

# LEPTONS

**e**

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

Mass  $m = 0.510998902 \pm 0.000000021$  MeV  
 $= (5.485799110 \pm 0.000000012) \times 10^{-4}$  u

$(m_{e^+} - m_{e^-})/m < 8 \times 10^{-9}$ , CL = 90%

$|q_{e^+} + q_{e^-}|/e < 4 \times 10^{-8}$

Magnetic moment  $\mu = 1.001159652187 \pm 0.000000000004$   $\mu_B$

$(g_{e^+} - g_{e^-}) / g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment  $d = (0.18 \pm 0.16) \times 10^{-26}$  ecm

Mean life  $\tau > 4.2 \times 10^{24}$  yr, CL = 68% [a]

**$\mu$**

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

Mass  $m = 105.658357 \pm 0.000005$  MeV  
 $= 0.1134289168 \pm 0.0000000034$  u

Mean life  $\tau = (2.19703 \pm 0.00004) \times 10^{-6}$  s

$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$

$c\tau = 658.654$  m

Magnetic moment  $\mu = 1.0011659160 \pm 0.0000000006$   $e\hbar/2m_\mu$

$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}} = (-2.6 \pm 1.6) \times 10^{-8}$

Electric dipole moment  $d = (3.7 \pm 3.4) \times 10^{-19}$  ecm

**Decay parameters** [b]

$\rho = 0.7518 \pm 0.0026$

$\eta = -0.007 \pm 0.013$

$\delta = 0.749 \pm 0.004$

$\xi P_\mu = 1.003 \pm 0.008$  [c]

$\xi P_\mu \delta / \rho > 0.99682$ , CL = 90% [c]

$\xi' = 1.00 \pm 0.04$

$\xi'' = 0.7 \pm 0.4$

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

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

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

$\beta'/A = (2 \pm 6) \times 10^{-3}$

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

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

$\mu^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$\frac{P}{(\text{MeV}/c)}$
$e^- \bar{\nu}_e \nu_\mu$	$\approx 100\%$		53
$e^- \bar{\nu}_e \nu_\mu \gamma$	[d] $(1.4 \pm 0.4) \%$		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 $< 1.2$ $\times 10^{-11}$	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  $m = 1777.03^{+0.30}_{-0.26}$  MeV

Mean life  $\tau = (290.6 \pm 1.1) \times 10^{-15}$  s

$c\tau = 87.11$   $\mu\text{m}$

Magnetic moment anomaly  $> -0.052$  and  $< 0.058$ , CL = 95%

Electric dipole moment  $d > -3.1$  and  $< 3.1 \times 10^{-16}$  ecm, CL = 95%

**Weak dipole moment**

$\text{Re}(d_\tau^w) < 0.56 \times 10^{-17}$  ecm, CL = 95%

$\text{Im}(d_\tau^w) < 1.5 \times 10^{-17}$  ecm, CL = 95%

**Weak anomalous magnetic dipole moment**

$\text{Re}(\alpha_\tau^w) < 4.5 \times 10^{-3}$ , CL = 90%

$\text{Im}(\alpha_\tau^w) < 9.9 \times 10^{-3}$ , CL = 90%

**Decay parameters**

See the  $\tau$  Particle Listings for a note concerning  $\tau$ -decay parameters.

- $\rho^T(e \text{ or } \mu) = 0.747 \pm 0.009$
- $\rho^T(e) = 0.749 \pm 0.011$
- $\rho^T(\mu) = 0.752 \pm 0.021$
- $\xi^T(e \text{ or } \mu) = 0.997 \pm 0.032$
- $\xi^T(e) = 0.996 \pm 0.044$
- $\xi^T(\mu) = 1.046 \pm 0.065$
- $\eta^T(e \text{ or } \mu) = 0.011 \pm 0.031$
- $\eta^T(\mu) = -0.013 \pm 0.097$
- $(\delta\xi)^T(e \text{ or } \mu) = 0.746 \pm 0.023$
- $(\delta\xi)^T(e) = 0.735 \pm 0.030$
- $(\delta\xi)^T(\mu) = 0.774 \pm 0.043$
- $\xi^T(\pi) = 0.992 \pm 0.046$
- $\xi^T(\rho) = 0.998 \pm 0.010$
- $\xi^T(a_1) = 0.998 \pm 0.077$
- $\xi^T(\text{all hadronic modes}) = 1.000 \pm 0.008$

$\tau^\pm$  modes are charge conjugates of the modes below. " $h^\pm$ " stands for  $\pi^\pm$  or  $K^\pm$ . " $\ell$ " stands for e or  $\mu$ . "Neutral" means neutral hadron whose decay products include  $\gamma$ 's and/or  $\pi^0$ 's.

$\tau^-$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (MeV/c)
<b>Modes with one charged particle</b>			
particle $^- \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$ ("1-prong")	(84.71 $\pm$ 0.13) %	S=1.2	-
particle $^- \geq 0$ neutrals $\geq 0K^0 \nu_\tau$	(85.32 $\pm$ 0.13) %	S=1.2	-
$\mu^- \bar{\nu}_\mu \nu_\tau$	[g] (17.37 $\pm$ 0.07) %		885
$\mu^- \bar{\nu}_\mu \nu_\tau \gamma$	[e] ( 3.6 $\pm$ 0.4 ) $\times 10^{-3}$		-
$e^- \bar{\nu}_e \nu_\tau$	[g] (17.83 $\pm$ 0.06) %		889
$e^- \bar{\nu}_e \nu_\tau \gamma$	[e] ( 1.75 $\pm$ 0.18) %		-
$h^- \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$	(49.51 $\pm$ 0.15) %	S=1.2	-
$h^- \geq 0K_L^0 \nu_\tau$	(12.35 $\pm$ 0.12) %	S=1.4	-
$h^- \nu_\tau$	(11.79 $\pm$ 0.12) %	S=1.4	-
$\pi^- \nu_\tau$	[g] (11.09 $\pm$ 0.12) %	S=1.4	883
$K^- \nu_\tau$	[g] ( 6.99 $\pm$ 0.27) $\times 10^{-3}$		820
$h^- \geq 1$ neutrals $\nu_\tau$	(36.88 $\pm$ 0.17) %	S=1.2	-
$h^- \pi^0 \nu_\tau$	(25.86 $\pm$ 0.14) %	S=1.1	-
$\pi^- \pi^0 \nu_\tau$	[g] (25.40 $\pm$ 0.14) %	S=1.1	878
$\pi^- \pi^0$ non- $\rho(770) \nu_\tau$	( 3.0 $\pm$ 3.2 ) $\times 10^{-3}$		878

$K^- \pi^0 \nu_\tau$	[g] ( 4.54 $\pm$ 0.33) $\times 10^{-3}$		814
$h^- \geq 2\pi^0 \nu_\tau$	(10.73 $\pm$ 0.16) %	S=1.2	-
$h^- 2\pi^0 \nu_\tau$	( 9.36 $\pm$ 0.14) %	S=1.2	-
$h^- 2\pi^0 \nu_\tau$ (ex. $K^0$ )	( 9.19 $\pm$ 0.14) %	S=1.2	-
$\pi^- 2\pi^0 \nu_\tau$ (ex. $K^0$ )	[g] ( 9.13 $\pm$ 0.14) %	S=1.2	862
$\pi^- 2\pi^0 \nu_\tau$ (ex. $K^0$ ), scalar	< 9 $\times 10^{-3}$	CL=95%	-
$\pi^- 2\pi^0 \nu_\tau$ (ex. $K^0$ ), vector	< 7 $\times 10^{-3}$	CL=95%	-
$K^- 2\pi^0 \nu_\tau$ (ex. $K^0$ )	[g] ( 6.0 $\pm$ 2.4 ) $\times 10^{-4}$		796
$h^- \geq 3\pi^0 \nu_\tau$	( 1.37 $\pm$ 0.11) %	S=1.1	-
$h^- 3\pi^0 \nu_\tau$	( 1.21 $\pm$ 0.10) %	S=1.1	-
$\pi^- 3\pi^0 \nu_\tau$ (ex. $K^0$ )	[g] ( 1.08 $\pm$ 0.10) %	S=1.1	836
$K^- 3\pi^0 \nu_\tau$ (ex. $K^0$ )	[g] ( 3.9 $\pm^{+2.3}_{-2.1}$ ) $\times 10^{-4}$		766
$h^- 4\pi^0 \nu_\tau$ (ex. $K^0$ )	( 1.6 $\pm$ 0.6 ) $\times 10^{-3}$		-
$h^- 4\pi^0 \nu_\tau$ (ex. $K^0, \eta$ )	[g] ( 1.0 $\pm^{+0.6}_{-0.5}$ ) $\times 10^{-3}$		-
$K^- \geq 0\pi^0 \geq 0K^0 \nu_\tau$	( 1.58 $\pm$ 0.06) %		-
$K^- \geq 1 (\pi^0 \text{ or } K^0) \nu_\tau$	( 8.8 $\pm$ 0.5 ) $\times 10^{-3}$		-

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

$K^0$ (particles) $^- \nu_\tau$	( 1.71 $\pm$ 0.06) %	S=1.1	-
$h^- \bar{K}^0 \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$	( 1.67 $\pm$ 0.06) %	S=1.1	-
$h^- \bar{K}^0 \nu_\tau$	( 1.06 $\pm$ 0.05) %	S=1.2	-
$\pi^- \bar{K}^0 \nu_\tau$	[g] ( 9.0 $\pm$ 0.4 ) $\times 10^{-3}$	S=1.1	812
$\pi^- \bar{K}^0$	< 1.7 $\times 10^{-3}$	CL=95%	812
(non- $K^*(892)^-$ ) $\nu_\tau$			
$K^- K^0 \nu_\tau$	[g] ( 1.55 $\pm$ 0.17) $\times 10^{-3}$		737
$K^- \bar{K}^0 \geq 0\pi^0 \nu_\tau$	( 3.12 $\pm$ 0.25) $\times 10^{-3}$		-
$h^- \bar{K}^0 \pi^0 \nu_\tau$	( 5.3 $\pm$ 0.4 ) $\times 10^{-3}$		-
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	[g] ( 3.8 $\pm$ 0.4 ) $\times 10^{-3}$		794
$\bar{K}^0 \rho^- \nu_\tau$	( 2.2 $\pm$ 0.5 ) $\times 10^{-3}$		-
$K^- K^0 \pi^0 \nu_\tau$	[g] ( 1.57 $\pm$ 0.21) $\times 10^{-3}$		685
$\pi^- \bar{K}^0 \geq 1\pi^0 \nu_\tau$	( 3.2 $\pm$ 1.0 ) $\times 10^{-3}$		-
$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$	( 2.6 $\pm$ 2.4 ) $\times 10^{-4}$		-
$K^- K^0 \pi^0 \pi^0 \nu_\tau$	< 1.6 $\times 10^{-4}$	CL=95%	-
$\pi^- K^0 \bar{K}^0 \nu_\tau$	[g] ( 1.19 $\pm$ 0.20) $\times 10^{-3}$	S=1.2	682
$\pi^- K_S^0 K_S^0 \nu_\tau$	( 3.0 $\pm$ 0.5 ) $\times 10^{-4}$	S=1.2	-
$\pi^- K_S^0 K_L^0 \nu_\tau$	( 6.0 $\pm$ 1.0 ) $\times 10^{-4}$	S=1.2	-
$\pi^- K^0 \bar{K}^0 \pi^0 \nu_\tau$	( 3.1 $\pm$ 2.3 ) $\times 10^{-4}$		-
$\pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$	< 2.0 $\times 10^{-4}$	CL=95%	-
$\pi^- K_S^0 K_L^0 \pi^0 \nu_\tau$	( 3.1 $\pm$ 1.2 ) $\times 10^{-4}$		-
$K^0 h^+ h^- h^- \geq 0$ neutrals $\nu_\tau$	< 1.7 $\times 10^{-3}$	CL=95%	-
$K^0 h^+ h^- h^- \nu_\tau$	( 2.3 $\pm$ 2.0 ) $\times 10^{-4}$		-

**Modes with three charged particles**

$h^- h^- h^+ \geq 0$ neut. $\nu_\tau$ ("3-prong")	(15.18±0.13) %	S=1.2	-
$h^- h^- h^+ \geq 0$ neutrals $\nu_\tau$ (ex. $K_S^0 \rightarrow \pi^+ \pi^-$ )	(14.58±0.13) %	S=1.2	-
$\pi^- \pi^+ \pi^- \geq 0$ neutrals $\nu_\tau$	(14.49±0.14) %	-	-
$h^- h^- h^+ \nu_\tau$	(9.97±0.10) %	S=1.1	-
$h^- h^- h^+ \nu_\tau$ (ex. $K^0$ )	(9.61±0.10) %	S=1.1	-
$h^- h^- h^+ \nu_\tau$ (ex. $K^0, \omega$ )	(9.56±0.10) %	S=1.1	-
$\pi^- \pi^+ \pi^- \nu_\tau$	(9.49±0.11) %	S=1.1	-
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex. $K^0$ )	(9.18±0.11) %	S=1.1	-
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex. $K^0$ ), non-axial vector	< 2.4 %	CL=95%	-
$\pi^- \pi^+ \pi^- \nu_\tau$ (ex. $K^0, \omega$ ) [g]	(9.13±0.11) %	S=1.1	-
$h^- h^- h^+ \geq 1$ neutrals $\nu_\tau$	(5.17±0.11) %	S=1.2	-
$h^- h^- h^+ \geq 1$ neutrals $\nu_\tau$ (ex. $K_S^0 \rightarrow \pi^+ \pi^-$ )	(4.97±0.11) %	S=1.2	-
$h^- h^- h^+ \pi^0 \nu_\tau$	(4.49±0.08) %	-	-
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. $K^0$ )	(4.30±0.08) %	-	-
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. $K^0, \omega$ )	(2.58±0.08) %	-	-
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	(4.32±0.08) %	-	-
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex. $K^0$ )	(4.20±0.08) %	-	-
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex. $K^0, \omega$ ) [g]	(2.47±0.08) %	-	-
$h^- h^- h^+ 2\pi^0 \nu_\tau$	(5.4 ± 0.4) × 10 <sup>-3</sup>	-	-
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex. $K^0$ )	(5.3 ± 0.4) × 10 <sup>-3</sup>	-	-
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex. $K^0, \omega, \eta$ ) [g]	(1.1 ± 0.4) × 10 <sup>-3</sup>	-	-
$h^- h^- h^+ \geq 3\pi^0 \nu_\tau$ [g]	(1.3 <sup>+0.8</sup> / <sub>-0.7</sub> ) × 10 <sup>-3</sup>	S=1.3	-
$h^- h^- h^+ 3\pi^0 \nu_\tau$	(2.9 ± 0.8) × 10 <sup>-4</sup>	-	-
$K^- h^+ h^- \geq 0$ neutrals $\nu_\tau$	(6.5 ± 0.5) × 10 <sup>-3</sup>	S=1.4	-
$K^- h^+ \pi^- \nu_\tau$ (ex. $K^0$ )	(4.3 ± 0.5) × 10 <sup>-3</sup>	S=1.5	-
$K^- h^+ \pi^- \pi^0 \nu_\tau$ (ex. $K^0$ )	(1.07±0.22) × 10 <sup>-3</sup>	-	-
$K^- \pi^+ \pi^- \geq 0$ neutrals $\nu_\tau$	(4.4 ± 0.5) × 10 <sup>-3</sup>	S=1.4	-
$K^- \pi^+ \pi^- \geq 0\pi^0 \nu_\tau$ (ex. $K^0$ )	(3.4 ± 0.5) × 10 <sup>-3</sup>	S=1.4	-
$K^- \pi^+ \pi^- \nu_\tau$	(3.2 ± 0.5) × 10 <sup>-3</sup>	S=1.5	-
$K^- \pi^+ \pi^- \nu_\tau$ (ex. $K^0$ ) [g]	(2.7 ± 0.5) × 10 <sup>-3</sup>	S=1.5	-
$K^- \pi^+ \pi^- \pi^0 \nu_\tau$	(1.20±0.25) × 10 <sup>-3</sup>	-	-
$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex. $K^0$ )	(6.7 ± 2.4) × 10 <sup>-4</sup>	-	-
$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex. $K^0, \eta$ ) [g]	(6.0 ± 2.4) × 10 <sup>-4</sup>	-	-
$K^- \pi^+ K^- \geq 0$ neut. $\nu_\tau$	< 9 × 10 <sup>-4</sup>	CL=95%	-
$K^- K^+ \pi^- \geq 0$ neut. $\nu_\tau$	(2.01±0.23) × 10 <sup>-3</sup>	-	-
$K^- K^+ \pi^- \nu_\tau$ [g]	(1.61±0.18) × 10 <sup>-3</sup>	685	-

$K^- K^+ \pi^- \pi^0 \nu_\tau$ [g]	(4.0 ± 1.6) × 10 <sup>-4</sup>	-
$K^- K^+ K^- \geq 0$ neut. $\nu_\tau$	< 2.1 × 10 <sup>-3</sup>	CL=95%
$K^- K^+ K^- \nu_\tau$	< 1.9 × 10 <sup>-4</sup>	CL=90%
$\pi^- K^+ \pi^- \geq 0$ neut. $\nu_\tau$	< 2.5 × 10 <sup>-3</sup>	CL=95%
$e^- e^- e^+ \bar{\nu}_e \nu_\tau$	(2.8 ± 1.5) × 10 <sup>-5</sup>	889
$\mu^- e^- e^+ \bar{\nu}_\mu \nu_\tau$	< 3.6 × 10 <sup>-5</sup>	CL=90% 885

**Modes with five charged particles**

$3h^- 2h^+ \geq 0$ neutrals $\nu_\tau$ (ex. $K_S^0 \rightarrow \pi^- \pi^+$ ) ("5-prong")	(9.9 ± 0.7) × 10 <sup>-4</sup>	-
$3h^- 2h^+ \nu_\tau$ (ex. $K^0$ ) [g]	(7.8 ± 0.6) × 10 <sup>-4</sup>	-
$3h^- 2h^+ \pi^0 \nu_\tau$ (ex. $K^0$ ) [g]	(2.2 ± 0.5) × 10 <sup>-4</sup>	-
$3h^- 2h^+ 2\pi^0 \nu_\tau$	< 1.1 × 10 <sup>-4</sup>	CL=90%

**Miscellaneous other allowed modes**

$(5\pi^-) \nu_\tau$	(7.9 ± 0.7) × 10 <sup>-3</sup>	-
$4h^- 3h^+ \geq 0$ neutrals $\nu_\tau$ ("7-prong")	< 2.4 × 10 <sup>-6</sup>	CL=90%
$X^-(S=-1) \nu_\tau$	(2.89±0.09) %	S=1.1
$K^*(892)^- \geq 0$ ( $h^0 \neq K_S^0$ ) $\nu_\tau$	(1.94±0.31) %	-
$K^*(892)^- \geq 0$ neutrals $\nu_\tau$	(1.33±0.13) %	-
$K^*(892)^- \nu_\tau$	(1.29±0.05) %	665
$K^*(892)^0 K^- \geq 0$ neutrals $\nu_\tau$	(3.2 ± 1.4) × 10 <sup>-3</sup>	-
$K^*(892)^0 K^- \nu_\tau$	(2.1 ± 0.4) × 10 <sup>-3</sup>	539
$\bar{K}^*(892)^0 \pi^- \geq 0$ neutrals $\nu_\tau$	(3.8 ± 1.7) × 10 <sup>-3</sup>	-
$\bar{K}^*(892)^0 \pi^- \nu_\tau$	(2.2 ± 0.5) × 10 <sup>-3</sup>	653
$(\bar{K}^*(892) \pi^-) \nu_\tau \rightarrow$ $\pi^- \bar{K}^0 \pi^0 \nu_\tau$	(1.0 ± 0.4) × 10 <sup>-3</sup>	-
$K_1(1270)^- \nu_\tau$	(4.7 ± 1.1) × 10 <sup>-3</sup>	433
$K_1(1400)^- \nu_\tau$	(1.7 ± 2.6) × 10 <sup>-3</sup>	S=1.7 335
$K^*(1410)^- \nu_\tau$	(1.5 <sup>+1.4</sup> / <sub>-1.0</sub> ) × 10 <sup>-3</sup>	-
$K_0^*(1430)^- \nu_\tau$	< 5 × 10 <sup>-4</sup>	CL=95%
$K_2^*(1430)^- \nu_\tau$	< 3 × 10 <sup>-3</sup>	CL=95%
$\eta \pi^- \nu_\tau$	< 1.4 × 10 <sup>-4</sup>	CL=95%
$\eta \pi^- \pi^0 \nu_\tau$ [g]	(1.74±0.24) × 10 <sup>-3</sup>	778
$\eta \pi^- \pi^0 \pi^0 \nu_\tau$	(1.4 ± 0.7) × 10 <sup>-4</sup>	746
$\eta K^- \nu_\tau$ [g]	(2.7 ± 0.6) × 10 <sup>-4</sup>	720
$\eta K^*(892)^- \nu_\tau$	(2.9 ± 0.9) × 10 <sup>-4</sup>	-
$\eta K^- \pi^0 \nu_\tau$	(1.8 ± 0.9) × 10 <sup>-4</sup>	-
$\eta \bar{K}^0 \pi^- \nu_\tau$	(2.2 ± 0.7) × 10 <sup>-4</sup>	-

$\eta\pi^+\pi^-\pi^-\geq 0$ neutrals $\nu_\tau$	< 3	$\times 10^{-3}$	CL=90%	-
$\eta\pi^-\pi^+\pi^-\nu_\tau$	( 3.4 $\pm$ 0.8 )	$\times 10^{-4}$		-
$\eta a_1(1260)^-\nu_\tau \rightarrow \eta\pi^-\rho^0\nu_\tau$	< 3.9	$\times 10^{-4}$	CL=90%	-
$\eta\eta\pi^-\nu_\tau$	< 1.1	$\times 10^{-4}$	CL=95%	637
$\eta\eta\pi^-\pi^0\nu_\tau$	< 2.0	$\times 10^{-4}$	CL=95%	559
$\eta'(958)\pi^-\nu_\tau$	< 7.4	$\times 10^{-5}$	CL=90%	-
$\eta'(958)\pi^-\pi^0\nu_\tau$	< 8.0	$\times 10^{-5}$	CL=90%	-
$\phi\pi^-\nu_\tau$	< 2.0	$\times 10^{-4}$	CL=90%	585
$\phi K^-\nu_\tau$	< 6.7	$\times 10^{-5}$	CL=90%	-
$f_1(1285)\pi^-\nu_\tau$	( 5.8 $\pm$ 2.3 )	$\times 10^{-4}$		-
$f_1(1285)\pi^-\nu_\tau \rightarrow \eta\pi^-\pi^+\pi^-\nu_\tau$	( 1.9 $\pm$ 0.7 )	$\times 10^{-4}$		-
$\pi(1300)^-\nu_\tau \rightarrow (\rho\pi)^-\nu_\tau \rightarrow (3\pi)^-\nu_\tau$	< 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 $\nu_\tau$	( 2.36 $\pm$ 0.08 ) %			-
$h^-\omega\nu_\tau$	[g] ( 1.93 $\pm$ 0.06 ) %			-
$h^-\omega\pi^0\nu_\tau$	[g] ( 4.3 $\pm$ 0.5 )	$\times 10^{-3}$		-
$h^-\omega 2\pi^0\nu_\tau$	( 1.9 $\pm$ 0.8 )	$\times 10^{-4}$		-

**Lepton Family number (LF), Lepton number (L), or Baryon number (B) violating modes**  
(In the modes below,  $\ell$  means a sum over  $e$  and  $\mu$  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	< 2.7	$\times 10^{-6}$	CL=90%	888
$\mu^-\gamma$	LF	< 1.1	$\times 10^{-6}$	CL=90%	885
$e^-\pi^0$	LF	< 3.7	$\times 10^{-6}$	CL=90%	883
$\mu^-\pi^0$	LF	< 4.0	$\times 10^{-6}$	CL=90%	880
$e^-K^0$	LF	< 1.3	$\times 10^{-3}$	CL=90%	819
$\mu^-K^0$	LF	< 1.0	$\times 10^{-3}$	CL=90%	815
$e^-\eta$	LF	< 8.2	$\times 10^{-6}$	CL=90%	804
$\mu^-\eta$	LF	< 9.6	$\times 10^{-6}$	CL=90%	800
$e^-\rho^0$	LF	< 2.0	$\times 10^{-6}$	CL=90%	722
$\mu^-\rho^0$	LF	< 6.3	$\times 10^{-6}$	CL=90%	718
$e^-K^*(892)^0$	LF	< 5.1	$\times 10^{-6}$	CL=90%	663
$\mu^-K^*(892)^0$	LF	< 7.5	$\times 10^{-6}$	CL=90%	657
$e^-\bar{K}^*(892)^0$	LF	< 7.4	$\times 10^{-6}$	CL=90%	663
$\mu^-\bar{K}^*(892)^0$	LF	< 7.5	$\times 10^{-6}$	CL=90%	657
$e^-\phi$	LF	< 6.9	$\times 10^{-6}$	CL=90%	596
$\mu^-\phi$	LF	< 7.0	$\times 10^{-6}$	CL=90%	590

$\pi^-\gamma$	L	< 2.8	$\times 10^{-4}$	CL=90%	883
$\pi^-\pi^0$	L	< 3.7	$\times 10^{-4}$	CL=90%	878
$e^-e^+e^-$	LF	< 2.9	$\times 10^{-6}$	CL=90%	888
$e^-\mu^+\mu^-$	LF	< 1.8	$\times 10^{-6}$	CL=90%	882
$e^+\mu^-\mu^-$	LF	< 1.5	$\times 10^{-6}$	CL=90%	882
$\mu^-e^+e^-$	LF	< 1.7	$\times 10^{-6}$	CL=90%	885
$\mu^+e^-e^-$	LF	< 1.5	$\times 10^{-6}$	CL=90%	885
$\mu^-\mu^+\mu^-$	LF	< 1.9	$\times 10^{-6}$	CL=90%	873
$e^-\pi^+\pi^-$	LF	< 2.2	$\times 10^{-6}$	CL=90%	877
$e^+\pi^-\pi^-$	L	< 1.9	$\times 10^{-6}$	CL=90%	877
$\mu^-\pi^+\pi^-$	LF	< 8.2	$\times 10^{-6}$	CL=90%	866
$\mu^+\pi^-\pi^-$	L	< 3.4	$\times 10^{-6}$	CL=90%	866
$e^-\pi^+K^-$	LF	< 6.4	$\times 10^{-6}$	CL=90%	814
$e^-\pi^-K^+$	LF	< 3.8	$\times 10^{-6}$	CL=90%	814
$e^+\pi^-K^-$	L	< 2.1	$\times 10^{-6}$	CL=90%	814
$e^-K^+K^-$	LF	< 6.0	$\times 10^{-6}$	CL=90%	739
$e^+K^-K^-$	L	< 3.8	$\times 10^{-6}$	CL=90%	739
$\mu^-\pi^+K^-$	LF	< 7.5	$\times 10^{-6}$	CL=90%	800
$\mu^-\pi^-K^+$	LF	< 7.4	$\times 10^{-6}$	CL=90%	800
$\mu^+\pi^-K^-$	L	< 7.0	$\times 10^{-6}$	CL=90%	800
$\mu^-K^+K^-$	LF	< 1.5	$\times 10^{-5}$	CL=90%	699
$\mu^+K^-K^-$	L	< 6.0	$\times 10^{-6}$	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%	700
$\mu^-\eta\eta$	LF	< 6.0	$\times 10^{-5}$	CL=90%	654
$e^-\pi^0\eta$	LF	< 2.4	$\times 10^{-5}$	CL=90%	798
$\mu^-\pi^0\eta$	LF	< 2.2	$\times 10^{-5}$	CL=90%	784
$\bar{p}\gamma$	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%	-
$\bar{p}\eta$	L,B	< 8.9	$\times 10^{-6}$	CL=90%	476
$\bar{p}\pi^0\eta$	L,B	< 2.7	$\times 10^{-5}$	CL=90%	-
$e^-$ light boson	LF	< 2.7	$\times 10^{-3}$	CL=95%	-
$\mu^-$ light boson	LF	< 5	$\times 10^{-3}$	CL=95%	-

## Heavy Charged Lepton Searches

### $L^\pm$ – charged lepton

Mass  $m > 92.4$  GeV, CL = 95% <sup>[h]</sup>  $m_\nu \approx 0$

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

Mass  $m > 93.5$  GeV, CL = 95%

## Neutrinos

See the Particle Listings for a Note “Neutrino Mass” giving details of neutrinos, masses, mixing, and the status of experimental searches.

### $\nu_e$

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

Mass  $m < 3$  eV Interpretation of tritium beta decay experiments is complicated by anomalies near the endpoint, and the limits are not without ambiguity.

Mean life/mass,  $\tau/m_{\nu_e} > 7 \times 10^9$  s/eV (solar)

Mean life/mass,  $\tau/m_{\nu_e} > 300$  s/eV, CL = 90% (reactor)

Magnetic moment  $\mu < 1.5 \times 10^{-10} \mu_B$ , CL = 90%

### $\nu_\mu$

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

Mass  $m < 0.19$  MeV, CL = 90% <sup>[i]</sup>

Mean life/mass,  $\tau/m_{\nu_\mu} > 15.4$  s/eV, CL = 90%

Magnetic moment  $\mu < 7.4 \times 10^{-10} \mu_B$ , CL = 90%

### $\nu_\tau$

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

Mass  $m < 18.2$  MeV, CL = 95% <sup>[j]</sup>

Magnetic moment  $\mu < 5.4 \times 10^{-7} \mu_B$ , CL = 90%

Electric dipole moment  $d < 5.2 \times 10^{-17}$  ecm, CL = 95%

## Number of Light Neutrino Types

(including  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ )

Number  $N = 2.994 \pm 0.012$  (Standard Model fits to LEP data)

Number  $N = 3.00 \pm 0.06$  (Direct measurement of invisible Z width)

## Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note “Neutrino Mass” giving details of neutrinos, masses, mixing, and the status of experimental searches.

There is now rather convincing evidence that neutrinos have nonzero mass from the apparent observation of neutrino oscillations, where the neutrinos come from  $\pi$  (or  $K$ )  $\rightarrow \mu \rightarrow e$  decays in the atmosphere; the mesons are produced in cosmic-ray cascades.

### Stable Neutral Heavy Lepton Mass Limits

Mass  $m > 45.0$  GeV, CL = 95% (Dirac)

Mass  $m > 39.5$  GeV, CL = 95% (Majorana)

### Neutral Heavy Lepton Mass Limits

Mass  $m > 83.3$  GeV, CL = 95%

(Dirac  $\nu_L$  coupling to  $e$ ,  $\mu$ ,  $\tau$ ; conservative case( $\tau$ ))

Mass  $m > 73.5$  GeV, CL = 95%

(Majorana  $\nu_L$  coupling to  $e$ ,  $\mu$ ,  $\tau$ ; conservative case( $\tau$ ))

### Solar Neutrinos

Detectors using gallium ( $E_\nu \gtrsim 0.2$  MeV), chlorine ( $E_\nu \gtrsim 0.8$  MeV), and Čerenkov effect in water ( $E_\nu \gtrsim 7$  MeV) measure significantly lower neutrino rates than are predicted from solar models. The deficit in the solar neutrino flux compared with solar model calculations could be explained by oscillations with  $\Delta m^2 \leq 10^{-5}$  eV<sup>2</sup> causing the disappearance of  $\nu_e$ .

### Atmospheric Neutrinos

Underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a  $\nu_\mu/\nu_e$  ratio much less than expected and also a deficiency of upward going  $\nu_\mu$  compared to downward. This could be explained by oscillations leading to the disappearance of  $\nu_\mu$  with  $\Delta m^2 \approx 10^{-3}$  to  $0.1 \text{ eV}^2$ . This is presently the best evidence for neutrino mass.

#### $\nu$ oscillation: $\bar{\nu}_e \not\leftrightarrow \bar{\nu}_e$ ( $\theta = \text{mixing angle}$ )

$$\Delta m^2 < 7 \times 10^{-4} \text{ eV}^2, \text{ CL} = 90\% \quad (\text{if } \sin^2 2\theta = 1)$$

$$\sin^2 2\theta < 0.02, \text{ CL} = 90\% \quad (\text{if } \Delta(m^2) \text{ is large})$$

#### $\nu$ oscillation: $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_e (\bar{\nu}_e)$ (any combination)

$$\Delta m^2 < 0.075 \text{ eV}^2, \text{ CL} = 90\% \quad (\text{if } \sin^2 2\theta = 1)$$

$$\sin^2 2\theta < 1.8 \times 10^{-3}, \text{ CL} = 90\% \quad (\text{if } \Delta(m^2) \text{ is large})$$

### NOTES

- [a] This is the best “electron disappearance” limit. The best limit for the mode  $e^- \rightarrow \nu \gamma$  is  $> 2.35 \times 10^{25} \text{ yr}$  (CL=68%).
- [b] See the “Note on Muon Decay Parameters” in the  $\mu$  Particle Listings for definitions and details.
- [c]  $P_\mu$  is the longitudinal polarization of the muon from pion decay. In standard V–A theory,  $P_\mu = 1$  and  $\rho = \delta = 3/4$ .
- [d] This only includes events with the  $\gamma$  energy  $> 10 \text{ MeV}$ . 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 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.
- [i] Assumes  $\nu_2$  is the dominant mass eigenstate.
- [j] Assumes  $\nu_3$  is the dominant mass eigenstate.