

# STRANGE MESONS

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

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

**$K^\pm$**

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

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

$$\text{Mean life } \tau = (1.2380 \pm 0.0021) \times 10^{-8} \text{ s} \quad (S = 1.9)$$

$$c\tau = 3.712 \text{ m}$$

### Slope parameter $g$ [b]

(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 [c,d]

Assuming  $\mu$ -e universality

$$\lambda_+(K_{\mu 3}^+) = \lambda_+(K_{e 3}^+) = (2.97 \pm 0.05) \times 10^{-2}$$

$$\lambda_0(K_{\mu 3}^+) = (1.96 \pm 0.12) \times 10^{-2}$$

Not assuming  $\mu$ -e universality

$$\lambda_+(K_{e 3}^+) = (2.96 \pm 0.06) \times 10^{-2}$$

$$\lambda_+(K_{\mu 3}^+) = (2.96 \pm 0.17) \times 10^{-2}$$

$$\lambda_0(K_{\mu 3}^+) = (1.96 \pm 0.13) \times 10^{-2}$$

$K_{e 3}$  form factor quadratic fit

$$\lambda'_+(K_{e 3}^\pm) \text{ linear coeff.} = (2.48 \pm 0.17) \times 10^{-2}$$

$$\lambda''_+(K_{e 3}^\pm) \text{ quadratic coeff.} = (0.19 \pm 0.09) \times 10^{-2}$$

$$K_{e 3}^+ \quad |f_S/f_+| = (-0.3^{+0.8}_{-0.7}) \times 10^{-2}$$

$$K_{e 3}^+ \quad |f_T/f_+| = (-1.2 \pm 2.3) \times 10^{-2}$$

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

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

$$K^+ \rightarrow e^+ \nu_e \gamma \quad |F_A + F_V| = 0.148 \pm 0.010$$

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

$$K^+ \rightarrow e^+ \nu_e \gamma \quad |F_A - F_V| < 0.49$$

$$K^+ \rightarrow \mu^+ \nu_\mu \gamma \quad |F_A - F_V| = -0.24 \text{ to } 0.04, \text{ CL} = 90\%$$

### Charge Radius

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

### CP violation parameters

$$\Delta(K_{\pi\mu\mu}^{\pm}) = -0.02 \pm 0.12$$

### T violation parameters

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

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

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

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

$K^+$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
<b>Leptonic and semileptonic modes</b>			
$K^+ \rightarrow e^+ \nu_e$	$(1.55 \pm 0.07) \times 10^{-5}$		247
$K^+ \rightarrow \mu^+ \nu_{\mu}$	$(63.55 \pm 0.11) \%$	S=1.2	236
$K^+ \rightarrow \pi^0 e^+ \nu_e$	$(5.07 \pm 0.04) \%$	S=2.1	228
Called $K_{e3}^+$ .			
$K^+ \rightarrow \pi^0 \mu^+ \nu_{\mu}$	$(3.353 \pm 0.034) \%$	S=1.8	215
Called $K_{\mu 3}^+$ .			
$K^+ \rightarrow \pi^0 \pi^0 e^+ \nu_e$	$(2.2 \pm 0.4) \times 10^{-5}$		206
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$	$(4.09 \pm 0.10) \times 10^{-5}$		203
$K^+ \rightarrow \pi^+ \pi^- \mu^+ \nu_{\mu}$	$(1.4 \pm 0.9) \times 10^{-5}$		151
$K^+ \rightarrow \pi^0 \pi^0 \pi^0 e^+ \nu_e$	$< 3.5 \times 10^{-6}$	CL=90%	135
<b>Hadronic modes</b>			
$K^+ \rightarrow \pi^+ \pi^0$	$(20.66 \pm 0.08) \%$	S=1.2	205
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	$(1.761 \pm 0.022) \%$	S=1.1	133
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$(5.59 \pm 0.04) \%$	S=1.3	125
<b>Leptonic and semileptonic modes with photons</b>			
$K^+ \rightarrow \mu^+ \nu_{\mu} \gamma$	[e,f] $(6.2 \pm 0.8) \times 10^{-3}$		236
$K^+ \rightarrow \mu^+ \nu_{\mu} \gamma (\text{SD}^+)$	[d,g] $< 3.0 \times 10^{-5}$	CL=90%	—
$K^+ \rightarrow \mu^+ \nu_{\mu} \gamma (\text{SD}^+ \text{INT})$	[d,g] $< 2.7 \times 10^{-5}$	CL=90%	—
$K^+ \rightarrow \mu^+ \nu_{\mu} \gamma (\text{SD}^- + \text{SD}^- \text{INT})$	[d,g] $< 2.6 \times 10^{-4}$	CL=90%	—
$K^+ \rightarrow e^+ \nu_e \gamma (\text{SD}^+)$	[d,g] $(1.53 \pm 0.23) \times 10^{-5}$		—
$K^+ \rightarrow e^+ \nu_e \gamma (\text{SD}^-)$	[d,g] $< 1.6 \times 10^{-4}$	CL=90%	—
$K^+ \rightarrow \pi^0 e^+ \nu_e \gamma$	[e,f] $(2.56 \pm 0.16) \times 10^{-4}$		228
$K^+ \rightarrow \pi^0 e^+ \nu_e \gamma (\text{SD})$	[d,g] $< 5.3 \times 10^{-5}$	CL=90%	228
$K^+ \rightarrow \pi^0 \mu^+ \nu_{\mu} \gamma$	[e,f] $(1.5 \pm 0.4) \times 10^{-5}$		215
$K^+ \rightarrow \pi^0 \pi^0 e^+ \nu_e \gamma$	$< 5 \times 10^{-6}$	CL=90%	206

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

$K^+ \rightarrow \pi^+ \pi^0 \gamma$	[e,f]	$(2.75 \pm 0.15) \times 10^{-4}$	205
$K^+ \rightarrow \pi^+ \pi^0 \gamma$ (DE)	[f,h]	$(4.3 \pm 0.7) \times 10^{-6}$	205
$K^+ \rightarrow \pi^+ \pi^0 \pi^0 \gamma$	[e,f]	$(7.6 \pm_{-3.0}^{+6.0}) \times 10^{-6}$	133
$K^+ \rightarrow \pi^+ \pi^+ \pi^- \gamma$	[e,f]	$(1.04 \pm 0.31) \times 10^{-4}$	125
$K^+ \rightarrow \pi^+ \gamma \gamma$	[f]	$(1.10 \pm 0.32) \times 10^{-6}$	227
$K^+ \rightarrow \pi^+ 3\gamma$	[f]	$< 1.0 \times 10^{-4}$ CL=90%	227
$K^\pm \rightarrow \pi^+ e^+ e^- \gamma$		$(1.19 \pm 0.13) \times 10^{-8}$	227

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

$K^+ \rightarrow e^+ \nu_e \nu \bar{\nu}$		$< 6 \times 10^{-5}$ CL=90%	247
$K^+ \rightarrow \mu^+ \nu_\mu \nu \bar{\nu}$		$< 6.0 \times 10^{-6}$ CL=90%	236
$K^+ \rightarrow e^+ \nu_e e^+ e^-$		$(2.48 \pm 0.20) \times 10^{-8}$	247
$K^+ \rightarrow \mu^+ \nu_\mu e^+ e^-$		$(7.06 \pm 0.31) \times 10^{-8}$	236
$K^+ \rightarrow e^+ \nu_e \mu^+ \mu^-$		$(1.7 \pm 0.5) \times 10^{-8}$	223
$K^+ \rightarrow \mu^+ \nu_\mu \mu^+ \mu^-$		$< 4.1 \times 10^{-7}$ 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

$K^+ \rightarrow \pi^+ \pi^+ e^- \bar{\nu}_e$	SQ	$< 1.2 \times 10^{-8}$ CL=90%	203
$K^+ \rightarrow \pi^+ \pi^+ \mu^- \bar{\nu}_\mu$	SQ	$< 3.0 \times 10^{-6}$ CL=95%	151
$K^+ \rightarrow \pi^+ e^+ e^-$	S1	$(2.88 \pm 0.13) \times 10^{-7}$	227
$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	S1	$(8.1 \pm 1.4) \times 10^{-8}$ S=2.7	172
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	S1	$(1.7 \pm 1.1) \times 10^{-10}$	227
$K^+ \rightarrow \pi^+ \pi^0 \nu \bar{\nu}$	S1	$< 4.3 \times 10^{-5}$ CL=90%	205
$K^+ \rightarrow \mu^- \nu e^+ e^+$	LF	$< 2.0 \times 10^{-8}$ CL=90%	236
$K^+ \rightarrow \mu^+ \nu_e$	LF	$[i] < 4 \times 10^{-3}$ CL=90%	236
$K^+ \rightarrow \pi^+ \mu^+ e^-$	LF	$< 1.3 \times 10^{-11}$ CL=90%	214
$K^+ \rightarrow \pi^+ \mu^- e^+$	LF	$< 5.2 \times 10^{-10}$ CL=90%	214
$K^+ \rightarrow \pi^- \mu^+ e^+$	L	$< 5.0 \times 10^{-10}$ CL=90%	214
$K^+ \rightarrow \pi^- e^+ e^+$	L	$< 6.4 \times 10^{-10}$ CL=90%	227
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	L	$[i] < 3.0 \times 10^{-9}$ CL=90%	172
$K^+ \rightarrow \mu^+ \bar{\nu}_e$	L	$[i] < 3.3 \times 10^{-3}$ CL=90%	236
$K^+ \rightarrow \pi^0 e^+ \bar{\nu}_e$	L	$< 3 \times 10^{-3}$ CL=90%	228
$K^+ \rightarrow \pi^+ \gamma$	[j]	$< 2.3 \times 10^{-9}$ CL=90%	227

**$K^0$**

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

50%  $K_S$ , 50%  $K_L$

$$\text{Mass } m = 497.614 \pm 0.024 \text{ MeV} \quad (S = 1.6)$$

$$m_{K^0} - m_{K^\pm} = 3.937 \pm 0.028 \text{ MeV} \quad (S = 1.8)$$

### 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** [c]

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

### **CPT-violation parameters** [c]

$$\text{Re } \delta = (2.3 \pm 2.7) \times 10^{-4}$$

$$\text{Im } \delta = (0.4 \pm 2.1) \times 10^{-5}$$

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

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

$$|m_{K^0} - m_{\bar{K}^0}| / m_{\text{average}} < 8 \times 10^{-19}, \text{ CL} = 90\% \text{ [k]}$$

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

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

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



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

Mean life  $\tau = (0.8953 \pm 0.0005) \times 10^{-10}$  s (S = 1.1) Assuming CPT

Mean life  $\tau = (0.8958 \pm 0.0005) \times 10^{-10}$  s Not assuming CPT  
 $c\tau = 2.6842$  cm Assuming CPT

### **CP-violation parameters** [l]

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

$$\text{Im}(\eta_{000}) = (-0.1 \pm 1.6) \times 10^{-2}$$

$$|\eta_{000}| = |A(K_S^0 \rightarrow 3\pi^0) / A(K_L^0 \rightarrow 3\pi^0)| < 0.018, \text{ CL} = 90\%$$

$$\text{CP asymmetry } A \text{ in } \pi^+ \pi^- e^+ e^- = (-1 \pm 4)\%$$

$K_S^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$\rho$ (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>l\bar{l}</math> pairs</b>			
$\pi^+ \pi^- \gamma$	[e,m] ( 1.79 ± 0.05 ) × 10 <sup>-3</sup>		206
$\pi^+ \pi^- e^+ e^-$	( 4.69 ± 0.30 ) × 10 <sup>-5</sup>		206
$\pi^0 \gamma \gamma$	[m] ( 4.9 ± 1.8 ) × 10 <sup>-8</sup>		231
$\gamma \gamma$	( 2.63 ± 0.17 ) × 10 <sup>-6</sup>	S=3.0	249
<b>Semileptonic modes</b>			
$\pi^\pm e^\mp \nu_e$	[n] ( 7.04 ± 0.08 ) × 10 <sup>-4</sup>		229
<b>CP violating (CP) and <math>\Delta S = 1</math> weak neutral current (S1) modes</b>			
$3\pi^0$	CP < 1.2 × 10 <sup>-7</sup>	CL=90%	139
$\mu^+ \mu^-$	S1 < 3.2 × 10 <sup>-7</sup>	CL=90%	225
$e^+ e^-$	S1 < 1.4 × 10 <sup>-7</sup>	CL=90%	249
$\pi^0 e^+ e^-$	S1 [m] ( 3.0 $\begin{smallmatrix} +1.5 \\ -1.2 \end{smallmatrix}$ ) × 10 <sup>-9</sup>		230
$\pi^0 \mu^+ \mu^-$	S1 ( 2.9 $\begin{smallmatrix} +1.5 \\ -1.2 \end{smallmatrix}$ ) × 10 <sup>-9</sup>		177



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

$$\begin{aligned}
 m_{K_L} - m_{K_S} &= (0.5292 \pm 0.0009) \times 10^{10} \hbar s^{-1} \quad (S = 1.2) \quad \text{Assuming } CPT \\
 &= (3.483 \pm 0.006) \times 10^{-12} \text{ MeV} \quad \text{Assuming } CPT \\
 &= (0.5290 \pm 0.0015) \times 10^{10} \hbar s^{-1} \quad (S = 1.1) \quad \text{Not assuming } \\
 &\quad CPT
 \end{aligned}$$

$$\begin{aligned}
 \text{Mean life } \tau &= (5.116 \pm 0.020) \times 10^{-8} \text{ s} \\
 c\tau &= 15.34 \text{ m}
 \end{aligned}$$

### Slope parameter $g$ [b]

(See Particle Listings for quadratic coefficients)

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

### $K_L$ decay form factors [c]

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

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

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

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

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

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

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

$$K_{e 3}^0 \quad |f_S/f_+| = (1.5_{-1.6}^{+1.4}) \times 10^{-2}$$

$$K_{e 3}^0 \quad |f_T/f_+| = (5_{-5}^{+4}) \times 10^{-2}$$

$$K_{\mu 3}^0 \quad |f_T/f_+| = (12 \pm 12) \times 10^{-2}$$

$$K_L \rightarrow \ell^+ \ell^- \gamma, K_L \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-: \alpha_{K^*} = -0.205 \pm 0.022 \quad (S = 1.8)$$

$$K_L^0 \rightarrow \ell^+ \ell^- \gamma, K_L^0 \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-: \alpha_{DIP} = -1.69 \pm 0.08 \quad (S = 1.7)$$

$$K_L \rightarrow \pi^+ \pi^- e^+ e^-: a_1/a_2 = -0.737 \pm 0.014 \text{ GeV}^2$$

$$K_L \rightarrow \pi^0 2\gamma: a_V = -0.43 \pm 0.06 \quad (S = 1.5)$$

### **CP-violation parameters** [1]

$$A_L = (0.332 \pm 0.006)\%$$

$$|\eta_{00}| = (2.221 \pm 0.011) \times 10^{-3} \quad (S = 1.8)$$

$$|\eta_{+-}| = (2.232 \pm 0.011) \times 10^{-3} \quad (S = 1.8)$$

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3} \quad (S = 1.8)$$

$$|\eta_{00}/\eta_{+-}| = 0.9951 \pm 0.0008^{[a]} \quad (S = 1.6)$$

$$\text{Re}(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3}^{[a]} \quad (S = 1.6)$$

Assuming *CPT*

$$\phi_{+-} = (43.51 \pm 0.05)^\circ \quad (S = 1.1)$$

$$\phi_{00} = (43.52 \pm 0.05)^\circ \quad (S = 1.1)$$

$$\phi_\epsilon = \phi_{SW} = (43.51 \pm 0.05)^\circ \quad (S = 1.1)$$

Not assuming *CPT*

$$\phi_{+-} = (43.4 \pm 0.7)^\circ \quad (S = 1.3)$$

$$\phi_{00} = (43.7 \pm 0.8)^\circ \quad (S = 1.2)$$

$$\phi_\epsilon = (43.5 \pm 0.7)^\circ \quad (S = 1.3)$$

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

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

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

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

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

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

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

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

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

### **T-violation parameters**

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

### **CPT invariance tests**

$$\phi_{00} - \phi_{+-} = (0.2 \pm 0.4)^\circ$$

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

### **$\Delta S = -\Delta Q$ 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	$p$ (MeV/c)
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**Semileptonic modes**

$\pi^\pm e^\mp \nu_e$ Called $K_{e3}^0$ .	[ $\eta$ ] (40.55 $\pm$ 0.12 ) %	S=1.8	229
$\pi^\pm \mu^\mp \nu_\mu$ Called $K_{\mu3}^0$ .	[ $\eta$ ] (27.04 $\pm$ 0.07 ) %	S=1.1	216
$(\pi \mu \text{atom})\nu$	( 1.05 $\pm$ 0.11 ) $\times 10^{-7}$		188
$\pi^0 \pi^\pm e^\mp \nu$	[ $\eta$ ] ( 5.20 $\pm$ 0.11 ) $\times 10^{-5}$		207
$\pi^\pm e^\mp \nu e^+ e^-$	[ $\eta$ ] ( 1.26 $\pm$ 0.04 ) $\times 10^{-5}$		229

**Hadronic modes, including Charge conjugation  $\times$  Parity Violating (CPV) modes**

$3\pi^0$	(19.52 $\pm$ 0.12 ) %	S=1.7	139
$\pi^+ \pi^- \pi^0$	(12.54 $\pm$ 0.05 ) %		133
$\pi^+ \pi^-$	CPV [ $\rho$ ] ( 1.966 $\pm$ 0.010 ) $\times 10^{-3}$	S=1.6	206
$\pi^0 \pi^0$	CPV ( 8.65 $\pm$ 0.06 ) $\times 10^{-4}$	S=1.8	209

**Semileptonic modes with photons**

$\pi^\pm e^\mp \nu_e \gamma$	[ $e, n, q$ ] ( 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  $l\bar{l}$  pairs**

$\pi^0 \pi^0 \gamma$	< 2.43 $\times 10^{-7}$	CL=90%	209
$\pi^+ \pi^- \gamma$	[ $e, q$ ] ( 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
$\pi^0 2\gamma$	[ $q$ ] ( 1.273 $\pm$ 0.034 ) $\times 10^{-6}$		231
$\pi^0 \gamma e^+ e^-$	( 1.62 $\pm$ 0.17 ) $\times 10^{-8}$		230

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

$2\gamma$	( 5.47 $\pm$ 0.04 ) $\times 10^{-4}$	S=1.2	249
$3\gamma$	< 2.4 $\times 10^{-7}$	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
$e^+ e^- \gamma \gamma$	[ $q$ ] ( 5.95 $\pm$ 0.33 ) $\times 10^{-7}$		249
$\mu^+ \mu^- \gamma \gamma$	[ $q$ ] ( 1.0 $^{+0.8}_{-0.6}$ ) $\times 10^{-8}$		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 $^{+6}_{-4}$ ) $\times 10^{-12}$		249
$\pi^+ \pi^- e^+ e^-$	S1 [ $q$ ] ( 3.11 $\pm$ 0.19 ) $\times 10^{-7}$		206
$\pi^0 \pi^0 e^+ e^-$	S1 < 6.6 $\times 10^{-9}$	CL=90%	209
$\mu^+ \mu^- e^+ e^-$	S1 ( 2.69 $\pm$ 0.27 ) $\times 10^{-9}$		225
$e^+ e^- e^+ e^-$	S1 ( 3.56 $\pm$ 0.21 ) $\times 10^{-8}$		249



$\pi^0 \mu^+ \mu^-$	<i>CP,S1</i>	$[r] < 3.8$	$\times 10^{-10}$	CL=90%	177
$\pi^0 e^+ e^-$	<i>CP,S1</i>	$[r] < 2.8$	$\times 10^{-10}$	CL=90%	230
$\pi^0 \nu \bar{\nu}$	<i>CP,S1</i>	$[s] < 6.7$	$\times 10^{-8}$	CL=90%	231
$\pi^0 \pi^0 \nu \bar{\nu}$	<i>S1</i>	$< 4.7$	$\times 10^{-5}$	CL=90%	209
$e^\pm \mu^\mp$	<i>LF</i>	$[n] < 4.7$	$\times 10^{-12}$	CL=90%	238
$e^\pm e^\pm \mu^\mp \mu^\mp$	<i>LF</i>	$[n] < 4.12$	$\times 10^{-11}$	CL=90%	225
$\pi^0 \mu^\pm e^\mp$	<i>LF</i>	$[n] < 7.6$	$\times 10^{-11}$	CL=90%	217
$\pi^0 \pi^0 \mu^\pm e^\mp$	<i>LF</i>	$< 1.7$	$\times 10^{-10}$	CL=90%	159

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

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

$K^*(892)^\pm$  mass  $m = 891.66 \pm 0.26$  MeV

Mass  $m = 895.5 \pm 0.8$  MeV

$K^*(892)^0$  mass  $m = 896.00 \pm 0.25$  MeV (S = 1.4)

$K^*(892)^\pm$  full width  $\Gamma = 50.8 \pm 0.9$  MeV

Full width  $\Gamma = 46.2 \pm 1.3$  MeV

$K^*(892)^0$  full width  $\Gamma = 50.3 \pm 0.6$  MeV (S = 1.1)

<b><math>K^*(892)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$K \pi$	$\sim 100$	%	289
$K^0 \gamma$	$(2.31 \pm 0.20) \times 10^{-3}$		307
$K^\pm \gamma$	$(9.9 \pm 0.9) \times 10^{-4}$		309
$K \pi \pi$	$< 7$	$\times 10^{-4}$ 95%	223

### **$K_1(1270)$**

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

Mass  $m = 1272 \pm 7$  MeV [t]

Full width  $\Gamma = 90 \pm 20$  MeV [t]

<b><math>K_1(1270)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K \rho$	$(42 \pm 6) \%$	45
$K_0^*(1430) \pi$	$(28 \pm 4) \%$	†
$K^*(892) \pi$	$(16 \pm 5) \%$	302
$K \omega$	$(11.0 \pm 2.0) \%$	†
$K f_0(1370)$	$(3.0 \pm 2.0) \%$	†
$\gamma K^0$	seen	539

### **$K_1(1400)$**

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

Mass  $m = 1403 \pm 7$  MeV

Full 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) %	292
$Kf_0(1370)$	(2.0 $\pm$ 2.0) %	†
$K\omega$	(1.0 $\pm$ 1.0) %	284
$K_0^*(1430)\pi$	not seen	†
$\gamma K^0$	seen	613

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

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

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
$\gamma K^0$	seen		619

**$K_0^*(1430) [u]$**

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

Mass  $m = 1425 \pm 50$  MeV

Full width  $\Gamma = 270 \pm 80$  MeV

<b><math>K_0^*(1430)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	(93 $\pm$ 10) %	619

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

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

$K_2^*(1430)^\pm$  mass  $m = 1425.6 \pm 1.5$  MeV (S = 1.1)

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

$K_2^*(1430)^\pm$  full width  $\Gamma = 98.5 \pm 2.7$  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)
$K\pi$	$(49.9 \pm 1.2) \%$		619
$K^*(892)\pi$	$(24.7 \pm 1.5) \%$		419
$K^*(892)\pi\pi$	$(13.4 \pm 2.2) \%$		372
$K\rho$	$(8.7 \pm 0.8) \%$	S=1.2	318
$K\omega$	$(2.9 \pm 0.8) \%$		311
$K^+\gamma$	$(2.4 \pm 0.5) \times 10^{-3}$	S=1.1	627
$K\eta$	$(1.5^{+3.4}_{-1.0}) \times 10^{-3}$	S=1.3	486
$K\omega\pi$	$< 7.2 \times 10^{-4}$	CL=95%	100
$K^0\gamma$	$< 9 \times 10^{-4}$	CL=90%	626

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

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

Mass  $m = 1717 \pm 27$  MeV (S = 1.4)

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)
$K\pi$	$(38.7 \pm 2.5) \%$	781
$K\rho$	$(31.4^{+5.0}_{-2.1}) \%$	570
$K^*(892)\pi$	$(29.9^{+2.2}_{-5.0}) \%$	618

### **$K_2(1770)$ [v]**

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

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
$K_2^*(1430)\pi$	dominant	288
$K^*(892)\pi$	seen	654
$Kf_2(1270)$	seen	55
$K\phi$	seen	441
$K\omega$	seen	607

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

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

Mass  $m = 1776 \pm 7$  MeV (S = 1.1)

Full width  $\Gamma = 159 \pm 21$  MeV (S = 1.3)

<b><math>K_3^*(1780)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$p$ (MeV/c)
$K\rho$	(31 $\pm$ 9 ) %		613
$K^*(892)\pi$	(20 $\pm$ 5 ) %		656
$K\pi$	(18.8 $\pm$ 1.0) %		813
$K\eta$	(30 $\pm$ 13 ) %		719
$K_2^*(1430)\pi$	< 16 %	95%	291

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

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

Mass  $m = 1816 \pm 13$  MeV

Full width  $\Gamma = 276 \pm 35$  MeV

<b><math>K_2(1820)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K_2^*(1430)\pi$	seen	327
$K^*(892)\pi$	seen	681
$K f_2(1270)$	seen	186
$K\omega$	seen	638

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

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

Mass  $m = 2045 \pm 9$  MeV ( $S = 1.1$ )

Full width  $\Gamma = 198 \pm 30$  MeV

<b><math>K_4^*(2045)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	(9.9 $\pm$ 1.2) %	958
$K^*(892)\pi\pi$	(9 $\pm$ 5 ) %	802
$K^*(892)\pi\pi\pi$	(7 $\pm$ 5 ) %	768
$\rho K\pi$	(5.7 $\pm$ 3.2) %	741
$\omega K\pi$	(5.0 $\pm$ 3.0) %	738
$\phi K\pi$	(2.8 $\pm$ 1.4) %	594
$\phi K^*(892)$	(1.4 $\pm$ 0.7) %	363

## NOTES

- [a] See the note in the  $K^\pm$  Particle Listings.
- [b] The definition of the slope parameter  $g$  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):
- $$|M|^2 = 1 + g(s_3 - s_0)/m_{\pi^+}^2 + \dots$$
- [c] For more details and definitions of parameters see the Particle Listings.
- [d] See the “Note on  $\pi^\pm \rightarrow \ell^\pm \nu \gamma$  and  $K^\pm \rightarrow \ell^\pm \nu \gamma$  Form Factors” in the  $\pi^\pm$  Particle Listings for definitions and details.
- [e] Most of this radiative mode, the low-momentum  $\gamma$  part, is also included in the parent mode listed without  $\gamma$ 's.
- [f] See the  $K^\pm$  Particle Listings for the energy limits used in this measurement.
- [g] Structure-dependent part.
- [h] Direct-emission branching fraction.
- [i] Derived from an analysis of neutrino-oscillation experiments.
- [j] Violates angular-momentum conservation.
- [k] 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.”
- [l] 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  $\text{Re}(\eta_{000}) \simeq 0$ .

- [m] See the  $K_S^0$  Particle Listings for the energy limits used in this measurement.
- [n] The value is for the sum of the charge states or particle/antiparticle states indicated.
- [o]  $\text{Re}(\epsilon'/\epsilon) = \epsilon'/\epsilon$  to a very good approximation provided the phases satisfy *CPT* invariance.
- [p] This mode includes gammas from inner bremsstrahlung but not the direct emission mode  $K_L^0 \rightarrow \pi^+ \pi^- \gamma$ (DE).
- [q] See the  $K_L^0$  Particle Listings for the energy limits used in this measurement.
- [r] Allowed by higher-order electroweak interactions.
- [s] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.
- [t] This is only an educated guess; the error given is larger than the error on the average of the published values. See the Particle Listings for details.
- [u] See the "Note on  $f_0(1370)$ " in the  $f_0(1370)$  Particle Listings and in the 1994 edition.
- [v] See the note in the  $L(1770)$  Particle Listings in Reviews of Modern Physics **56** S1 (1984), p. S200. See also the "Note on  $K_2(1770)$  and the  $K_2(1820)$ " in the  $K_2(1770)$  Particle Listings .
- [w] See the "Note on  $K_2(1770)$  and the  $K_2(1820)$ " in the  $K_2(1770)$  Particle Listings .