

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

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

**$K^\pm$**

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

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

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

$$c\tau = 3.711$$
 m

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

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

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

## **$CP$ 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)

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

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

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

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

## **$K^\pm$ 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## Charge radius

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

## Forward-backward asymmetry

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

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

<b>K<sup>+</sup> 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] ( $2.56 \pm 0.16$ ) $\times 10^{-4}$		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] ( $7.6 \begin{array}{l} +6.0 \\ -3.0 \end{array} \times 10^{-6}$ )		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
$\mu^+ \nu_\mu \nu \bar{\nu}$	<	2.4	$\times 10^{-6}$	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
$\pi^+ \nu \bar{\nu}$	$S1$	(	$1.7 \pm 1.1$	) $\times 10^{-10}$		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
$\pi^+ \mu^- e^+$	$LF$	<	5.2	$\times 10^{-10}$	CL=90%	214
$\pi^- \mu^+ e^+$	$L$	<	5.0	$\times 10^{-10}$	CL=90%	214
$\pi^- e^+ e^+$	$L$	<	2.2	$\times 10^{-10}$	CL=90%	227
$\pi^- \mu^+ \mu^+$	$L$	[j] <	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

 **$K^0$** 

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

50%  $K_S$ , 50%  $K_L$ Mass  $m = 497.611 \pm 0.013$  MeV ( $S = 1.2$ ) $m_{K^0} - m_{K^\pm} = 3.934 \pm 0.020$  MeV ( $S = 1.6$ )**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]**

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

 **$CP$ -violation parameters**

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

**CPT-violation parameters [e]**

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

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

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

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

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

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

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

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

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

**CP-violation parameters [n]**

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

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

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

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

<b><math>K_S^0</math> DECAY MODES</b>	Fraction $(\Gamma_i/\Gamma)$	Scale factor/ Confidence level	$p$ (MeV/c)
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**Hadronic modes**

$\pi^0\pi^0$	$(30.69 \pm 0.05) \%$	209
$\pi^+\pi^-$	$(69.20 \pm 0.05) \%$	206
$\pi^+\pi^-\pi^0$	$(3.5 \pm 1.1) \times 10^{-7}$	133

**Modes with photons or  $\ell\bar{\ell}$  pairs**

$\pi^+\pi^-\gamma$	$[g,o] (1.79 \pm 0.05) \times 10^{-3}$	206
$\pi^+\pi^-e^+e^-$	$(4.79 \pm 0.15) \times 10^{-5}$	206
$\pi^0\gamma\gamma$	$[o] (4.9 \pm 1.8) \times 10^{-8}$	230
$\gamma\gamma$	$(2.63 \pm 0.17) \times 10^{-6}$	$S=3.0$ 249

**Semileptonic modes**

$\pi^\pm e^\mp \nu_e$	$[p] (7.04 \pm 0.08) \times 10^{-4}$	229
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**$CP$  violating ( $CP$ ) and  $\Delta S = 1$  weak neutral current ( $S1$ ) modes**

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

 **$K_L^0$** 

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

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

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

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

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

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

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

**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

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

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

$$K_{e3}^0 \quad |f_S/f_+| = (1.5^{+1.4}_{-1.6}) \times 10^{-2}$$

$$K_{e3}^0 \quad |f_T/f_+| = (5^{+4}_{-5}) \times 10^{-2}$$

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

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

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

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

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

### **$CP$ -violation parameters [n]**

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

$$|\eta_{00}| = (2.220 \pm 0.011) \times 10^{-3} \quad (S = 1.8)$$

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

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

$$|\eta_{00}/\eta_{+-}| = 0.9950 \pm 0.0007 [q] \quad (S = 1.6)$$

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

Assuming  $CPT$

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

$$\phi_{00} = (43.52 \pm 0.05)^\circ \quad (S = 1.3)$$

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

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

Not assuming  $CPT$

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

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

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

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

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

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

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

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

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

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

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

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

### T-violation parameters

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

### CPT invariance tests

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

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

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

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

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

$K_L^0$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ $\rho$	Confidence level (MeV/c)
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### Semileptonic modes

$\pi^\pm e^\mp \nu_e$ 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

### Hadronic modes, including Charge conjugation x Parity Violating (CPV) modes

$3\pi^0$	(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

### Semileptonic modes with photons

$\pi^\pm e^\mp \nu_e \gamma$	[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

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

$\pi^0 \pi^0 \gamma$	< 2.43 $\times 10^{-7}$	CL=90%	209
$\pi^+ \pi^- \gamma$	[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

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

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

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

$\mu^+ \mu^-$	$S1$	$( 6.84 \pm 0.11 ) \times 10^{-9}$		225
$e^+ e^-$	$S1$	$( 9 \pm 6 ) \times 10^{-12}$		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

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

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

also known as  $\kappa$ ; was  $K_0^*(800)$ Mass (T-Matrix Pole  $\sqrt{s}$ ) =  $(630\text{--}730) - i(260\text{--}340)$  MeVMass (Breit-Wigner) =  $824 \pm 30$  MeVFull width (Breit-Wigner) =  $478 \pm 50$  MeV

<b><math>K_0^*(700)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	100 %	240

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

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

 $K^*(892)^\pm$  hadroproduced mass  $m = 891.66 \pm 0.26$  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  $\Gamma = 50.8 \pm 0.9$  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	(MeV/c) <i>p</i>
$K\pi$	~ 100 %		289
$K^0\gamma$	( $2.46 \pm 0.21$ ) $\times 10^{-3}$		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  $m = 1253 \pm 7$  MeV [v] ( $S = 2.2$ )  
Full width  $\Gamma = 90 \pm 20$  MeV [v]

<b><math>K_1(1270)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	<i>p</i> (MeV/c)
$K\rho$	(42 $\pm 6$ ) %	†
$K_0^*(1430)\pi$	(28 $\pm 4$ ) %	†
$K^*(892)\pi$	(16 $\pm 5$ ) %	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  $m = 1403 \pm 7$  MeV  
Full width  $\Gamma = 174 \pm 13$  MeV ( $S = 1.6$ )

<b><math>K_1(1400)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	<i>p</i> (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

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

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

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

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

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

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
$K\eta$	$(8.6^{+2.7}_{-3.4})$ %	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

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

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

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)
$K\pi$	( $38.7 \pm 2.5$ ) %	782
$K\rho$	( $31.4^{+5.0}_{-2.1}$ ) %	571
$K^*(892)\pi$	( $29.9^{+2.2}_{-5.0}$ ) %	618
$K\phi$	seen	387

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

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

Mass  $m = 1773 \pm 8$  MeVFull 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  $m = 1776 \pm 7$  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%	290

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

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

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)
$K_2^*(1430)\pi$	seen	328
$K^*(892)\pi$	seen	683
$K f_2(1270)$	seen	191
$K\omega$	seen	640
$K\phi$	seen	483

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

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

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

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

<b><math>K_4^*(2045)</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	$p$ (MeV/c)
$K\pi$	(9.9 $\pm$ 1.2) %	960
$K^*(892)\pi\pi$	(9 $\pm$ 5) %	804
$K^*(892)\pi\pi\pi$	(7 $\pm$ 5) %	770
$\rho K\pi$	(5.7 $\pm$ 3.2) %	744
$\omega K\pi$	(5.0 $\pm$ 3.0) %	740
$\phi K\pi$	(2.8 $\pm$ 1.4) %	597
$\phi K^*(892)$	(1.4 $\pm$ 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  $K_L^0 \rightarrow \pi^+ \pi^- \gamma$  (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 the “Note on  $f_0(1370)$ ” in the  $f_0(1370)$  Particle Listings and in the 1994 edition.
- [y] 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 .
- [z] See the “Note on  $K_2(1770)$  and the  $K_2(1820)$ ” in the  $K_2(1770)$  Particle Listings .