{\text{cm}} &= \left[ (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 \right]^{1/2}, \\ &= \left[ m_1^2 + m_2^2 + 2E_1 E_2 (1 - \beta_1 \beta_2 \cos \theta) \right]^{1/2}, \end{aligned} \quad (49.2)$$

where  $\theta$  is the angle between the particles. In the frame where one particle (of mass  $m_2$ ) is at rest (lab frame),

$$E_{\text{cm}} = (m_1^2 + m_2^2 + 2E_{1 \text{ lab}} m_2)^{1/2}. \quad (49.3)$$

The velocity of the center-of-mass in the lab frame is

$$\boldsymbol{\beta}_{\text{cm}} = \mathbf{p}_{\text{lab}} / (E_{1 \text{ lab}} + m_2), \quad (49.4)$$

where  $\mathbf{p}_{\text{lab}} \equiv \mathbf{p}_{1 \text{ lab}}$  and

$$\gamma_{\text{cm}} = (E_{1 \text{ lab}} + m_2) / E_{\text{cm}}. \quad (49.5)$$

The c.m. momenta of particles 1 and 2 are of magnitude

$$p_{\text{cm}} = p_{\text{lab}} \frac{m_2}{E_{\text{cm}}}. \quad (49.6)$$

For example, if a 0.80 GeV/c kaon beam is incident on a proton target, the center of mass energy is 1.699 GeV and the center of mass momentum of either particle is 0.442 GeV/c. It is also useful to note that

$$E_{\text{cm}} dE_{\text{cm}} = m_2 dE_{1 \text{ lab}} = m_2 \beta_{1 \text{ lab}} dp_{\text{lab}}. \quad (49.7)$$

### 49.3 Lorentz-invariant amplitudes

The matrix elements for a scattering or decay process are written in terms of an invariant amplitude  $-i\mathcal{M}$ . As an example, the  $S$ -matrix for  $2 \rightarrow 2$  scattering is related to  $\mathcal{M}$  by

$$\langle p'_1 p'_2 | S - 1 | p_1 p_2 \rangle = i(2\pi)^4 \delta^4(p_1 + p_2 - p'_1 - p'_2) \mathcal{M}(p_1, p_2; p'_1, p'_2). \quad (49.8)$$

The state normalization is such that

$$\langle p' | p \rangle = (2\pi)^3 2E_p \delta^3(\mathbf{p}' - \mathbf{p}), \quad (49.9)$$

with  $E_p = \sqrt{\mathbf{p}^2 + m^2}$ .

#### 49.4 Particle decays

The partial decay rate of a particle of mass  $M$  into  $n$  bodies in its rest frame is given in terms of the Lorentz-invariant matrix element  $\mathcal{M}$  by

$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 d\Phi_n(P; p_1, \dots, p_n), \quad (49.11)$$

where  $d\Phi_n$  is an element of  $n$ -body phase space given by

$$d\Phi_n(P; p_1, \dots, p_n) = \delta^4(P - \sum_{i=1}^n p_i) \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 2E_i}. \quad (49.12)$$

This phase space is reduced by combinatoric factors whenever there are identical particles in the final state. The phase space can be generated recursively, viz.

$$\begin{aligned} d\Phi_n(P; p_1, \dots, p_n) &= d\Phi_j(q; p_1, \dots, p_j) \\ &\times d\Phi_{n-j+1}(P; q, p_{j+1}, \dots, p_n) (2\pi)^3 dq^2, \end{aligned} \quad (49.13)$$

where  $q^2 = (\sum_{i=1}^j E_i)^2 - |\sum_{i=1}^j \mathbf{p}_i|^2$ . This form is particularly useful in the case where a particle decays into another particle that subsequently decays.

##### 49.4.1 Survival probability

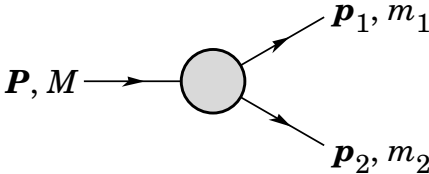
If a particle of mass  $M$  has mean proper lifetime  $\tau$  ( $= 1/\Gamma$ ) and has momentum  $(E, \mathbf{p})$ , then the probability that it lives for a time  $t_0$  or greater before decaying is given by

$$P(t_0) = e^{-t_0 \Gamma/\gamma} = e^{-Mt_0 \Gamma/E}, \quad (49.14)$$

and the probability that it travels a distance  $x_0$  or greater is

$$P(x_0) = e^{-Mx_0 \Gamma/|\mathbf{p}|}. \quad (49.15)$$

##### 49.4.2 Two-body decays



**Figure 49.1:** Definitions of variables for two-body decays.

In the rest frame of a particle of mass  $M$ , decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M}, \quad (49.16)$$

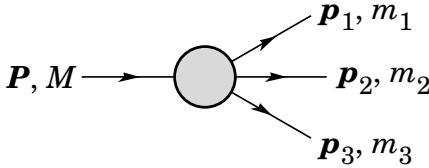
$$|\mathbf{p}_1| = |\mathbf{p}_2| = \frac{1}{2M} \sqrt{\lambda(M^2, m_1^2, m_2^2)}, \quad (49.17)$$

and

$$d\Gamma = \frac{1}{32\pi^2} |\mathcal{M}|^2 \frac{|\mathbf{p}_1|}{M^2} d\Omega, \quad (49.18)$$

where  $\lambda(\alpha, \beta, \gamma) = \alpha^2 + \beta^2 + \gamma^2 - 2\alpha\beta - 2\alpha\gamma - 2\beta\gamma$  is the Källén function and  $d\Omega = d\phi_1 d(\cos\theta_1)$  is the solid angle of particle 1. The invariant mass  $M$  can be determined from the energies and momenta using Eq. (49.2) with  $M = E_{\text{cm}}$ .

## 49.4.3 Three-body decays



**Figure 49.2:** Definitions of variables for three-body decays.

Defining  $p_{ij} = p_i + p_j$  and  $m_{ij}^2 = p_{ij}^2$ , then  $m_{12}^2 + m_{23}^2 + m_{13}^2 = M^2 + m_1^2 + m_2^2 + m_3^2$  and  $m_{12}^2 = (P - p_3)^2 = M^2 + m_3^2 - 2ME_3$ , where  $E_3$  is the energy of particle 3 in the rest frame of  $M$ . In that frame, the momenta of the three decay particles lie in a plane. The relative orientation of these three momenta is fixed if their energies are known. The momenta can therefore be specified in space by giving three Euler angles  $(\alpha, \beta, \gamma)$  that specify the orientation of the final system relative to the initial particle. The direction of any one of the particles relative to the frame in which the initial particle is described can be specified in space by two angles  $(\alpha, \beta)$  while a third angle,  $\gamma$ , can be set as the azimuthal angle of a second particle around the first [1]. Then

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M} |\mathcal{M}|^2 dE_1 dE_3 d\alpha d(\cos\beta) d\gamma. \quad (49.19)$$

Alternatively

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M^2} |\mathcal{M}|^2 |\mathbf{p}_1^*| |\mathbf{p}_3| dm_{12} d\Omega_1^* d\Omega_3, \quad (49.20)$$

where  $(|\mathbf{p}_1^*|, \Omega_1^*)$  is the momentum of particle 1 in the rest frame of 1 and 2, and  $\Omega_3$  is the angle of particle 3 in the rest frame of the decaying particle.  $|\mathbf{p}_1^*|$  and  $|\mathbf{p}_3|$  are given by

$$|\mathbf{p}_1^*| = \frac{1}{2m_{12}} \sqrt{\lambda(m_{12}^2, m_1^2, m_2^2)}, \quad (49.21a)$$

and

$$|\mathbf{p}_3| = \frac{1}{2M} \sqrt{\lambda(M^2, m_{12}^2, m_3^2)}. \quad (49.21b)$$

[Compare with Eq. (49.17).]

If the decaying particle is a scalar or we average over its spin states, then integration over the angles in Eq. (49.19) gives

$$\begin{aligned} d\Gamma &= \frac{1}{(2\pi)^3} \frac{1}{8M} \overline{|\mathcal{M}|^2} dE_1 dE_3 \\ &= \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathcal{M}|^2} dm_{12}^2 dm_{23}^2. \end{aligned} \quad (49.22)$$

This is the standard form for the Dalitz plot.

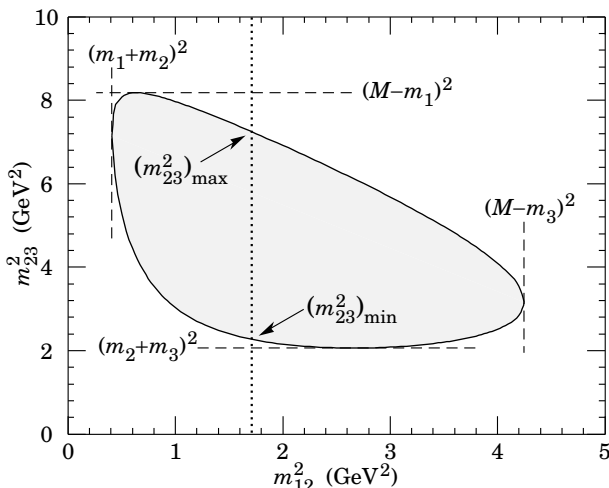
## 49.4.3.1 Dalitz plot

For a given value of  $m_{12}^2$ , the range of  $m_{23}^2$  is determined by its values when  $\mathbf{p}_2$  is parallel or antiparallel to  $\mathbf{p}_3$ :

$$(m_{23}^2)_{\max} = (E_2^* + E_3^*)^2 - \left( \sqrt{E_2^{*2} - m_2^2} - \sqrt{E_3^{*2} - m_3^2} \right)^2, \quad (49.23a)$$

$$(m_{23}^2)_{\min} = (E_2^* + E_3^*)^2 - \left( \sqrt{E_2^{*2} - m_2^2} + \sqrt{E_3^{*2} - m_3^2} \right)^2. \quad (49.23b)$$

Here  $E_2^* = (m_{12}^2 - m_1^2 + m_2^2)/2m_{12}$  and  $E_3^* = (M^2 - m_{12}^2 - m_3^2)/2m_{12}$  are the energies of particles 2 and 3 in the  $m_{12}$  rest frame. The scatter plot in  $m_{12}^2$  and  $m_{23}^2$  is called a Dalitz plot. If  $|\mathcal{M}|^2$  is constant, the allowed region of the plot will be uniformly populated with events [see Eq. (49.22)]. A nonuniformity in the plot gives immediate information on  $|\mathcal{M}|^2$ . For example, in the case of  $D \rightarrow K\pi\pi$ , bands appear when  $m_{(K\pi)} = m_{K^*(892)}$ , reflecting the appearance of the decay chain  $D \rightarrow K^*(892)\pi \rightarrow K\pi\pi$ .



**Figure 49.3:** Dalitz plot for a three-body final state. In this example, the state is  $\pi^+\bar{K}^0p$  at 3 GeV. Four-momentum conservation restricts events to the shaded region.

#### 49.4.4 Kinematic limits

##### 49.4.4.1 Three-body decays

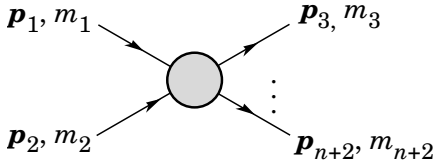
In a three-body decay (Fig. 49.2) the maximum of  $|\mathbf{p}_3|$ , [given by Eq. (49.21)], is achieved when  $m_{12} = m_1 + m_2$ , *i.e.*, particles 1 and 2 have the same vector velocity in the rest frame of the decaying particle. If, in addition,  $m_3 > m_1, m_2$ , then  $|\mathbf{p}_3|_{\max} > |\mathbf{p}_1|_{\max}, |\mathbf{p}_2|_{\max}$ . The distribution of  $m_{12}$  values possesses an end-point or maximum value at  $m_{12} = M - m_3$ . This can be used to constrain the mass difference of a parent particle and one invisible decay product.

#### 49.4.5 Multibody decays

The above results may be generalized to final states containing any number of particles by combining some of the particles into “effective particles” and treating the final states as 2 or 3 “effective particle” states. Thus, if  $p_{ijk\dots} = p_i + p_j + p_k + \dots$ , then

$$m_{ijk\dots} = \sqrt{p_{ijk\dots}^2}, \quad (49.26)$$

and  $m_{ijk\dots}$  may be used in place of *e.g.*,  $m_{12}$  in the relations in Sec. 49.4.3 or Sec. 49.4.4 above.



**Figure 49.5:** Definitions of variables for production of an  $n$ -body final state.

## 49.5 Cross sections

The differential cross section is given by

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2; p_3, \dots, p_{n+2}) . \quad (49.27)$$

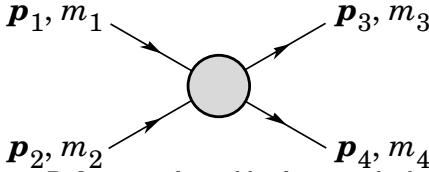
[See Eq. (49.12).] In the rest frame of  $m_2$ (lab),

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = m_2 p_{1 \text{ lab}} ; \quad (49.28a)$$

while in the center-of-mass frame

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = p_{1 \text{ cm}} \sqrt{s} . \quad (49.28b)$$

### 49.5.1 Two-body reactions



**Figure 49.6:** Definitions of variables for a two-body final state.

Two particles of momenta  $p_1$  and  $p_2$  and masses  $m_1$  and  $m_2$  scatter to particles of momenta  $p_3$  and  $p_4$  and masses  $m_3$  and  $m_4$ ; the Lorentz-invariant Mandelstam variables are defined by

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2 = m_1^2 + 2E_1 E_2 - 2\mathbf{p}_1 \cdot \mathbf{p}_2 + m_2^2 , \quad (49.29)$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2 = m_1^2 - 2E_1 E_3 + 2\mathbf{p}_1 \cdot \mathbf{p}_3 + m_3^2 , \quad (49.30)$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2 = m_1^2 - 2E_1 E_4 + 2\mathbf{p}_1 \cdot \mathbf{p}_4 + m_4^2 , \quad (49.31)$$

and they satisfy

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2 . \quad (49.32)$$

The two-body cross section may be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\mathbf{p}_{1 \text{ cm}}|^2} |\mathcal{M}|^2 . \quad (49.33)$$



In the center-of-mass frame

$$t = (E_{1\text{cm}} - E_{3\text{cm}})^2 - (p_{1\text{cm}} - p_{3\text{cm}})^2 - 4p_{1\text{cm}} p_{3\text{cm}} \sin^2(\theta_{\text{cm}}/2) \\ = t_0 - 4p_{1\text{cm}} p_{3\text{cm}} \sin^2(\theta_{\text{cm}}/2), \quad (49.34)$$

where  $\theta_{\text{cm}}$  is the angle between particle 1 and 3. The limiting values  $t_0$  ( $\theta_{\text{cm}} = 0$ ) and  $t_1$  ( $\theta_{\text{cm}} = \pi$ ) for  $2 \rightarrow 2$  scattering are

$$t_0(t_1) = \left[ \frac{m_1^2 - m_3^2 - m_2^2 + m_4^2}{2\sqrt{s}} \right]^2 - (p_{1\text{cm}} \mp p_{3\text{cm}})^2. \quad (49.35)$$

In the literature the notation  $t_{\min}$  ( $t_{\max}$ ) for  $t_0$  ( $t_1$ ) is sometimes used, which should be discouraged since  $t_0 > t_1$ . The center-of-mass energies and momenta of the incoming particles are

$$E_{1\text{cm}} = \frac{s + m_1^2 - m_2^2}{2\sqrt{s}}, \quad E_{2\text{cm}} = \frac{s + m_2^2 - m_1^2}{2\sqrt{s}}, \quad (49.36)$$

For  $E_{3\text{cm}}$  and  $E_{4\text{cm}}$ , change  $m_1$  to  $m_3$  and  $m_2$  to  $m_4$ . Then

$$p_{i\text{cm}} = \sqrt{E_{i\text{cm}}^2 - m_i^2} \quad \text{and} \quad p_{1\text{cm}} = \frac{p_{1\text{lab}} m_2}{\sqrt{s}}. \quad (49.37)$$

Here the subscript lab refers to the frame where particle 2 is at rest. [For other relations see Eqs. (49.2)–(49.4).]

### 49.5.2 Inclusive reactions

Choose some direction (usually the beam direction) for the  $z$ -axis; then the energy and momentum of a particle can be written as

$$E = m_T \cosh y, \quad p_x, p_y, p_z = m_T \sinh y, \quad (49.38)$$

where  $m_T$ , conventionally called the ‘transverse mass’, is given by

$$m_T^2 = m^2 + p_x^2 + p_y^2. \quad (49.39)$$

and the rapidity  $y$  is defined by

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \\ = \ln \left( \frac{E + p_z}{m_T} \right) = \tanh^{-1} \left( \frac{p_z}{E} \right). \quad (49.40)$$

Note that the definition of the transverse mass in Eq. (49.39) differs from that used by experimentalists at hadron colliders (see Sec. 49.6.1 below). Under a boost in the  $z$ -direction to a frame with velocity  $\beta$ ,  $y \rightarrow y - \tanh^{-1} \beta$ . Hence the shape of the rapidity distribution  $dN/dy$  is invariant, as are differences in rapidity. The invariant cross section may also be rewritten

$$E \frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi dy p_T dp_T} \implies \frac{d^2\sigma}{\pi dy d(p_T^2)}. \quad (49.41)$$

The second form is obtained using the identity  $dy/dp_z = 1/E$ , and the third form represents the average over  $\phi$ .

Feynman’s  $x$  variable is given by

$$x = \frac{p_z}{p_{z\text{max}}} \approx \frac{E + p_z}{(E + p_z)_{\text{max}}} \quad (p_T \ll |p_z|). \quad (49.42)$$

In the c.m. frame,

$$x \approx \frac{2p_{z\text{cm}}}{\sqrt{s}} = \frac{2m_T \sinh y_{\text{cm}}}{\sqrt{s}} \quad (49.43)$$

and

$$= (y_{\text{cm}})_{\text{max}} = \ln(\sqrt{s}/m) . \quad (49.44)$$

The invariant mass  $M$  of the two-particle system described in Sec. 49.4.2 can be written in terms of these variables as

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2) \cosh \Delta y - \mathbf{p}_T(1) \cdot \mathbf{p}_T(2)] , \quad (49.45)$$

where

$$E_T(i) = \sqrt{|\mathbf{p}_T(i)|^2 + m_i^2} , \quad (49.46)$$

and  $\mathbf{p}_T(i)$  denotes the transverse momentum vector of particle  $i$ .

For  $p \gg m$ , the rapidity [Eq. (49.40)] may be expanded to obtain

$$\begin{aligned} y &= \frac{1}{2} \ln \frac{\cos^2(\theta/2) + m^2/4p^2 + \dots}{\sin^2(\theta/2) + m^2/4p^2 + \dots} \\ &\approx -\ln \tan(\theta/2) \equiv \eta \end{aligned} \quad (49.47)$$

where  $\cos \theta = p_z/p$ . The pseudorapidity  $\eta$  defined by the second line is approximately equal to the rapidity  $y$  for  $p \gg m$  and  $\theta \gg 1/\gamma$ , and in any case can be measured when the mass and momentum of the particle are unknown. From the definition one can obtain the identities

$$\sinh \eta = \cot \theta , \quad \cosh \eta = 1/\sin \theta , \quad \tanh \eta = \cos \theta . \quad (49.48)$$

## 49.6 Transverse variables

At hadron colliders, a significant and unknown proportion of the energy of the incoming hadrons in each event escapes down the beam-pipe. Consequently if invisible particles are created in the final state, their net momentum can only be constrained in the plane transverse to the beam direction. Defining the  $z$ -axis as the beam direction, this net momentum is equal to the missing transverse energy vector

$$\mathbf{E}_T^{\text{miss}} = - \sum_i \mathbf{p}_T(i) , \quad (49.49)$$

where the sum runs over the transverse momenta of all visible final state particles.

### 49.6.1 Single production with semi-invisible final state

Consider a single heavy particle of mass  $M$  produced in association with visible particles which decays as in Fig. 49.1 to two particles, of which one (labeled particle 1) is invisible. The mass of the parent particle can be constrained with the quantity  $M_T$  defined by

$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\mathbf{p}_T(1) + \mathbf{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \mathbf{p}_T(1) \cdot \mathbf{p}_T(2)] , \end{aligned} \quad (49.50)$$

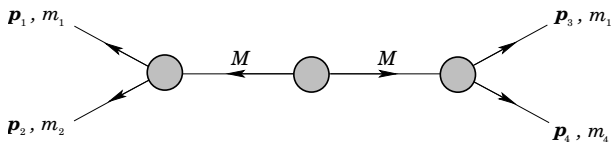
where

$$\mathbf{p}_T(1) = \mathbf{E}_T^{\text{miss}} . \quad (49.51)$$

This quantity is called the ‘transverse mass’ by hadron collider experimentalists but it should be noted that it is quite different from that used in the description of inclusive reactions [Eq. (49.39)]. The distribution of event  $M_T$  values possesses an end-point at  $M_T^{\text{max}} = M$ . If  $m_1 = m_2 = 0$  then

$$M_T^2 = 2|\mathbf{p}_T(1)||\mathbf{p}_T(2)|(1 - \cos \phi_{12}) , \quad (49.52)$$

where  $\phi_{ij}$  is defined as the angle between particles  $i$  and  $j$  in the transverse plane.



**Figure 49.7:** Definitions of variables for pair production of semi-invisible final states. Particles 1 and 3 are invisible while particles 2 and 4 are visible.

#### 49.6.2 Pair production with semi-invisible final states

Consider two identical heavy particles of mass  $M$  produced such that their combined center-of-mass is at rest in the transverse plane (Fig. 49.7). Each particle decays to a final state consisting of an invisible particle of fixed mass  $m_1$  together with an additional visible particle.  $M$  and  $m_1$  can be constrained with the variables  $M_{T2}$  and  $M_{CT}$  which are defined in Refs. [4] and [5].<sup>1</sup>

---

<sup>1</sup>Further discussion and all references may be found in the full *Review of Particle Physics*. The numbering of references and equations used here corresponds to that version.

## 51. Cross-Section Formulae for Specific Processes

Revised August 2019 by H. Baer (Oklahoma U.) and R.N. Cahn (LBNL).

### PART I: Standard Model Processes

Setting aside leptonproduction (for which, see Sec. 16 of this *Review*), the cross sections of primary interest are those with light incident particles,  $e^+e^-$ ,  $\gamma\gamma$ ,  $q\bar{q}$ ,  $gq$ ,  $gg$ , *etc.*, where  $g$  and  $q$  represent gluons and light quarks. The produced particles include both light particles and heavy ones -  $t$ ,  $W$ ,  $Z$ , and the Higgs boson  $H$ . We provide the production cross sections calculated within the Standard Model for several such processes.

#### 51.1 Resonance Formation

Resonant cross sections are generally described by the Breit-Wigner formula (Sec. 18 of this *Review*).

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[ \frac{\Gamma^2/4}{(E-E_0)^2 + \Gamma^2/4} \right] B_{in}B_{out}, \quad (51.1)$$

where  $E$  is the c.m. energy,  $J$  is the spin of the resonance, and the number of polarization states of the two incident particles are  $2S_1+1$  and  $2S_2+1$ . The c.m. momentum in the initial state is  $k$ ,  $E_0$  is the c.m. energy at the resonance, and  $\Gamma$  is the full width at half maximum height of the resonance. The branching fraction for the resonance into the initial-state channel is  $B_{in}$  and into the final-state channel is  $B_{out}$ . For a narrow resonance, the factor in square brackets may be replaced by  $\pi\Gamma\delta(E-E_0)/2$ .

#### 51.2 Production of light particles

The production of point-like, spin-1/2 fermions in  $e^+e^-$  annihilation through a virtual photon,  $e^+e^- \rightarrow \gamma^* \rightarrow f\bar{f}$ , at c.m. energy squared  $s$  is

$$\frac{d\sigma}{d\Omega} = N_c \frac{\alpha^2}{4s} \beta [1 + \cos^2\theta + (1-\beta^2)\sin^2\theta] Q_f^2, \quad (51.2)$$

where  $\beta$  is  $v/c$  for the produced fermions in the c.m.,  $\theta$  is the c.m. scattering angle, and  $Q_f$  is the charge of the fermion. The factor  $N_c$  is 1 for charged leptons and 3 for quarks. In the ultrarelativistic limit,  $\beta \rightarrow 1$ ,

$$\sigma = N_c Q_f^2 \frac{4\pi\alpha^2}{3s} = N_c Q_f^2 \frac{86.8 \text{ nb}}{s(\text{GeV}^2)}. \quad (51.3)$$

The cross section for the annihilation of a  $q\bar{q}$  pair into a distinct pair  $q'\bar{q}'$  through a gluon is completely analogous up to color factors, with the replacement  $\alpha \rightarrow \alpha_s$ . Treating all quarks as massless, averaging over the colors of the initial quarks and defining  $t = -s\sin^2(\theta/2)$ ,  $u = -s\cos^2(\theta/2)$ , one finds

$$\frac{d\sigma}{d\Omega}(q\bar{q} \rightarrow q'\bar{q}') = \frac{\alpha_s^2}{9s} \frac{t^2 + u^2}{s^2}. \quad (51.4)$$

Crossing symmetry gives

$$\frac{d\sigma}{d\Omega}(qq' \rightarrow qq') = \frac{\alpha_s^2}{9s} \frac{s^2 + u^2}{t^2}. \quad (51.5)$$

If the quarks  $q$  and  $q'$  are identical, we have

$$\frac{d\sigma}{d\Omega}(q\bar{q} \rightarrow q\bar{q}) = \frac{\alpha_s^2}{9s} \left[ \frac{t^2 + u^2}{s^2} + \frac{s^2 + u^2}{t^2} - \frac{2u^2}{3st} \right], \quad (51.6)$$

and by crossing

$$\frac{d\sigma}{d\Omega}(qq \rightarrow qq) = \frac{\alpha_s^2}{9s} \left[ \frac{t^2 + s^2}{u^2} + \frac{s^2 + u^2}{t^2} - \frac{2s^2}{3ut} \right]. \quad (51.7)$$

Annihilation of  $e^+e^-$  into  $\gamma\gamma$  has the cross section

$$\frac{d\sigma}{d\Omega}(e^+e^- \rightarrow \gamma\gamma) = \frac{\alpha^2}{2s} \frac{u^2 + t^2}{tu}. \quad (51.8)$$

The related QCD process also has a triple-gluon coupling. The cross section is

$$\frac{d\sigma}{d\Omega}(q\bar{q} \rightarrow gg) = \frac{8\alpha_s^2}{27s}(t^2 + u^2)\left(\frac{1}{tu} - \frac{9}{4s^2}\right). \quad (51.9)$$

The crossed reactions are

$$\frac{d\sigma}{d\Omega}(qg \rightarrow qg) = \frac{\alpha_s^2}{9s}(s^2 + u^2)\left(-\frac{1}{su} + \frac{9}{4t^2}\right), \quad (51.10)$$

$$\frac{d\sigma}{d\Omega}(gg \rightarrow q\bar{q}) = \frac{\alpha_s^2}{24s}(t^2 + u^2)\left(\frac{1}{tu} - \frac{9}{4s^2}\right), \quad (51.11)$$

$$\frac{d\sigma}{d\Omega}(gg \rightarrow gg) = \frac{9\alpha_s^2}{8s}\left(3 - \frac{ut}{s^2} - \frac{su}{t^2} - \frac{st}{u^2}\right). \quad (51.12)$$

Lepton-quark scattering is analogous (neglecting  $Z$  exchange)

$$\frac{d\sigma}{d\Omega}(eq \rightarrow eq) = \frac{\alpha^2}{2s} e_q^2 \frac{s^2 + u^2}{t^2}, \quad (51.13)$$

$e_q$  is the quark charge. For  $\nu$ -scattering with the four-Fermi interaction

$$\frac{d\sigma}{d\Omega}(\nu d \rightarrow \ell^- u) = \frac{G_F^2 s}{4\pi^2}, \quad (51.14)$$

where the Cabibbo angle suppression is ignored. Similarly

$$\frac{d\sigma}{d\Omega}(\nu\bar{u} \rightarrow \ell^- \bar{d}) = \frac{G_F^2 s}{4\pi^2} \frac{(1 + \cos\theta)^2}{4}. \quad (51.15)$$

For deep inelastic scattering (presented in more detail in Section 19) we consider quarks of type  $i$  carrying a fraction  $x = Q^2/(2M\nu)$  of the nucleon's energy, where  $\nu = E - E'$  is the energy lost by the lepton in the nucleon rest frame. With  $y = \nu/E$  we have the correspondences

$$1 + \cos\theta \rightarrow 2(1 - y), \quad d\Omega_{cm} \rightarrow 4\pi f_i(x) dx dy, \quad (51.16)$$

where the latter incorporates the quark distribution,  $f_i(x)$ . We find

$$\begin{aligned} \frac{d\sigma}{dx dy}(eN \rightarrow eX) &= \frac{4\pi\alpha^2 xs}{Q^4} \frac{1}{2} \left[1 + (1 - y)^2\right] \\ &\times \left[\frac{4}{9}(u(x) + \bar{u}(x) + \dots) + \frac{1}{9}(d(x) + \bar{d}(x) + \dots)\right] \end{aligned} \quad (51.17)$$

where now  $s = 2ME$  is the cm energy squared for the electron-nucleon collision and we have suppressed contributions from higher mass quarks.

Similarly,

$$\frac{d\sigma}{dx dy}(\nu N \rightarrow \ell^- X) = \frac{G_F^2 xs}{\pi} [(d(x) + \dots) + (1 - y)^2(\bar{u}(x) + \dots)], \quad (51.18)$$

$$\frac{d\sigma}{dx dy}(\bar{\nu} N \rightarrow \ell^+ X) = \frac{G_F^2 xs}{\pi} [(\bar{d}(x) + \dots) + (1 - y)^2(u(x) + \dots)]. \quad (51.19)$$

Quasi-elastic neutrino scattering ( $\nu_\mu n \rightarrow \mu^- p$ ,  $\bar{\nu}_\mu p \rightarrow \mu^+ n$ ) is directly related to the crossed reaction, neutron decay.

### 51.3 Hadroproduction of heavy quarks

For hadroproduction of heavy quarks  $Q = c, b, t$ , it is important to include mass effects in the formulae. For  $q\bar{q} \rightarrow Q\bar{Q}$ , one has

$$\frac{d\sigma}{d\Omega}(q\bar{q} \rightarrow Q\bar{Q}) = \frac{\alpha_s^2}{9s^3} \sqrt{1 - \frac{4m_Q^2}{s}} \left[(m_Q^2 - t)^2 + (m_Q^2 - u)^2 + 2m_Q^2 s\right], \quad (51.20)$$

while for  $gg \rightarrow Q\bar{Q}$  one has

$$\begin{aligned}
 \frac{d\sigma}{d\Omega}(gg \rightarrow Q\bar{Q}) &= \frac{\alpha_s^2}{32s} \sqrt{1 - \frac{4m_Q^2}{s}} \left[ \frac{6}{s^2} (m_Q^2 - t)(m_Q^2 - u) \right. \\
 &- \frac{m_Q^2(s - 4m_Q^2)}{3(m_Q^2 - t)(m_Q^2 - u)} + \frac{4}{3} \frac{(m_Q^2 - t)(m_Q^2 - u) - 2m_Q^2(m_Q^2 + t)}{(m_Q^2 - t)^2} \\
 &+ \frac{4}{3} \frac{(m_Q^2 - t)(m_Q^2 - u) - 2m_Q^2(m_Q^2 + u)}{(m_Q^2 - u)^2} \\
 &\left. - 3 \frac{(m_Q^2 - t)(m_Q^2 - u) + m_Q^2(u - t)}{s(m_Q^2 - t)} - 3 \frac{(m_Q^2 - t)(m_Q^2 - u) + m_Q^2(t - u)}{s(m_Q^2 - u)} \right]. \quad (51.21)
 \end{aligned}$$

## 51.4 Production of Weak Gauge Bosons

### 51.4.1 *W and Z resonant production*

Resonant production of a single  $W$  or  $Z$  is governed by the partial widths

$$\Gamma(W \rightarrow \ell_i \bar{\nu}_i) = \frac{\sqrt{2}G_F m_W^3}{12\pi} \quad (51.22)$$

$$\Gamma(W \rightarrow q_i \bar{q}_j) = 3 \frac{\sqrt{2}G_F |V_{ij}|^2 m_W^3}{12\pi} \quad (51.23)$$

$$\begin{aligned}
 \Gamma(Z \rightarrow f\bar{f}) &= N_c \frac{\sqrt{2}G_F m_Z^3}{6\pi} \\
 &\times \left[ (T_3 - Q_f \sin^2 \theta_W)^2 + (Q_f \sin^2 \theta_W)^2 \right]. \quad (51.24)
 \end{aligned}$$

The weak mixing angle is  $\theta_W$ . The CKM matrix elements are  $V_{ij}$ .  $N_c$  is 3 for  $q\bar{q}$  and 1 for leptonic final states. These widths along with associated branching fractions may be applied to the resonance production formula of Sec. 51.1 to gain the total  $W$  or  $Z$  production cross section.

### 51.4.2 *Production of pairs of weak gauge bosons*

The cross section for  $f\bar{f} \rightarrow W^+W^-$  is given in term of the couplings of the left-handed and right-handed fermion  $f$ ,  $\ell = 2(T_3 - Qx_W)$ ,  $r = -2Qx_W$ , where  $T_3$  is the third component of weak isospin for the left-handed  $f$ ,  $Q$  is its electric charge (in units of the proton charge), and  $x_W = \sin^2 \theta_W$ :

$$\begin{aligned}
 \frac{d\sigma}{dt} &= \frac{2\pi\alpha^2}{N_c s^2} \left\{ \left[ \left( Q + \frac{\ell + r}{4x_W} \frac{s}{s - m_Z^2} \right)^2 + \left( \frac{\ell - r}{4x_W} \frac{s}{s - m_Z^2} \right)^2 \right] A(s, t, u) \right. \\
 &+ \frac{1}{2x_W} \left( Q + \frac{\ell}{2x_W} \frac{s}{s - m_Z^2} \right) (\Theta(-Q)I(s, t, u) - \Theta(Q)I(s, u, t)) \\
 &\left. + \frac{1}{8x_W^2} (\Theta(-Q)E(s, t, u) + \Theta(Q)E(s, u, t)) \right\}, \quad (51.26)
 \end{aligned}$$

where  $\Theta(x)$  is 1 for  $x > 0$  and 0 for  $x < 0$ , and where

$$\begin{aligned} A(s, t, u) &= \left( \frac{tu}{m_W^4} - 1 \right) \left( \frac{1}{4} - \frac{m_W^2}{s} + 3 \frac{m_W^4}{s^2} \right) + \frac{s}{m_W^2} - 4, \\ I(s, t, u) &= \left( \frac{tu}{m_W^4} - 1 \right) \left( \frac{1}{4} - \frac{m_W^2}{2s} - \frac{m_W^4}{st} \right) + \frac{s}{m_W^2} - 2 + 2 \frac{m_W^2}{t}, \\ E(s, t, u) &= \left( \frac{tu}{m_W^4} - 1 \right) \left( \frac{1}{4} + \frac{m_W^4}{t^2} \right) + \frac{s}{m_W^2}, \end{aligned} \quad (51.27)$$

and  $s, t, u$  are the usual Mandelstam variables with  $s = (p_f + p_{\bar{f}})^2$ ,  $t = (p_f - p_{W^-})^2$ ,  $u = (p_f - p_{W^+})^2$ . The factor  $N_c$  is 3 for quarks and 1 for leptons.

The analogous cross-section for  $q_i \bar{q}_j \rightarrow W^\pm Z^0$  is

$$\begin{aligned} \frac{d\sigma}{dt} &= \frac{\pi\alpha^2 |V_{ij}|^2}{6s^2 x_W^2} \left\{ \left( \frac{1}{s - m_W^2} \right)^2 \left[ \left( \frac{9 - 8x_W}{4} \right) (ut - m_W^2 m_Z^2) \right. \right. \\ &\quad \left. \left. + (8x_W - 6) s (m_W^2 + m_Z^2) \right] \right. \\ &\quad \left. + \left[ \frac{ut - m_W^2 m_Z^2 - s(m_W^2 + m_Z^2)}{s - m_W^2} \right] \left[ \frac{\ell_j}{t} - \frac{\ell_i}{u} \right] \right. \\ &\quad \left. + \frac{ut - m_W^2 m_Z^2}{4(1 - x_W)} \left[ \frac{\ell_j^2}{t^2} + \frac{\ell_i^2}{u^2} \right] + \frac{s(m_W^2 + m_Z^2)}{2(1 - x_W)} \frac{\ell_i \ell_j}{tu} \right\}, \end{aligned} \quad (51.28)$$

where  $\ell_i$  and  $\ell_j$  are the couplings of the left-handed  $q_i$  and  $q_j$  as defined above. The CKM matrix element between  $q_i$  and  $q_j$  is  $V_{ij}$ .

The cross section for  $q_i \bar{q}_i \rightarrow Z^0 Z^0$  is

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{96} \frac{\ell_i^4 + r_i^4}{x_W^2 (1 - x_W^2)^2 s^2} \left[ \frac{t}{u} + \frac{u}{t} + \frac{4m_Z^2 s}{tu} - m_Z^4 \left( \frac{1}{t^2} + \frac{1}{u^2} \right) \right]. \quad (51.29)$$

## 51.5 Production of Higgs Bosons

### 51.5.1 Resonant Production

The Higgs boson of the Standard Model can be produced resonantly in the collisions of quarks, leptons,  $W$  or  $Z$  bosons, gluons, or photons. The production cross section is thus controlled by the partial width of the Higgs boson into the entrance channel and its total width. The partial widths are given by the relations

$$\Gamma(H \rightarrow f\bar{f}) = \frac{G_F m_f^2 m_H N_c}{4\pi\sqrt{2}} (1 - 4m_f^2/m_H^2)^{3/2}, \quad (51.30)$$

$$\Gamma(H \rightarrow W^+W^-) = \frac{G_F m_H^3 \beta_W}{32\pi\sqrt{2}} (4 - 4a_W + 3a_W^2), \quad (51.31)$$

$$\Gamma(H \rightarrow ZZ) = \frac{G_F m_H^3 \beta_Z}{64\pi\sqrt{2}} (4 - 4a_Z + 3a_Z^2). \quad (51.32)$$

where  $N_c$  is 3 for quarks and 1 for leptons and where  $a_W = 1 - \beta_W^2 = 4m_W^2/m_H^2$  and  $a_Z = 1 - \beta_Z^2 = 4m_Z^2/m_H^2$ . The decay to two gluons proceeds through quark loops, with the  $t$  quark dominating. Explicitly,

$$\Gamma(H \rightarrow gg) = \frac{\alpha_s^2 G_F m_H^3}{36\pi^3 \sqrt{2}} \left| \sum_q I(m_q^2/m_H^2) \right|^2, \quad (51.33)$$

where  $I(z)$  is complex for  $z < 1/4$ . For  $z < 2 \times 10^{-3}$ ,  $|I(z)|$  is small so the light quarks contribute negligibly. For  $m_H < 2m_t$ ,  $z > 1/4$  and

$$I(z) = 3 \left[ 2z + 2z(1-4z) \left( \sin^{-1} \frac{1}{2\sqrt{z}} \right)^2 \right], \quad (51.34)$$

which has the limit  $I(z) \rightarrow 1$  as  $z \rightarrow \infty$ .

### 51.5.2 Higgs Boson Production in $W^*$ and $Z^*$ decay

The Standard Model Higgs boson can be produced in the decay of a virtual  $W$  or  $Z$  ("Higgstrahlung"): In particular, if  $k$  is the c.m. momentum of the Higgs boson,

$$\sigma(q_i \bar{q}_j \rightarrow WH) = \frac{\pi \alpha^2 |V_{ij}|^2}{36 \sin^4 \theta_W} \frac{2k}{\sqrt{s}} \frac{k^2 + 3m_W^2}{(s - m_W^2)^2} \quad (51.35)$$

$$\sigma(f \bar{f} \rightarrow ZH) = \frac{2\pi \alpha^2 (\ell_f^2 + r_f^2)}{48 N_c \sin^4 \theta_W \cos^4 \theta_W} \frac{2k}{\sqrt{s}} \frac{k^2 + 3m_Z^2}{(s - m_Z^2)^2}. \quad (51.36)$$

where  $\ell$  and  $r$  are defined as above.

### 51.5.3 $W$ and $Z$ Fusion

Just as high-energy electrons can be regarded as sources of virtual photon beams, at very high energies they are sources of virtual  $W$  and  $Z$  beams. For Higgs boson production, it is the longitudinal components of the  $W$ s and  $Z$ s that are important. The distribution of longitudinal  $W$ s carrying a fraction  $y$  of the electron's energy is

$$f(y) = \frac{g^2}{16\pi^2} \frac{1-y}{y}, \quad (51.37)$$

where  $g = e/\sin \theta_W$ . In the limit  $s \gg m_H \gg m_W$ , the rate  $\Gamma(H \rightarrow W_L W_L) = (g^2/64\pi)(m_H^3/m_W^2)$  and in the equivalent  $W$  approximation

$$\begin{aligned} \sigma(e^+ e^- \rightarrow \bar{\nu}_e \nu_e H) &= \frac{1}{16m_W^2} \left( \frac{\alpha}{\sin^2 \theta_W} \right)^3 \\ &\times \left[ \left( 1 + \frac{m_H^2}{s} \right) \log \frac{s}{m_H^2} - 2 + 2 \frac{m_H^2}{s} \right]. \end{aligned} \quad (51.38)$$

There are significant corrections to this relation when  $m_H$  is not large compared to  $m_W$ . For  $m_H = 150$  GeV, the estimate is too high by 51% for  $\sqrt{s} = 1000$  GeV, 32% too high at  $\sqrt{s} = 2000$  GeV, and 22% too high at  $\sqrt{s} = 4000$  GeV. Fusion of  $ZZ$  to make a Higgs boson can be treated similarly. Identical formulae apply for Higgs production in the collisions of quarks whose charges permit the emission of a  $W^+$  and a  $W^-$ , except that QCD corrections and CKM matrix elements are required. Even in the absence of QCD corrections, the fine-structure constant ought to be evaluated at the scale of the collision, say  $m_W$ . All quarks contribute to the  $ZZ$  fusion process. <sup>1</sup>

<sup>1</sup>Further discussion and all references may be found in the full *Review*; the equation and reference numbering corresponds to that version.



## 52. Neutrino Cross Section Measurements

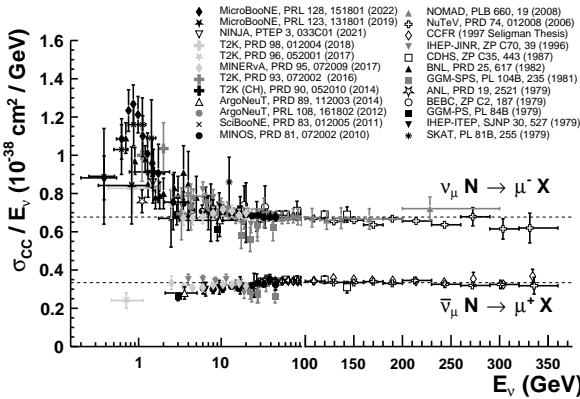
Revised August 2023 by G.P. Zeller (FNAL).

Highlights from full review.

Neutrino cross sections are an essential ingredient in all neutrino experiments. The table and plot below summarize accelerator-based neutrino cross section measurements performed in the  $\sim 0.1 - 300$  GeV range that are of particular interest to short and long distance neutrino oscillation physics.

**Table 52.1:** List of experiment names, beam properties, nuclear targets, and durations for modern accelerator-based neutrino experiments studying neutrino-nucleus scattering.

Experiment	beam	$\langle E_\nu \rangle, \langle E_{\bar{\nu}} \rangle$ (GeV)	neutrino target(s)	run period
ArgoNeuT	$\nu, \bar{\nu}$	4.3, 3.6	Ar	2009 – 2010
FASEP	$\nu, \bar{\nu}$	$> 200$	W, emulsion	2021 –
ICARUS (CNGS)	$\nu$	20	Ar	2010 – 2012
ICARUS (FNAL)	$\nu$	0.8	Ar	2021 –
K2K	$\nu$	1.3	CH, H <sub>2</sub> O	2003 – 2004
MicroBooNE	$\nu$	0.8	Ar	2015 – 2020
MINERvA	$\nu, \bar{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H <sub>2</sub> O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu, \bar{\nu}$	0.8, 0.7	CH <sub>2</sub>	2002 – 2019
MINOS	$\nu, \bar{\nu}$	3.5, 6.1	Fe	2004 – 2016
NINJA	$\nu, \bar{\nu}$	0.6, 0.6	Fe, emulsion	2015 –
NOMAD	$\nu, \bar{\nu}$	23.4, 19.7	C	1995 – 1998
NOvA	$\nu, \bar{\nu}$	2.0, 2.0	CH <sub>2</sub>	2010 –
SBND	$\nu$	0.8	Ar	2024 –
SciBooNE	$\nu, \bar{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	$\nu, \bar{\nu}$	0.6, 0.6	CH, H <sub>2</sub> O, Fe	2010 –



**Figure 52.1:** Measurements of per nucleon  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV.

## 6. Atomic and Nuclear Properties of Materials

**Table 6.1:** Abridged from <https://pdg.lbl.gov/atomicNuclearProperties> by D.E. Groom (2023). See web pages for more detail about entries in this table and for several hundred others. Quantities in parentheses are for gases at 20° C and 1 atm. Boiling points are at 1 atm. Refractive indices  $n$  are evaluated at the sodium D line blend (589.2 nm); values  $\gg 1$  in brackets indicate  $(n - 1) \times 10^6$  for gases at 0° C and 1 atm.

Material	Z	A	(Z/A)	Nucl.coll. length $\lambda_T$ {g cm <sup>-2</sup> }	Nucl.inter. length $\lambda_I$ {g cm <sup>-2</sup> }	Rad.len. $X_0$ {g cm <sup>-2</sup> }	$dE/dx _{min}$ {MeV g <sup>-1</sup> cm <sup>2</sup> }	Density {g cm <sup>-3</sup> } {(g $\ell^{-1}$ )}	Melting point (K)	Boiling point (K)	Refract. index @ Na D
H <sub>2</sub>	1	1.008(7)	0.99212	42.8	52.0	63.05	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D <sub>2</sub>	1	2.014101764(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.94(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.0121831(5)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.419
C graphite	6	12.0107(8)	0.49976	61.1	85.8	42.70	1.742	2.210			
N <sub>2</sub>	7	14.007(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O <sub>2</sub>	8	15.999(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F <sub>2</sub>	9	18.998403163(6)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815385(7)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl <sub>2</sub>	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ce	32	72.630(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(5)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	

Material	$(Z/A)$	Nucl.coll. length $\lambda_T$ {g cm <sup>-2</sup> }	Nucl.inter. length $\lambda_I$ {g cm <sup>-2</sup> }	Rad.len. $X_0$ {g cm <sup>-2</sup> }	$dE/dx _{\min}$ {MeV g <sup>-1</sup> cm <sup>2</sup> }	Density {g cm <sup>-3</sup> }	Melting point (K)	Boiling point (K)	Refract. index @ Na D
Air (dry, 1 atm)	0.49919	61.3	90.1	36.62	(1.815)	(1.205)		78.80	[289]
Shielding concrete	0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)	0.49707	64.6	96.5	28.17	1.696	2.230			
Lead glass SF5	0.44522	84.0	133.4	10.07	1.406	4.080			1.6727
Standard rock	0.50000	66.8	101.3	26.54	1.688	2.650			
Methane (CH <sub>4</sub> )	0.62334	54.0	73.8	46.47	(2.417)	(0.667)	90.68	111.7	[444.]
Ethane (C <sub>2</sub> H <sub>6</sub> )	0.59861	55.0	75.9	45.66	(2.304)	(1.263)	90.36	184.5	
Propane (C <sub>3</sub> H <sub>8</sub> )	0.58962	55.3	76.7	45.37	(2.262)	0.493(1.868)	85.52	231.0	
Butane (C <sub>4</sub> H <sub>10</sub> )	0.59497	55.5	77.1	45.23	(2.278)	(2.489)	134.9	272.6	
Octane (C <sub>8</sub> H <sub>18</sub> )	0.57778	55.8	77.8	45.00	2.123	0.703	214.4	398.8	
Paraffin (C <sub>8</sub> H <sub>2</sub> (CH <sub>2</sub> ) <sub>n</sub> ≈23CH <sub>3</sub> )	0.57275	56.0	78.3	44.85	2.088	0.930			
Nylon (type 6, 6/6)	0.54790	57.5	81.6	41.92	1.973	1.18			
Polycarbonate (Lexan)	0.52697	58.3	83.6	41.50	1.886	1.20			
Polyethylene ((CH <sub>2</sub> CH <sub>2</sub> ) <sub>n</sub> )	0.57034	56.1	78.5	44.77	2.079	0.89			
Polyethylene terephthalate (Mylar)	0.52037	58.9	84.9	39.95	1.848	1.40			
Polyimide film (Kapton)	0.51264	59.2	85.5	40.58	1.820	1.42			
Polydimethylacrylate (acrylic)	0.53937	58.1	82.8	40.55	1.929	1.19			1.49
Polystyrene	0.55998	56.1	78.5	44.77	2.041	0.90			
Polystyrene ([C <sub>6</sub> H <sub>5</sub> CHCH <sub>2</sub> ] <sub>n</sub> )	0.53768	57.5	81.7	43.79	1.936	1.06			1.59
Polytetrafluoroethylene (Teflon)	0.47992	63.5	94.4	34.84	1.671	2.20			
Polyvinyltoluene	0.54141	57.3	81.3	43.90	1.956	1.03			1.58
Aluminum oxide (sapphire)	0.49038	65.5	98.4	27.94	1.647	3.970	2327.	3273.	1.77
Barium fluoride (BaF <sub>2</sub> )	0.42207	90.8	149.0	9.91	1.303	4.893	1641.	2533.	1.47
Bismuth germanate (BGO)	0.42065	96.2	159.1	7.97	1.251	7.130	1317.		2.15
Carbon dioxide gas (CO <sub>2</sub> )	0.49989	60.7	88.9	36.20	1.819	(1.842)			[449.]
Solid carbon dioxide (dry ice)	0.49989	60.7	88.9	36.20	1.787	1.563		Sublimes at 194.7 K	
Cesium iodide (CsI)	0.41569	100.6	171.5	8.39	1.243	4.510	894.2	1553.	1.79
Lithium fluoride (LiF)	0.46262	61.0	88.7	39.26	1.614	2.635	1121.	1946.	1.39
Lithium hydride (LiH)	0.50321	50.8	68.1	79.62	1.897	0.820	965.		
Lead tungstate (PbWO <sub>4</sub> )	0.41315	100.6	168.3	7.39	1.229	8.300	1403.		2.20
Silicon dioxide (SiO <sub>2</sub> , fused quartz)	0.49930	65.2	97.8	27.05	1.699	2.200	1986.	3223.	1.46
Sodium chloride (NaCl)	0.47910	71.2	110.1	21.91	1.847	2.170	1075.	1738.	1.54
Sodium iodide (NaI)	0.42697	93.1	154.6	9.49	1.305	3.667	933.2	1577.	1.77
Water (H <sub>2</sub> O)	0.55509	58.5	83.3	36.08	1.992	1.000	273.1	373.1	1.33
Silica aerogel	0.50093	65.0	97.3	27.25	1.740	0.200	(0.03 H <sub>2</sub> O, 0.97 SiO <sub>2</sub> )		
Epoxy (Epotek-301-1)	0.53409	58.1	83.0	41.22	1.925	1.190			
G10	0.51166	56.8	78.4	32.17	1.762	1.800			

## Notes







2024

JULY			AUGUST			SEPTEMBER		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		
OCTOBER			NOVEMBER			DECEMBER		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		

2025

JULY			AUGUST			SEPTEMBER		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		
OCTOBER			NOVEMBER			DECEMBER		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		

2025

JANUARY			FEBRUARY			MARCH		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		
APRIL			MAY			JUNE		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		

2026

JANUARY			FEBRUARY			MARCH		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		
APRIL			MAY			JUNE		
S	M	T	S	M	T	S	M	T
1	2	3	1	2	3	1	2	3
4	5	6	4	5	6	4	5	6
7	8	9	7	8	9	7	8	9
10	11	12	10	11	12	10	11	12
13	14	15	13	14	15	13	14	15
16	17	18	16	17	18	16	17	18
19	20	21	19	20	21	19	20	21
22	23	24	22	23	24	22	23	24
25	26	27	25	26	27	25	26	27
28	29	30	28	29	30	28	29	30
31			31			31		