

# STRANGE MESONS

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

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

 **$K^\pm$** 

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

$$\text{Mass } m = 493.677 \pm 0.016 \text{ MeV} \text{ [a]} \quad (S = 2.8)$$

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

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

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

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

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

### 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 $g$ [c]

(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 [d,e]

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

$$\lambda_+(K_{e3}^+) = (2.956 \pm 0.025) \times 10^{-2}$$

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

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

$K_{e3}$  form factor quadratic fit

$$\lambda'_+(K_{e3}^\pm) \text{ linear coeff.} = (2.59 \pm 0.04) \times 10^{-2}$$

$$\lambda''_+(K_{e3}^\pm) \text{ quadratic coeff.} = (0.186 \pm 0.021) \times 10^{-2}$$

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

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

$$M_V \text{ (VECTOR POLE MASS FOR } K_{e3}^\pm \text{ DECAY)} = 890.3 \pm 2.8 \text{ MeV}$$

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

$$M_S \text{ (SCALAR POLE MASS FOR } K_{\mu 3}^\pm \text{ DECAY)} = 1215 \pm 50 \text{ MeV}$$

$$\Lambda_+ \text{ (DISPERSIVE VECTOR FORM FACTOR IN } K_{e3}^\pm \text{ DECAY)} = (2.460 \pm 0.017) \times 10^{-2}$$

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

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

$$K_{e3}^+ \quad |f_S/f_+| = (-0.08^{+0.34}_{-0.40}) \times 10^{-2}$$

$$K_{e3}^+ \quad |f_T/f_+| = (-1.2^{+1.3}_{-1.1}) \times 10^{-2}$$

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

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

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

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

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

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

### Charge radius

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

### Forward-backward asymmetry

$$A_{FB}(K_{\pi\mu\mu}^\pm) = \frac{\Gamma(\cos(\theta_{K\mu}) > 0) - \Gamma(\cos(\theta_{K\mu}) < 0)}{\Gamma(\cos(\theta_{K\mu}) > 0) + \Gamma(\cos(\theta_{K\mu}) < 0)} < 2.3 \times 10^{-2}, \text{ CL} = 90\%$$

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

<b><math>K^+</math> DECAY MODES</b>	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 $K_{e3}^+$ .			
$\pi^0 \mu^+ \nu_\mu$	( $3.352 \pm 0.033$ ) %	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>			
$\mu^+ \nu_\mu \gamma$	[f,g] ( $6.2 \pm 0.8$ ) $\times 10^{-3}$		236
$\mu^+ \nu_\mu \gamma$ (SD <sup>+</sup> )	[d,h] ( $1.33 \pm 0.22$ ) $\times 10^{-5}$		–
$\mu^+ \nu_\mu \gamma$ (SD <sup>+</sup> INT)	[d,h] < 2.7 $\times 10^{-5}$	CL=90%	–
$\mu^+ \nu_\mu \gamma$ (SD <sup>-</sup> + SD <sup>-</sup> INT)	[d,h] < 2.6 $\times 10^{-4}$	CL=90%	–
$e^+ \nu_e \gamma$	( $9.4 \pm 0.4$ ) $\times 10^{-6}$		247
$\pi^0 e^+ \nu_e \gamma$	[f,g] ( $2.66 \pm 0.09$ ) $\times 10^{-4}$		228
$\pi^0 e^+ \nu_e \gamma$ (SD)	[d,h] < 5.3 $\times 10^{-5}$	CL=90%	228
$\pi^0 \mu^+ \nu_\mu \gamma$	[f,g] ( $1.25 \pm 0.25$ ) $\times 10^{-5}$		215
$\pi^0 \pi^0 e^+ \nu_e \gamma$	< 5 $\times 10^{-6}$	CL=90%	206
<b>Hadronic modes with photons or <math>\ell\bar{\ell}</math> pairs</b>			
$\pi^+ \pi^0 \gamma$ (INT)	( - 4.2 $\pm 0.9$ ) $\times 10^{-6}$		–
$\pi^+ \pi^0 \gamma$ (DE)	[f,i] ( $6.0 \pm 0.4$ ) $\times 10^{-6}$		205
$\pi^+ \pi^0 e^+ e^-$	( $4.24 \pm 0.14$ ) $\times 10^{-6}$		205
$\pi^+ \pi^0 \pi^0 \gamma$	[f,g] ( $7.6 \begin{smallmatrix} +6.0 \\ -3.0 \end{smallmatrix}$ ) $\times 10^{-6}$		133
$\pi^+ \pi^+ \pi^- \gamma$	[f,g] ( $7.1 \pm 0.5$ ) $\times 10^{-6}$		125
$\pi^+ \gamma \gamma$	[f] ( $1.01 \pm 0.06$ ) $\times 10^{-6}$		227
$\pi^+ 3\gamma$	[f] < 1.0 $\times 10^{-4}$	CL=90%	227
$\pi^+ e^+ e^- \gamma$	( $1.19 \pm 0.13$ ) $\times 10^{-8}$		227

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

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

**Lepton family number (LF), Lepton number (L),  $\Delta S = \Delta Q$  (SQ) violating modes, or  $\Delta S = 1$  weak neutral current (S1) modes**

$\pi^+ \pi^+ e^- \bar{\nu}_e$	SQ	<	1.3	$\times 10^{-8}$	CL=90%	203
$\pi^+ \pi^+ \mu^- \bar{\nu}_\mu$	SQ	<	3.0	$\times 10^{-6}$	CL=95%	151
$\pi^+ e^+ e^-$	S1	(	$3.00 \pm 0.09$	$) \times 10^{-7}$		227
$\pi^+ \mu^+ \mu^-$	S1	(	$9.4 \pm 0.6$	$) \times 10^{-8}$	S=2.6	172
$\pi^+ \nu \bar{\nu}$	S1	(	$1.14$	$\begin{matrix} +0.40 \\ -0.33 \end{matrix}$	$) \times 10^{-10}$	227
$\pi^+ \pi^0 \nu \bar{\nu}$	S1	<	4.3	$\times 10^{-5}$	CL=90%	205
$\mu^- \nu e^+ e^+$	LF	<	2.1	$\times 10^{-8}$	CL=90%	236
$\mu^+ \nu_e$	LF	[j] <	4	$\times 10^{-3}$	CL=90%	236
$\pi^+ \mu^+ e^-$	LF	<	1.3	$\times 10^{-11}$	CL=90%	214
$\pi^+ \mu^- e^+$	LF	<	6.6	$\times 10^{-11}$	CL=90%	214
$\pi^- \mu^+ e^+$	L	<	4.2	$\times 10^{-11}$	CL=90%	214
$\pi^- e^+ e^+$	L	<	2.2	$\times 10^{-10}$	CL=90%	227
$\pi^- \mu^+ \mu^+$	L	<	4.2	$\times 10^{-11}$	CL=90%	172
$\mu^+ \bar{\nu}_e$	L	[j] <	3.3	$\times 10^{-3}$	CL=90%	236
$\pi^0 e^+ \bar{\nu}_e$	L	<	3	$\times 10^{-3}$	CL=90%	228
$\pi^+ \gamma$		[k] <	2.3	$\times 10^{-9}$	CL=90%	227



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

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 [e]**

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

**CP-violation parameters**

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

**CPT-violation parameters** [e]

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

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

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

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

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

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

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

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

**$K_S^0$**

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

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

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

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

**CP-violation parameters** [n]

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

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

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

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

$K_S^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Hadronic modes</b>			
$\pi^0 \pi^0$	(30.69 ± 0.05) %		209
$\pi^+ \pi^-$	(69.20 ± 0.05) %		206
$\pi^+ \pi^- \pi^0$	( 3.5 $\begin{smallmatrix} +1.1 \\ -0.9 \end{smallmatrix}$ ) × 10 <sup>-7</sup>		133
<b>Modes with photons or <math>\ell\bar{\ell}</math> pairs</b>			
$\pi^+ \pi^- \gamma$	[g,o] ( 1.79 ± 0.05 ) × 10 <sup>-3</sup>		206
$\pi^+ \pi^- e^+ e^-$	( 4.79 ± 0.15 ) × 10 <sup>-5</sup>		206
$\pi^0 \gamma \gamma$	[o] ( 4.9 ± 1.8 ) × 10 <sup>-8</sup>		230
$\gamma \gamma$	( 2.63 ± 0.17 ) × 10 <sup>-6</sup>	S=3.1	249
<b>Semileptonic modes</b>			
$\pi^\pm e^\mp \nu_e$	[p] ( 7.04 ± 0.08 ) × 10 <sup>-4</sup>		229

**CP violating (CP) and  $\Delta S = 1$  weak neutral current (S1) modes**

$3\pi^0$	CP	< 2.6	$\times 10^{-8}$	CL=90%	139
$\mu^+ \mu^-$	S1	< 2.1	$\times 10^{-10}$	CL=90%	225
$e^+ e^-$	S1	< 9	$\times 10^{-9}$	CL=90%	249
$\pi^0 e^+ e^-$	S1	[o]	$( 3.0 \begin{smallmatrix} +1.5 \\ -1.2 \end{smallmatrix} ) \times 10^{-9}$		230
$\pi^0 \mu^+ \mu^-$	S1		$( 2.9 \begin{smallmatrix} +1.5 \\ -1.2 \end{smallmatrix} ) \times 10^{-9}$		177



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

$$m_{K_L} - m_{K_S}$$

$$= (0.5293 \pm 0.0009) \times 10^{10} \hbar \text{ s}^{-1} \quad (S = 1.3) \quad \text{Assuming } CPT$$

$$= (3.484 \pm 0.006) \times 10^{-12} \text{ MeV} \quad \text{Assuming } CPT$$

$$= (0.5289 \pm 0.0010) \times 10^{10} \hbar \text{ s}^{-1} \quad \text{Not assuming } CPT$$

$$\text{Mean life } \tau = (5.116 \pm 0.021) \times 10^{-8} \text{ s} \quad (S = 1.1)$$

$$c\tau = 15.34 \text{ m}$$

**Slope parameters [c]**

(See Particle Listings for other linear and quadratic coefficients)

$$K_L^0 \rightarrow \pi^+ \pi^- \pi^0: g = 0.678 \pm 0.008 \quad (S = 1.5)$$

$$K_L^0 \rightarrow \pi^+ \pi^- \pi^0: h = 0.076 \pm 0.006$$

$$K_L^0 \rightarrow \pi^+ \pi^- \pi^0: k = 0.0099 \pm 0.0015$$

$$K_L^0 \rightarrow \pi^0 \pi^0 \pi^0: h = (0.6 \pm 1.2) \times 10^{-3}$$

**$K_L$  decay form factors [e]**

Linear parametrization assuming  $\mu$ -e universality

$$\lambda_+(K_{\mu 3}^0) = \lambda_+(K_{e 3}^0) = (2.82 \pm 0.04) \times 10^{-2} \quad (S = 1.1)$$

$$\lambda_0(K_{\mu 3}^0) = (1.38 \pm 0.18) \times 10^{-2} \quad (S = 2.2)$$

Quadratic parametrization assuming  $\mu$ -e universality

$$\lambda'_+(K_{\mu 3}^0) = \lambda'_+(K_{e 3}^0) = (2.40 \pm 0.12) \times 10^{-2} \quad (S = 1.2)$$

$$\lambda''_+(K_{\mu 3}^0) = \lambda''_+(K_{e 3}^0) = (0.20 \pm 0.05) \times 10^{-2} \quad (S = 1.2)$$

$$\lambda_0(K_{\mu 3}^0) = (1.16 \pm 0.09) \times 10^{-2} \quad (S = 1.2)$$

Pole parametrization assuming  $\mu$ -e universality

$$M_V^\mu(K_{\mu 3}^0) = M_V^e(K_{e 3}^0) = 878 \pm 6 \text{ MeV} \quad (S = 1.1)$$

$$M_S^\mu(K_{\mu 3}^0) = 1252 \pm 90 \text{ MeV} \quad (S = 2.6)$$

Dispersive parametrization assuming  $\mu$ -e universality

$$\Lambda_+ = (2.51 \pm 0.06) \times 10^{-2} \quad (S = 1.5)$$

$$\ln(C) = (1.75 \pm 0.18) \times 10^{-1} \quad (S = 2.0)$$

$$\begin{aligned}
 K_{e3}^0 \quad |f_S/f_+| &= (1.5_{-1.6}^{+1.4}) \times 10^{-2} \\
 K_{e3}^0 \quad |f_T/f_+| &= (5_{-5}^{+4}) \times 10^{-2} \\
 K_{\mu 3}^0 \quad |f_T/f_+| &= (12 \pm 12) \times 10^{-2} \\
 K_L \rightarrow \ell^+ \ell^- \gamma, K_L \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-: \alpha_{K^*} &= -0.205 \pm 0.022 \quad (S = 1.8) \\
 K_L^0 \rightarrow \ell^+ \ell^- \gamma, K_L^0 \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-: \alpha_{DIP} &= -1.69 \pm 0.08 \quad (S = 1.7) \\
 K_L \rightarrow \pi^+ \pi^- e^+ e^-: a_1/a_2 &= -0.737 \pm 0.014 \text{ GeV}^2 \\
 K_L \rightarrow \pi^0 2\gamma: a_V &= -0.43 \pm 0.06 \quad (S = 1.5)
 \end{aligned}$$

### **CP-violation parameters** [ $\eta$ ]

$$\begin{aligned}
 A_L &= (0.332 \pm 0.006)\% \\
 |\eta_{00}| &= (2.220 \pm 0.011) \times 10^{-3} \quad (S = 1.8) \\
 |\eta_{+-}| &= (2.232 \pm 0.011) \times 10^{-3} \quad (S = 1.8) \\
 |\epsilon| &= (2.228 \pm 0.011) \times 10^{-3} \quad (S = 1.8) \\
 |\eta_{00}/\eta_{+-}| &= 0.9950 \pm 0.0007 \text{ [q]} \quad (S = 1.6) \\
 \text{Re}(\epsilon'/\epsilon) &= (1.66 \pm 0.23) \times 10^{-3} \text{ [q]} \quad (S = 1.6)
 \end{aligned}$$

Assuming *CPT*

$$\begin{aligned}
 \phi_{+-} &= (43.51 \pm 0.05)^\circ \quad (S = 1.2) \\
 \phi_{00} &= (43.52 \pm 0.05)^\circ \quad (S = 1.3) \\
 \phi_\epsilon = \phi_{\text{SW}} &= (43.52 \pm 0.05)^\circ \quad (S = 1.2) \\
 \text{Im}(\epsilon'/\epsilon) &= -(\phi_{00} - \phi_{+-})/3 = (-0.002 \pm 0.005)^\circ \quad (S = 1.7)
 \end{aligned}$$

Not assuming *CPT*

$$\begin{aligned}
 \phi_{+-} &= (43.4 \pm 0.5)^\circ \quad (S = 1.2) \\
 \phi_{00} &= (43.7 \pm 0.6)^\circ \quad (S = 1.2) \\
 \phi_\epsilon &= (43.5 \pm 0.5)^\circ \quad (S = 1.3) \\
 \text{CP asymmetry } A \text{ in } K_L^0 \rightarrow \pi^+ \pi^- e^+ e^- &= (13.7 \pm 1.5)\% \\
 \beta_{CP} \text{ from } K_L^0 \rightarrow e^+ e^- e^+ e^- &= -0.19 \pm 0.07 \\
 \gamma_{CP} \text{ from } K_L^0 \rightarrow e^+ e^- e^+ e^- &= 0.01 \pm 0.11 \quad (S = 1.6) \\
 j \text{ for } K_L^0 \rightarrow \pi^+ \pi^- \pi^0 &= 0.0012 \pm 0.0008 \\
 f \text{ for } K_L^0 \rightarrow \pi^+ \pi^- \pi^0 &= 0.004 \pm 0.006 \\
 |\eta_{+-\gamma}| &= (2.35 \pm 0.07) \times 10^{-3} \\
 \phi_{+-\gamma} &= (44 \pm 4)^\circ \\
 |\epsilon'_{+-\gamma}|/\epsilon &< 0.3, \text{ CL} = 90\% \\
 |g_{E1}| \text{ for } K_L^0 \rightarrow \pi^+ \pi^- \gamma &< 0.21, \text{ CL} = 90\%
 \end{aligned}$$

**T-violation parameters**

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

**CPT invariance tests**

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

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

**$\Delta S = -\Delta Q$  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 $K_{e3}^0$ .	[p] (40.55 $\pm$ 0.11 ) %	S=1.7	229
$\pi^\pm \mu^\mp \nu_\mu$ Called $K_{\mu 3}^0$ .	[p] (27.04 $\pm$ 0.07 ) %	S=1.1	216
$(\pi \mu \text{atom})\nu$	( 1.05 $\pm$ 0.11 ) $\times 10^{-7}$		188
$\pi^0 \pi^\pm e^\mp \nu$	[p] ( 5.20 $\pm$ 0.11 ) $\times 10^{-5}$		207
$\pi^\pm e^\mp \nu e^+ e^-$	[p] ( 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 [r] ( 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>			
$\pi^\pm e^\mp \nu_e \gamma$	[g,p,s] ( 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
<b>Hadronic modes with photons or <math>\ell\bar{\ell}</math> pairs</b>			
$\pi^0 \pi^0 \gamma$	< 2.43 $\times 10^{-7}$	CL=90%	209
$\pi^+ \pi^- \gamma$	[g,s] ( 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
$\pi^0 2\gamma$	[s] ( 1.273 $\pm$ 0.033 ) $\times 10^{-6}$		230
$\pi^0 \gamma e^+ e^-$	( 1.62 $\pm$ 0.17 ) $\times 10^{-8}$		230
<b>Other modes with photons or <math>\ell\bar{\ell}</math> pairs</b>			
$2\gamma$	( 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



$e^+ e^- \gamma \gamma$	[s]	$( 5.95 \pm 0.33 ) \times 10^{-7}$	249
$\mu^+ \mu^- \gamma \gamma$	[s]	$( 1.0 \begin{smallmatrix} +0.8 \\ -0.6 \end{smallmatrix} ) \times 10^{-8}$	225

**Charge conjugation  $\times$  Parity (CP) or Lepton Family number (LF) violating modes, or  $\Delta S = 1$  weak neutral current (S1) modes**

$\mu^+ \mu^-$	S1	$( 6.84 \pm 0.11 ) \times 10^{-9}$	225
$e^+ e^-$	S1	$( 9 \begin{smallmatrix} +6 \\ -4 \end{smallmatrix} ) \times 10^{-12}$	249
$\pi^+ \pi^- e^+ e^-$	S1	[s] $( 3.11 \pm 0.19 ) \times 10^{-7}$	206
$\pi^0 \pi^0 e^+ e^-$	S1	$< 6.6 \times 10^{-9}$	CL=90% 209
$\pi^0 \pi^0 \mu^+ \mu^-$	S1	$< 9.2 \times 10^{-11}$	CL=90% 57
$\mu^+ \mu^- e^+ e^-$	S1	$( 2.69 \pm 0.27 ) \times 10^{-9}$	225
$e^+ e^- e^+ e^-$	S1	$( 3.56 \pm 0.21 ) \times 10^{-8}$	249
$\pi^0 \mu^+ \mu^-$	CP,S1	[t] $< 3.8 \times 10^{-10}$	CL=90% 177
$\pi^0 e^+ e^-$	CP,S1	[t] $< 2.8 \times 10^{-10}$	CL=90% 230
$\pi^0 \nu \bar{\nu}$	CP,S1	[u] $< 3.0 \times 10^{-9}$	CL=90% 230
$\pi^0 \pi^0 \nu \bar{\nu}$	S1	$< 8.1 \times 10^{-7}$	CL=90% 209
$e^\pm \mu^\mp$	LF	[p] $< 4.7 \times 10^{-12}$	CL=90% 238
$e^\pm e^\pm \mu^\mp \mu^\mp$	LF	[p] $< 4.12 \times 10^{-11}$	CL=90% 225
$\pi^0 \mu^\pm e^\mp$	LF	[p] $< 7.6 \times 10^{-11}$	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
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**$K_0^*(700)$**

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

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

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

Mass (T-Matrix Pole  $\sqrt{s}$ ) =  $(630-730) - i(260-340)$  MeV

Mass (Breit-Wigner) =  $845 \pm 17$  MeV

Full width (Breit-Wigner) =  $468 \pm 30$  MeV

<b><math>K_0^*(700)</math> DECAY MODES</b>	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 ( $S = 1.9$ )

<b><math>K^*(892)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (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 [v]

<b><math>K_1(1270)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor	$p$ (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
$K\omega$	$(11.0 \pm 2.0) \%$		†
$Kf_0(1370)$	$(3.0 \pm 2.0) \%$		†
$\gamma K^0$	seen		528

 **$K_1(1400)$** 

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

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 ( $\Gamma_i/\Gamma$ )	$p$ (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
$K_0^*(1430)\pi$	not seen	†
$\gamma K^0$	seen	613
$K\phi$	seen	†

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

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

Mass  $m = 1414 \pm 15$  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	$p$ (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
$K\phi$	seen		†

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

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

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

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

<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
$K\eta'(958)$	seen	†

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

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

$K_2^*(1430)^\pm$  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  $\Gamma = 100.0 \pm 2.1$  MeV

$K_2^*(1430)^0$  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

**$K(1460)$** 

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

<b><math>K(1460)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K^*(892)\pi$	seen	—
$K\rho$	seen	—
$K_0^*(1430)\pi$	seen	—
$K\phi$	seen	—

 **$K_1(1650)$** 

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

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  $\Gamma = 322 \pm 110$  MeV (S = 4.2)

<b><math>K^*(1680)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	(38.7±2.5) %	782
$K\rho$	(31.4 <sup>+5.0</sup> <sub>-2.1</sub> ) %	571
$K^*(892)\pi$	(29.9 <sup>+2.2</sup> <sub>-5.0</sub> ) %	618
$K\phi$	seen	387
$K\eta$	( 1.4 <sup>+1.0</sup> <sub>-0.8</sub> ) %	683

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

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

Mass  $m = 1773 \pm 8$  MeV  
 Full width  $\Gamma = 186 \pm 14$  MeV

<b><math>K_2(1770)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi\pi$		794
$K_2^*(1430)\pi$	seen	287
$K^*(892)\pi$	seen	654
$Kf_2(1270)$	seen	53
$K\phi$	seen	441
$K\omega$	seen	607

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

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

Mass  $m = 1779 \pm 8$  MeV (S = 1.2)Full width  $\Gamma = 161 \pm 17$  MeV (S = 1.1)

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

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

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

Mass  $m = 1819 \pm 12$  MeVFull width  $\Gamma = 264 \pm 34$  MeV

<b><math>K_2(1820)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi\pi$	seen	819
$K_2^*(1430)\pi$	seen	328
$K^*(892)\pi$	seen	683
$Kf_2(1270)$	seen	191
$K\omega$	seen	640
$K\phi$	seen	483

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

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

Mass  $m = 1994^{+60}_{-50}$  MeV (S = 2.8)Full width  $\Gamma = 348^{+50}_{-30}$  MeV (S = 1.3)

<b><math>K_2^*(1980)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K^*(892)\pi$	possibly seen	791
$K\rho$	possibly seen	762
$Kf_2(1270)$	possibly seen	424
$K\phi$	seen	627
$K\eta$	seen	850

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

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

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

## NOTES

- [a] See the note in the  $K^\pm$  Particle Listings.
- [b] Neglecting photon channels. See, *e.g.*, A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).
- [c] 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):
- $$|M|^2 = 1 + g(s_3 - s_0)/m_{\pi^+}^2 + \dots$$
- [d] See the review on “Form Factors for Radiative Pion and Kaon Decays” for definitions and details.
- [e] For more details and definitions of parameters see the Particle Listings.
- [f] See the  $K^\pm$  Particle Listings for the energy limits used in this measurement.
- [g] Most of this radiative mode, the low-momentum  $\gamma$  part, is also included in the parent mode listed without  $\gamma$ 's.
- [h] Structure-dependent part.
- [i] Direct-emission branching fraction.
- [j] Derived from an analysis of neutrino-oscillation experiments.
- [k] Violates angular-momentum conservation.
- [l] 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.”
- [n] 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):

$$\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} = \frac{A(K_L^0 \rightarrow \pi^+ \pi^-)}{A(K_S^0 \rightarrow \pi^+ \pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = \frac{A(K_L^0 \rightarrow \pi^0 \pi^0)}{A(K_S^0 \rightarrow \pi^0 \pi^0)} = \epsilon - 2\epsilon'$$

$$\delta = \frac{\Gamma(K_L^0 \rightarrow \pi^- \ell^+ \nu) - \Gamma(K_L^0 \rightarrow \pi^+ \ell^- \nu)}{\Gamma(K_L^0 \rightarrow \pi^- \ell^+ \nu) + \Gamma(K_L^0 \rightarrow \pi^+ \ell^- \nu)},$$

$$\text{Im}(\eta_{+-0})^2 = \frac{\Gamma(K_S^0 \rightarrow \pi^+ \pi^- \pi^0)^{CP \text{ viol.}}}{\Gamma(K_L^0 \rightarrow \pi^+ \pi^- \pi^0)},$$

$$\text{Im}(\eta_{000})^2 = \frac{\Gamma(K_S^0 \rightarrow \pi^0 \pi^0 \pi^0)}{\Gamma(K_L^0 \rightarrow \pi^0 \pi^0 \pi^0)}.$$

where for the last two relations *CPT* is assumed valid, *i.e.*,  $\text{Re}(\eta_{+-0}) \simeq 0$  and  $\text{Re}(\eta_{000}) \simeq 0$ .

- [o] See the  $K_S^0$  Particle Listings for the energy limits used in this measurement.
- [p] The value is for the sum of the charge states or particle/antiparticle states indicated.
- [q]  $\text{Re}(\epsilon'/\epsilon) = \epsilon'/\epsilon$  to a very good approximation provided the phases satisfy *CPT* invariance.
- [r] This mode includes gammas from inner bremsstrahlung but not the direct emission mode  $K_L^0 \rightarrow \pi^+ \pi^- \gamma(\text{DE})$ .
- [s] See the  $K_L^0$  Particle Listings for the energy limits used in this measurement.
- [t] Allowed by higher-order electroweak interactions.
- [u] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.
- [v] Our estimate. See the Particle Listings for details.
- [x] See our minireview under the  $K_2(1770)$  in the 2004 edition of this *Review*.