# $\mu$

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

## $\mu$ MASS (atomic mass units u)

The primary determination of a muon's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the muon in u. In this datablock we give the result in u, and in the following datablock in MeV.

| *VALUE* (u) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **0.1134289168±0.0000000034** | [1] MOHR | 99 | RVUE | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.113428913 ±0.000000017 | [2] COHEN | 87 | RVUE | 1986 CODATA value |

[1] MOHR 99 make use of other 1998 CODATA entries below.
[2] COHEN 87 make use of other 1986 CODATA entries below.

## $\mu$ MASS

The conversion from u (atomic mass units, see the above datablock) to MeV is 931.494013 ± 0.000037 MeV/u. The conversion error dominates the precision quoted in the following entry.

Where $m_\mu/m_e$ was measured, we have used the 1986 CODATA value of $m_e$= 0.51099906 ± 0.00000015 MeV.

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|
| **105.6583568±0.0000052** | MOHR | 99 | RVUE | | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 105.658353 ±0.000016 | [3] COHEN | 87 | RVUE | | 1986 CODATA value |
| 105.658386 ±0.000044 | [4] MARIAM | 82 | CNTR | + | |
| 105.65836 ±0.00026 | [5] CROWE | 72 | CNTR | | |
| 105.65865 ±0.00044 | [6] CRANE | 71 | CNTR | | |

[3] Converted to MeV using the 1998 CODATA value of the conversion constant, 931.494013 ± 0.0000037 MeV/u.
[4] MARIAM 82 give $m_\mu/m_e$ = 206.768259(62).
[5] CROWE 72 give $m_\mu/m_e$ = 206.7682(5).
[6] CRANE 71 give $m_\mu/m_e$ = 206.76878(85).

## $\mu$ MEAN LIFE $\tau$

Measurements with an error $>$ $0.001 \times 10^{-6}$ s have been omitted.

| *VALUE* ($10^{-6}$ s) | *DOCUMENT ID* | | *TECN* | *CHG* |
|---|---|---|---|---|
| **2.19703 ±0.00004 OUR AVERAGE** | | | | |
| 2.197078±0.000073 | BARDIN | 84 | CNTR | + |
| 2.197025±0.000155 | BARDIN | 84 | CNTR | − |
| 2.19695 ±0.00006 | GIOVANETTI | 84 | CNTR | + |
| 2.19711 ±0.00008 | BALANDIN | 74 | CNTR | + |
| 2.1973 ±0.0003 | DUCLOS | 73 | CNTR | + |

## $\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of *CPT* invariance.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **1.000024±0.000078** | BARDIN | 84 | CNTR | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1.0008 ±0.0010 | BAILEY | 79 | CNTR | Storage ring |
| 1.000 ±0.001 | MEYER | 63 | CNTR | Mean life $\mu^+$/ $\mu^-$ |

## $(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$

A test of *CPT* invariance. Calculated from the mean-life ratio, above.

| *VALUE* | *DOCUMENT ID* |
|---|---|
| **$(2\pm8) \times 10^{-5}$ OUR EVALUATION** | |

## $\mu/p$ MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass and to reduce experimental muon Larmor frequency measurements to the muon magnetic moment anomaly. Measurements with an error $>$ 0.00001 have been omitted.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|
| **3.18334539±0.00000010** | [7] MOHR | 99 | RVUE | | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 3.18334513±0.00000039 | LIU | 99 | CNTR | + | HFS in muonium |
| 3.18334547±0.00000047 | [7] COHEN | 87 | RVUE | | 1986 CODATA value |
| 3.1833441 ±0.0000017 | KLEMPT | 82 | CNTR | + | Precession strob |
| 3.1833461 ±0.0000011 | MARIAM | 82 | CNTR | + | HFS splitting |
| 3.1833448 ±0.0000029 | CAMANI | 78 | CNTR | + | See KLEMPT 82 |
| 3.1833403 ±0.0000044 | CASPERSON | 77 | CNTR | + | HFS splitting |
| 3.1833402 ±0.0000072 | COHEN | 73 | RVUE | | 1973 CODATA value |
| 3.1833467 ±0.0000082 | CROWE | 72 | CNTR | + | Precession phase |

[7] CODATA values fitted using their selection of data, plus other data from multiparameter fits.

# $\mu$ MAGNETIC MOMENT ANOMALY

The parity-violating decay of muons in a storage ring is observed. The difference frequency $\omega_a$ between the muon spin precision and the orbital angular frequency $(e/m_\mu c)\langle B\rangle$ is measured, as is the free proton NMR frequency $\omega_p$, thus determining the ratio $R=\omega_a/\omega_p$. Given the magnetic moment ratio $\lambda=\mu_\mu/\mu_p$ (from hyperfine structure in muonium), $(g-2)/2 = R/(\lambda-R)$.

The new precision results from the Brookhaven MUG2 Collaboration have inspired reevaluation of the theoretical value. Most of the problem concerns the hadronic contributions. Examples of the present uncertainty in this changing field are two theoretical values presented by A. Nyffeler in his theory review at a March 2003 Moriond Conference: 11659167.4 $\pm$ 7.5 (had) $\pm$4.0 (light-by-light scattering) $\pm$0.35 (QED + EW) using experimental input from $e^+e^-$ around the $\rho$ (CMD-2), and 11659192.6 $\pm$ 5.9 $\pm$ 4.0 $\pm$ 0.35 from precision $\tau$ decay studies (ALEPH).

## $\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

| *VALUE* (units $10^{-10}$) | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|
| **11659203$\pm$ 7 OUR AVERAGE** | | | | | |
| 11659204$\pm$ 7$\pm$5 | BENNETT | 02 | MUG2 | + | Storage ring |
| 11659202$\pm$ 14$\pm$6 | BROWN | 01 | MUG2 | + | Storage ring |
| 11659191$\pm$ 59 | BROWN | 00 | MUG2 | + | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 11659100$\pm$ 110 | [8] BAILEY | 79 | CNTR | + | Storage ring |
| 11659360$\pm$ 120 | [8] BAILEY | 79 | CNTR | $-$ | Storage ring |
| 11659230$\pm$ 85 | [8] BAILEY | 79 | CNTR | $\pm$ | Storage ring |
| 11620000$\pm$5000 | CHARPAK | 62 | CNTR | + | |

[8] BAILEY 79 values recalculated by HUGHES 99 using the COHEN 87 $\mu/p$ magnetic moment. The improved MOHR 99 value does not change the result.

## $(g_{\mu^+} - g_{\mu^-})\ /\ g_{\text{average}}$

A test of *CPT* invariance.

| *VALUE* (units $10^{-8}$) | *DOCUMENT ID* | |
|---|---|---|
| **$-$2.6$\pm$1.6** | BAILEY | 79 |

# $\mu$ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

| *VALUE* ($10^{-19}$ ecm) | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|
| **3.7$\pm$3.4** | [9] BAILEY | 78 | CNTR | $\pm$ | Storage ring |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 8.6$\pm$4.5 | BAILEY | 78 | CNTR | + | Storage rings |
| 0.8$\pm$4.3 | BAILEY | 78 | CNTR | $-$ | Storage rings |

[9] This is the combination of the two BAILEY 78 results given below.

## MUON-ELECTRON CHARGE RATIO ANOMALY $q_{\mu^+}/q_{e^-} + 1$

| *VALUE* | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|
| **(1.1±2.1) × 10$^{-9}$** | [10] MEYER | 00 | CNTR | + | 1s–2s muonium interval |

[10] MEYER 00 measure the 1s–2s muonium interval, and then interpret the result in terms of muon-electron charge ratio $q_{\mu^+}/q_{e^-}$.

## $\mu^-$ DECAY MODES

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

| | Mode | | | Fraction ($\Gamma_i/\Gamma$) | | Confidence level |
|---|---|---|---|---|---|---|
| $\Gamma_1$ | $e^- \overline{\nu}_e \nu_\mu$ | | | $\approx$ 100% | | |
| $\Gamma_2$ | $e^- \overline{\nu}_e \nu_\mu \gamma$ | | [a] | (1.4±0.4) % | | |
| $\Gamma_3$ | $e^- \overline{\nu}_e \nu_\mu e^+ e^-$ | | [b] | (3.4±0.4) $\times 10^{-5}$ | | |
| | **Lepton Family number (*LF*) violating modes** | | | | | |
| $\Gamma_4$ | $e^- \nu_e \overline{\nu}_\mu$ | *LF* | [c] | < 1.2 | % | 90% |
| $\Gamma_5$ | $e^- \gamma$ | *LF* | | < 1.2 | $\times 10^{-11}$ | 90% |
| $\Gamma_6$ | $e^- e^+ e^-$ | *LF* | | < 1.0 | $\times 10^{-12}$ | 90% |
| $\Gamma_7$ | $e^- 2\gamma$ | *LF* | | < 7.2 | $\times 10^{-11}$ | 90% |

[a] This only includes events with the $\gamma$ energy > 10 MeV. Since the $e^- \overline{\nu}_e \nu_\mu$ and $e^- \overline{\nu}_e \nu_\mu \gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[b] See the Particle Listings below for the energy limits used in this measurement.

[c] A test of additive vs. multiplicative lepton family number conservation.

## $\mu^-$ BRANCHING RATIOS

### $\Gamma(e^- \overline{\nu}_e \nu_\mu \gamma)/\Gamma_{total}$ — $\Gamma_2/\Gamma$

| *VALUE* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **0.014 ±0.004** | | CRITTENDEN | 61 | CNTR | $\gamma$ KE > 10 MeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | 862 | BOGART | 67 | CNTR | $\gamma$ KE > 14.5 MeV |
| 0.0033±0.0013 | | CRITTENDEN | 61 | CNTR | $\gamma$ KE > 20 MeV |
| | 27 | ASHKIN | 59 | CNTR | |

### $\Gamma(e^- \overline{\nu}_e \nu_\mu e^+ e^-)/\Gamma_{total}$ — $\Gamma_3/\Gamma$

| *VALUE* (units $10^{-5}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|---|
| **3.4±0.2±0.3** | 7443 | [11] BERTL | 85 | SPEC | + | SINDRUM |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | | | |
|---|---|---|---|---|---|---|
| 2.2±1.5 | 7 | [12] CRITTENDEN | 61 | HLBC | + | $E(e^+ e^-)>10$ MeV |
| 2 | 1 | [13] GUREVICH | 60 | EMUL | + | |
| 1.5±1.0 | 3 | [14] LEE | 59 | HBC | + | |

[11] BERTL 85 has transverse momentum cut $p_T > 17$ MeV/$c$. Systematic error was increased by us.

[12] CRITTENDEN 61 count only those decays where total energy of either ($e^+$, $e^-$) combination is >10 MeV.

[13] GUREVICH 60 interpret their event as either virtual or real photon conversion. $e^+$ and $e^-$ energies not measured.

[14] In the three LEE 59 events, the sum of energies E($e^+$) + E($e^-$) + E($e^+$) was 51 MeV, 55 MeV, and 33 MeV.

## $\Gamma(e^- \nu_e \overline{\nu}_\mu)/\Gamma_{\text{total}}$ — $\Gamma_4/\Gamma$

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

| VALUE | CL% | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **< 0.012** | 90 | [15] FREEDMAN | 93 | CNTR | + | $\nu$ oscillation search |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| < 0.018 | 90 | KRAKAUER | 91B | CALO | + | |
| < 0.05 | 90 | [16] BERGSMA | 83 | CALO | | $\overline{\nu}_\mu e \to \mu^- \overline{\nu}_e$ |
| < 0.09 | 90 | JONKER | 80 | CALO | | See BERGSMA 83 |
| −0.001±0.061 | | WILLIS | 80 | CNTR | + | |
| 0.13 ±0.15 | | BLIETSCHAU | 78 | HLBC | ± | Avg. of 4 values |
| < 0.25 | 90 | EICHTEN | 73 | HLBC | + | |

[15] FREEDMAN 93 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton family number violation.

[16] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \to \mu^- \overline{\nu}_e)/\sigma(\nu_\mu e^- \to \mu^- \nu_e)$, which is essentially equivalent to $\Gamma(e^- \nu_e \overline{\nu}_\mu)/\Gamma_{\text{total}}$ for small values like that quoted.

## $\Gamma(e^- \gamma)/\Gamma_{\text{total}}$ — $\Gamma_5/\Gamma$

Forbidden by lepton family number conservation.

| VALUE (units $10^{-11}$) | CL% | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **< 1.2** | 90 | BROOKS | 99 | SPEC | + | LAMPF |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| < 1.2 | 90 | AHMED | 02 | SPEC | + | MEGA |
| < 4.9 | 90 | BOLTON | 88 | CBOX | + | LAMPF |
| <100 | 90 | AZUELOS | 83 | CNTR | + | TRIUMF |
| < 17 | 90 | KINNISON | 82 | SPEC | + | LAMPF |
| <100 | 90 | SCHAAF | 80 | ELEC | + | SIN |

## $\Gamma(e^- e^+ e^-)/\Gamma_{\text{total}}$ — $\Gamma_6/\Gamma$

Forbidden by lepton family number conservation.

| VALUE (units $10^{-12}$) | CL% | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **< 1.0** | 90 | [17] BELLGARDT | 88 | SPEC | + | SINDRUM |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | | | |
|---|---|---|---|---|---|---|
| $<$ 36 | 90 | BARANOV | 91 | SPEC | + | ARES |
| $<$ 35 | 90 | BOLTON | 88 | CBOX | + | LAMPF |
| $<$ 2.4 | 90 | [17] BERTL | 85 | SPEC | + | SINDRUM |
| $<$160 | 90 | [17] BERTL | 84 | SPEC | + | SINDRUM |
| $<$130 | 90 | [17] BOLTON | 84 | CNTR | | LAMPF |

[17] These experiments assume a constant matrix element.

### $\Gamma(e^- 2\gamma)/\Gamma_{\rm total}$ — $\Gamma_7/\Gamma$

Forbidden by lepton family number conservation.

| *VALUE* (units $10^{-11}$) | *CL%* | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|---|
| **$<$ 7.2** | 90 | BOLTON | 88 | CBOX | + | LAMPF |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $<$ 840 | 90 | [18] AZUELOS | 83 | CNTR | + | TRIUMF |
| $<$5000 | 90 | [19] BOWMAN | 78 | CNTR | | DEPOMMIER 77 data |

[18] AZUELOS 83 uses the phase space distribution of BOWMAN 78.

[19] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse $\mu$ mass.

## LIMIT ON $\mu^- \rightarrow e^-$ CONVERSION

Forbidden by lepton family number conservation.

### $\sigma(\mu^-\,{}^{32}\mathrm{S} \rightarrow e^-\,{}^{32}\mathrm{S})$ / $\sigma(\mu^-\,{}^{32}\mathrm{S} \rightarrow \nu_\mu\,{}^{32}\mathrm{P}^*)$

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$<7 \times 10^{-11}$** | 90 | BADERT... | 80 | STRC | SIN |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<4 \times 10^{-10}$ | 90 | BADERT... | 77 | STRC | SIN |

### $\sigma(\mu^-\,\mathrm{Cu} \rightarrow e^-\,\mathrm{Cu})$ / $\sigma(\mu^-\,\mathrm{Cu} \rightarrow \text{capture})$

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<1.6 \times 10^{-8}$ | 90 | BRYMAN | 72 | SPEC |

### $\sigma(\mu^-\,\mathrm{Ti} \rightarrow e^-\,\mathrm{Ti})$ / $\sigma(\mu^-\,\mathrm{Ti} \rightarrow \text{capture})$

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$<4.3 \times 10^{-12}$** | 90 | [20] DOHMEN | 93 | SPEC | SINDRUM II |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<4.6 \times 10^{-12}$ | 90 | AHMAD | 88 | TPC | TRIUMF |
| $<1.6 \times 10^{-11}$ | 90 | BRYMAN | 85 | TPC | TRIUMF |

[20] DOHMEN 93 assumes $\mu^- \rightarrow e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

### $\sigma(\mu^-\,\mathrm{Pb} \rightarrow e^-\,\mathrm{Pb})$ / $\sigma(\mu^-\,\mathrm{Pb} \rightarrow \text{capture})$

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$<4.6 \times 10^{-11}$** | 90 | HONECKER | 96 | SPEC | SINDRUM II |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<4.9 \times 10^{-10}$ | 90 | AHMAD | 88 | TPC | TRIUMF |

## LIMIT ON $\mu^- \rightarrow e^+$ CONVERSION

Forbidden by total lepton number conservation.

### $\sigma(\mu^- \, ^{32}\text{S} \rightarrow e^+ \, ^{32}\text{Si}^*) \, / \, \sigma(\mu^- \, ^{32}\text{S} \rightarrow \nu_\mu \, ^{32}\text{P}^*)$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<9 × 10$^{-10}$** | 90 | BADERT... | 80 | STRC | SIN |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<1.5 \times 10^{-9}$ | 90 | BADERT... | 78 | STRC | SIN |

### $\sigma(\mu^- \, ^{127}\text{I} \rightarrow e^+ \, ^{127}\text{Sb}^*) \, / \, \sigma(\mu^- \, ^{127}\text{I} \rightarrow \text{anything})$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<3 × 10$^{-10}$** | 90 | [21] ABELA | 80 | CNTR | Radiochemical tech. |

[21] ABELA 80 is upper limit for $\mu^- e^+$ conversion leading to particle-stable states of $^{127}$Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

### $\sigma(\mu^- \text{Cu} \rightarrow e^+ \text{Co}) \, / \, \sigma(\mu^- \text{Cu} \rightarrow \nu_\mu \text{Ni})$

| VALUE | CL% | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2.6 \times 10^{-8}$ | 90 | BRYMAN | 72 | SPEC |
| $<2.2 \times 10^{-7}$ | 90 | CONFORTO | 62 | OSPK |

### $\sigma(\mu^- \text{Ti} \rightarrow e^+ \text{Ca}) \, / \, \sigma(\mu^- \text{Ti} \rightarrow \text{capture})$

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|---|
| **<3.6 × 10$^{-11}$** | 90 | 1 | [22,23] KAULARD | 98 | SPEC | − | SINDRUM II |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| $<1.7 \times 10^{-12}$ | 90 | 1 | [23,24] KAULARD | 98 | SPEC | − | SINDRUM II |
| $<4.3 \times 10^{-12}$ | 90 | | [24] DOHMEN | 93 | SPEC | | SINDRUM II |
| $<8.9 \times 10^{-11}$ | 90 | | [22] DOHMEN | 93 | SPEC | | SINDRUM II |
| $<1.7 \times 10^{-10}$ | 90 | | [25] AHMAD | 88 | TPC | | TRIUMF |

[22] This limit assumes a giant resonance excitation of the daughter Ca nucleus (mean energy and width both 20 MeV).
[23] KAULARD 98 obtained these same limits using the unified classical analysis of FELDMAN 98.
[24] This limit assumes the daughter Ca nucleus is left in the ground state. However, the probability of this is unknown.
[25] Assuming a giant-resonance-excitation model.

## LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

### $R_g = G_C \, / \, G_F$

The effective Lagrangian for the $\mu^+ e^- \rightarrow \mu^- e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2} \, G_C \, [\overline{\psi}_\mu \gamma_\lambda \, (1 - \gamma_5) \, \psi_e] \, [\overline{\psi}_\mu \gamma_\lambda \, (1 - \gamma_5) \, \psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on $G_C/G_F$, where $G_F$ is the Fermi coupling constant.

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|---|
| **< 0.0030** | 90 | 1 | [26] WILLMANN | 99 | SPEC | + | $\mu^+$ at 26 GeV/$c$ |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| < 0.14 | 90 | 1 | [27] GORDEEV | 97 | SPEC | + | JINR phasotron |
| < 0.018 | 90 | 0 | [28] ABELA | 96 | SPEC | + | $\mu^+$ at 24 MeV |
| < 6.9 | 90 | | NI | 93 | CBOX | | LAMPF |
| < 0.16 | 90 | | MATTHIAS | 91 | SPEC | | LAMPF |
| < 0.29 | 90 | | HUBER | 90B | CNTR | | TRIUMF |
| <20 | 95 | | BEER | 86 | CNTR | | TRIUMF |
| <42 | 95 | | MARSHALL | 82 | CNTR | | |

[26] WILLMANN 99 quote both probability $P_{M\overline{M}} < 8.3 \times 10^{-11}$ at 90%CL in a 0.1 T field and $R_g = G_C/G_F$.

[27] GORDEEV 97 quote limits on both $f = G_{MM}/GF$ and the probability $W_{MM} < 4.7 \times 10^{-7}$ (90%CL).

[28] ABELA 96 quote both probability $P_{M\overline{M}} < 8 \times 10^{-9}$ at 90% CL and $R_g = G_C/G_F$.

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## $\mu$ DECAY PARAMETERS

### $\rho$ PARAMETER

$(V-A)$ theory predicts $\rho = 0.75$.

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **0.7518±0.0026** | | DERENZO | 69 | RVUE | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.762 ±0.008 | 170k | [29] FRYBERGER | 68 | ASPK | + | 25–53 MeV $e^+$ |
| 0.760 ±0.009 | 280k | [29] SHERWOOD | 67 | ASPK | + | 25–53 MeV $e^+$ |
| 0.7503±0.0026 | 800k | [29] PEOPLES | 66 | ASPK | + | 20–53 MeV $e^+$ |

[29] $\eta$ constrained = 0. These values incorporated into a two parameter fit to $\rho$ and $\eta$ by DERENZO 69.

### $\eta$ PARAMETER

$(V-A)$ theory predicts $\eta = 0$.

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **−0.007±0.013 OUR AVERAGE** | | | | | | |
| −0.007±0.013 | 5.3M | [30] BURKARD | 85B | FIT | + | 9–53 MeV $e^+$ |
| −0.12 ±0.21 | 6346 | DERENZO | 69 | HBC | + | 1.6–6.8 MeV $e^+$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| −0.012±0.015±0.003 | 5.3M | [31] BURKARD | 85B | CNTR | + | 9–53 MeV $e^+$ |
| 0.011±0.081±0.026 | 5.3M | BURKARD | 85B | CNTR | + | 9–53 MeV $e^+$ |
| −0.7 ±0.5 | 170k | [32] FRYBERGER | 68 | ASPK | + | 25–53 MeV $e^+$ |
| −0.7 ±0.6 | 280k | [32] SHERWOOD | 67 | ASPK | + | 25–53 MeV $e^+$ |
| 0.05 ±0.5 | 800k | [32] PEOPLES | 66 | ASPK | + | 20–53 MeV $e^+$ |
| −2.0 ±0.9 | 9213 | [33] PLANO | 60 | HBC | + | Whole spectrum |

[30] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

[31] $\alpha = \alpha' = 0$ assumed.

[32] $\rho$ constrained = 0.75.

[33] Two parameter fit to $\rho$ and $\eta$; PLANO 60 discounts value for $\eta$.

## $\delta$ PARAMETER

$(V-A)$ theory predicts $\delta = 0.75$.

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **0.7486±0.0026±0.0028** | | [34] BALKE | 88 | SPEC | + | Surface $\mu^+$'s |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | [35] VOSSLER | 69 | | | |
| 0.752 ±0.009 | 490k | FRYBERGER | 68 | ASPK | + | 25–53 MeV $e^+$ |
| 0.782 ±0.031 | | KRUGER | 61 | | | |
| 0.78 ±0.05 | 8354 | PLANO | 60 | HBC | + | Whole spectrum |

[34] BALKE 88 uses $\rho = 0.752 \pm 0.003$.

[35] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

## $|(\xi$ PARAMETER$)\times(\mu$ LONGITUDINAL POLARIZATION$)|$

$(V-A)$ theory predicts $\xi = 1$, longitudinal polarization $= 1$.

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **1.0027±0.0079±0.0030** | | BELTRAMI | 87 | CNTR | | SIN, $\pi$ decay in flight |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 1.0013±0.0030±0.0053 | | [36] IMAZATO | 92 | SPEC | + | $K^+ \rightarrow \mu^+ \nu_\mu$ |
| 0.975 ±0.015 | | AKHMANOV | 68 | EMUL | | 140 kG |
| 0.975 ±0.030 | 66k | GUREVICH | 64 | EMUL | | See AKHMANOV 68 |
| 0.903 ±0.027 | | [37] ALI-ZADE | 61 | EMUL | + | 27 kG |
| 0.93 ±0.06 | 8354 | PLANO | 60 | HBC | + | 8.8 kG |
| 0.97 ±0.05 | 9k | BARDON | 59 | CNTR | | Bromoform target |

[36] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_\mu| > 0.990$. This measurement is of $K^+$ decay, not $\pi^+$ decay, so we do not include it in an average, nor do we yet set up a separate data block for $K$ results.

[37] Depolarization by medium not known sufficiently well.

## $\xi \times (\mu$ LONGITUDINAL POLARIZATION$) \times \delta / \rho$

| VALUE | CL% | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **>0.99682** | 90 | [38] JODIDIO | 86 | SPEC | + | TRIUMF |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >0.9966 | 90 | [39] STOKER | 85 | SPEC | + | $\mu$-spin rotation |
| >0.9959 | 90 | CARR | 83 | SPEC | + | 11 kG |

[38] JODIDIO 86 includes data from CARR 83 and STOKER 85. The value here is from the erratum.

[39] STOKER 85 find $(\xi P_\mu \delta/\rho)$ >0.9955 and >0.9966, where the first limit is from new $\mu$ spin-rotation data and the second is from combination with CARR 83 data. In $V-A$ theory, $(\delta/\rho) = 1.0$.

## $\xi'$ = LONGITUDINAL POLARIZATION OF $e^+$

$(V-A)$ theory predicts the longitudinal polarization = $\pm1$ for $e^{\pm}$, respectively. We have flipped the sign for $e^-$ so our programs can average.

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **1.00 ±0.04 OUR AVERAGE** | | | | | | |
| 0.998±0.045 | 1M | BURKARD | 85 | CNTR | + | Bhabha + annihil |
| 0.89 ±0.28 | 29k | SCHWARTZ | 67 | OSPK | − | Moller scattering |
| 0.94 ±0.38 | | BLOOM | 64 | CNTR | + | Brems. transmiss. |
| 1.04 ±0.18 | | DUCLOS | 64 | CNTR | + | Bhabha scattering |
| 1.05 ±0.30 | | BUHLER | 63 | CNTR | + | Annihilation |

## $\xi''$ PARAMETER

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **0.65±0.36** | 326k | [40] BURKARD | 85 | CNTR | + | Bhabha + annihil |

[40] BURKARD 85 measure $(\xi''-\xi\xi')/\xi$ and $\xi'$ and set $\xi = 1$.

## TRANSVERSE $e^+$ POLARIZATION IN PLANE OF $\mu$ SPIN, $e^+$ MOMENTUM

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.016±0.021±0.01 | 5.3M | BURKARD | 85B | CNTR | + | Annihil 9–53 MeV |

## TRANSVERSE $e^+$ POLARIZATION NORMAL TO PLANE OF $\mu$ SPIN, $e^+$ MOMENTUM

Zero if $T$ invariance holds.

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **0.007±0.022±0.007** | 5.3M | BURKARD | 85B | CNTR | + | Annihil 9–53 MeV |

## $\alpha/A$

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **0.4± 4.3** | | [41] BURKARD | 85B | FIT | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 15 ±50 ±14 | 5.3M | BURKARD | 85B | CNTR | + | 9–53 MeV $e^+$ |

[41] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

## $\alpha'/A$

Zero if $T$ invariance holds.

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **− 0.2± 4.3** | | [42] BURKARD | 85B | FIT | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| −47 ±50 ±14 | 5.3M | [43] BURKARD | 85B | CNTR | + | 9–53 MeV $e^+$ |

[42] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[43] BURKARD 85B measure $e^+$ polarizations $P_{T_1}$ and $P_{T_2}$ versus $e^+$ energy.

### $\beta/A$

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **3.9± 6.2** | | [44] BURKARD | 85B | FIT | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 2 ±17 ±6 | 5.3M | BURKARD | 85B | CNTR | + | 9–53 MeV $e^+$ |

[44] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

### $\beta'/A$

Zero if $T$ invariance holds.

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| **1.5± 6.3** | | [45] BURKARD | 85B | FIT | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 17 ±17 ±6 | 5.3M | [46] BURKARD | 85B | CNTR | + | 9–53 MeV $e^+$ |

[45] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

[46] BURKARD 85B measure $e^+$ polarizations $P_{T_1}$ and $P_{T_2}$ versus $e^+$ energy.

### $a/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

| VALUE (units $10^{-3}$) | CL% | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| <15.9 | 90 | [47] BURKARD | 85B | FIT |

[47] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

### $a'/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

| VALUE (units $10^{-3}$) | DOCUMENT ID | | TECN |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| 5.3±4.1 | [48] BURKARD | 85B | FIT |

[48] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

### $(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

| VALUE (units $10^{-3}$) | CL% | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| <1.04 | 90 | [49] BURKARD | 85B | FIT |

[49] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

### $c/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

| *VALUE* (units $10^{-3}$) | *CL%* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| <6.4 | 90 | [50] BURKARD | 85B | FIT |

[50] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

### $c'/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

| *VALUE* (units $10^{-3}$) | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $3.5\pm2.0$ | [51] BURKARD | 85B | FIT |

[51] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

## $\overline{\eta}$ PARAMETER

$(V-A)$ theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|
| **0.02 ±0.08 OUR AVERAGE** | | | | | |
| $-0.014\pm0.090$ | EICHENBER... | 84 | ELEC | + | $\rho$ free |
| $+0.09\ \pm0.14$ | BOGART | 67 | CNTR | + | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $-0.035\pm0.098$ | EICHENBER... | 84 | ELEC | + | $\rho$=0.75 assumed |

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