K^0_L

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

$m_{K^0_L} - m_{K^0_S}$

For earlier measurements, beginning with GOOD 61 and FITCH 61, see our 1986 edition, Physics Letters **170B** 132 (1986).

OUR FIT is described in the note on "*CP* violation in K_L decays" in the K^0_L Particle Listings. The result labeled "OUR FIT Assuming *CPT*" ["OUR FIT Not assuming *CPT*"] includes all measurements except those with the comment "Not assuming *CPT*" ["Assuming *CPT*"]. Measurements with neither comment do not assume *CPT* and enter both fits.

VALUE (10^{10} $\hbar$ s^{-1})		*DOCUMENT ID*	*TECN*	*COMMENT*
0.5292±0.0009	**OUR FIT**	Error includes scale factor of 1.2. Assuming *CPT*		
0.5290±0.0015	**OUR FIT**	Error includes scale factor of 1.1. Not assuming *CPT*		
0.5261±0.0015		[1,2] ALAVI-HARATI 03	KTEV	Assuming *CPT*
0.5288±0.0043		[2,3] ALAVI-HARATI 03	KTEV	Not assuming *CPT*
0.5240±0.0044	±0.0033	APOSTOLA... 99C	CPLR	K^0-$\overline{K}^0$ to $\pi^+\pi^-$
0.5297±0.0030	±0.0022	[4] SCHWINGEN... 95	E773	20–160 GeV *K* beams
0.5286±0.0028		[5] GIBBONS 93	E731	Assuming *CPT*
0.5257±0.0049	±0.0021	[4] GIBBONS 93C	E731	Not assuming *CPT*
0.5340±0.00255	±0.0015	[6] GEWENIGER 74C	SPEC	Gap method
0.5334±0.0040	±0.0015	[6,7] GJESDAL 74	SPEC	Assuming *CPT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5343±0.0063	±0.0025	[8] ANGELOPO... 01	CPLR	
0.5295±0.0020	±0.0003	[9] ANGELOPO... 98D	CPLR	Assuming *CPT*
0.5307±0.0013		[10] ADLER 96C	RVUE	
0.5274±0.0029	±0.0005	[9] ADLER 95	CPLR	Sup. by ANGELOPOULOS 98D
0.482 ±0.014		[11] ARONSON 82B	SPEC	*E*=30–110 GeV
0.534 ±0.007		[12] CARNEGIE 71	ASPK	Gap method
0.542 ±0.006		[12] ARONSON 70	ASPK	Gap method
0.542 ±0.006		CULLEN 70	CNTR	

[1] ALAVI-HARATI 03 fit Δm and $\tau_{K^0_S}$ simultaneously. ϕ_{+-} is constrained to the Superweak value, i.e. *CPT* is assumed. See "K^0_S Mean Life" section for correlation information.

[2] The two ALAVI-HARATI 03 values use the same data. The first enters the "Assuming *CPT*" fit and the second enters the "Not assuming *CPT*" fit. They use 40–160 GeV *K* beams.

[3] ALAVI-HARATI 03 fit Δm, ϕ_{+-}, and τ_{K_S} simultaneously. See ϕ_{+-} in the "K_L *CP* violation" section for correlation information.

[4] Fits Δm and ϕ_{+-} simultaneously. GIBBONS 93C systematic error is from B. Winstein via private communication. 20–160 GeV *K* beams.

[5] GIBBONS 93 value assume $\phi_{+-} = \phi_{00} = \phi_{SW} = (43.7 \pm 0.2)^\circ$, i.e. assumes *CPT*. 20–160 GeV *K* beams.

[6] These two experiments have a common systematic error due to the uncertainty in the momentum scale, as pointed out in WAHL 89.

[7] GJESDAL 74 uses charge asymmetry in $K^0_{\ell 3}$ decays.

[8] ANGELOPOULOS 01 uses strong interactions strangeness tagging at two different times.

[9] Uses $\overline{K}^0_{e3}$ and K^0_{e3} strangeness tagging at production and decay. Assumes *CPT* conservation on $\Delta S{=}-\Delta Q$ transitions.

[10] ADLER 96C is the result of a fit which includes nearly the same data as entered into the "OUR FIT" value above.

[11] ARONSON 82 find that Δm may depend on the kaon energy.

[12] ARONSON 70 and CARNEGIE 71 use K^0_S mean life = $(0.862 \pm 0.006) \times 10^{-10}$ s. We have not attempted to adjust these values for the subsequent change in the K^0_S mean life or in η_{+-}.

K^0_L MEAN LIFE

VALUE (10^{-8} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5.114±0.021 OUR FIT					
5.099±0.021 OUR AVERAGE					
5.072±0.011±0.035	13M	[13] AMBROSINO	06	KLOE	$\sum_i \mathrm{B}_i = 1$
5.092±0.017±0.025	15M	AMBROSINO	05C	KLOE	
5.154±0.044	0.4M	VOSBURGH	72	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.15 ±0.14		DEVLIN	67	CNTR	

[13] AMBROSINO 06 uses $\phi \to K_L K_S$ with K_L tagged by $K_S \to \pi^+\pi^-$. The four major K_L BR's are measured, the small remainder ($\pi^+\pi^-$,$\pi^0\pi^0$,$\gamma\gamma$) is taken from PDG 04. This KLOE K_L lifetime is obtained by imposing $\sum_i \mathrm{B}_i = 1$. The correlation matrix among the four measured K_L BR's and this K_L lifetime is

$$\begin{array}{cccccc} & K_{e3} & K_{\mu3} & 3\pi^0 & \pi^+\pi^-\pi^0 & \tau_{K_L} \\ K_{e3} & 1 & -0.25 & -0.56 & -0.07 & 0.25 \\ K_{\mu3} & & 1 & -0.43 & -0.20 & 0.33 \\ 3\pi^0 & & & 1 & -0.39 & -0.21 \\ \pi^+\pi^-\pi^0 & & & & 1 & -0.39 \\ \tau_{K_L} & & & & & 1 \end{array}$$

These correlations are taken into account in our fit. The average of this KLOE mean life measurement and the independent KLOE measurement in AMBROSINO 05C is $(5.084 \pm 0.023) \times 10^{-8}$ s.

K^0_L DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic modes			
Γ_1	$\pi^\pm e^\mp \nu_e$ Called K^0_{e3}.	[a]	(40.53 ± 0.15) %	S=2.1
Γ_2	$\pi^\pm \mu^\mp \nu_\mu$ Called $K^0_{\mu3}$.	[a]	(27.02 ± 0.07) %	
Γ_3	$(\pi\mu\,\mathrm{atom})\nu$		$(1.05 \pm 0.11) \times 10^{-7}$	
Γ_4	$\pi^0\pi^\pm e^\mp \nu$	[a]	$(5.20 \pm 0.11) \times 10^{-5}$	

Hadronic modes, including Charge conjugation×Parity Violating (*CPV*) modes

Γ_5	$3\pi^0$			$(19.56 \pm 0.14)\ \%$	S=1.9
Γ_6	$\pi^+\pi^-\pi^0$			$(12.56 \pm 0.05)\ \%$	
Γ_7	$\pi^+\pi^-$	*CPV*		$(1.976 \pm 0.008) \times 10^{-3}$	
Γ_8	$\pi^0\pi^0$	*CPV*		$(8.69 \pm 0.04) \times 10^{-4}$	S=1.1

Semileptonic modes with photons

Γ_9	$\pi^\pm e^\mp \nu_e \gamma$		[*a*,*b*,*c*]	$(3.79 \pm 0.08) \times 10^{-3}$	
Γ_{10}	$\pi^\pm \mu^\mp \nu_\mu \gamma$			$(5.64 \pm 0.23) \times 10^{-4}$	

Hadronic modes with photons or $\ell\overline{\ell}$ pairs

Γ_{11}	$\pi^0\pi^0\gamma$			$< 5.6 \times 10^{-6}$	
Γ_{12}	$\pi^+\pi^-\gamma$		[*b*,*c*]	$(4.17 \pm 0.15) \times 10^{-5}$	
Γ_{13}	$\pi^0 2\gamma$		[*c*]	$(1.49 \pm 0.08) \times 10^{-6}$	S=2.0
Γ_{14}	$\pi^0\gamma e^+ e^-$			$(2.3 \pm 0.4) \times 10^{-8}$	

Other modes with photons or $\ell\overline{\ell}$ pairs

Γ_{15}	2γ			$(5.48 \pm 0.05) \times 10^{-4}$	S=1.2
Γ_{16}	3γ			$< 2.4 \times 10^{-7}$	CL=90%
Γ_{17}	$e^+e^-\gamma$			$(10.0 \pm 0.5) \times 10^{-6}$	S=1.5
Γ_{18}	$\mu^+\mu^-\gamma$			$(3.59 \pm 0.11) \times 10^{-7}$	S=1.3
Γ_{19}	$e^+e^-\gamma\gamma$		[*c*]	$(5.95 \pm 0.33) \times 10^{-7}$	
Γ_{20}	$\mu^+\mu^-\gamma\gamma$		[*c*]	$(1.0\ ^{+0.8}_{-0.6}) \times 10^{-8}$	

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

Γ_{21}	$\mu^+\mu^-$	*S1*		$(6.87 \pm 0.11) \times 10^{-9}$	
Γ_{22}	e^+e^-	*S1*		$(9\ ^{+6}_{-4}) \times 10^{-12}$	
Γ_{23}	$\pi^+\pi^-e^+e^-$	*S1*	[*c*]	$(3.11 \pm 0.19) \times 10^{-7}$	
Γ_{24}	$\pi^0\pi^0e^+e^-$	*S1*		$< 6.6 \times 10^{-9}$	CL=90%
Γ_{25}	$\mu^+\mu^-e^+e^-$	*S1*		$(2.69 \pm 0.27) \times 10^{-9}$	
Γ_{26}	$e^+e^-e^+e^-$	*S1*		$(3.56 \pm 0.21) \times 10^{-8}$	
Γ_{27}	$\pi^0\mu^+\mu^-$	*CP*,*S1*	[*d*]	$< 3.8 \times 10^{-10}$	CL=90%
Γ_{28}	$\pi^0e^+e^-$	*CP*,*S1*	[*d*]	$< 2.8 \times 10^{-10}$	CL=90%
Γ_{29}	$\pi^0\nu\overline{\nu}$	*CP*,*S1*	[*e*]	$< 5.9 \times 10^{-7}$	CL=90%
Γ_{30}	$e^\pm\mu^\mp$	*LF*	[*a*]	$< 4.7 \times 10^{-12}$	CL=90%
Γ_{31}	$e^\pm e^\pm\mu^\mp\mu^\mp$	*LF*	[*a*]	$< 4.12 \times 10^{-11}$	CL=90%
Γ_{32}	$\pi^0\mu^\pm e^\mp$	*LF*	[*a*]	$< 6.2 \times 10^{-9}$	CL=90%

[*a*] The value is for the sum of the charge states or particle/antiparticle states indicated.

[*b*] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

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

[*d*] Allowed by higher-order electroweak interactions.

[*e*] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life and 10 branching ratios uses 17 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 14.8$ for 10 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta p_i \delta p_j \right\rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1	x_2	x_5	x_6	x_7	x_8	x_{15}
x_2	−15						
x_5	−87	−23					
x_6	−34	−20	8				
x_7	3	−2	−6	8			
x_8	2	−12	5	−5	69		
x_{15}	−62	−18	73	5	2	13	
Γ	−28	−9	26	21	0	0	19

	Mode	Rate (10^8 s^{-1})	Scale factor
Γ_1	$\pi^{\pm} e^{\mp} \nu_e$ Called K^0_{e3}.	[*a*] 0.0792 ±0.0004	1.1
Γ_2	$\pi^{\pm} \mu^{\mp} \nu_\mu$ Called $K^0_{\mu3}$.	[*a*] 0.05285±0.00024	
Γ_5	$3\pi^0$	0.03824±0.00035	1.6
Γ_6	$\pi^+ \pi^- \pi^0$	0.02455±0.00016	1.1
Γ_7	$\pi^+ \pi^-$	(3.865 ±0.022) × 10^{-4}	
Γ_8	$\pi^0 \pi^0$	(1.699 ±0.011) × 10^{-4}	1.1
Γ_{15}	2γ	(1.072 ±0.011) × 10^{-4}	1.3

K^0_L DECAY RATES

$\Gamma(\pi^+\pi^-\pi^0)$ Γ_6

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.455±0.016 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.32 $^{+0.13}_{-0.15}$	192	BALDO-... 75	HLBC	Assumes *CP*
2.35 ±0.20	180	[14] JAMES 72	HBC	Assumes *CP*
2.71 ±0.28	99	CHO 71	DBC	Assumes *CP*
2.5 ±0.3	98	[14] JAMES 71	HBC	Assumes *CP*
2.12 ±0.33	50	MEISNER 71	HBC	Assumes *CP*
2.20 ±0.35	53	WEBBER 70	HBC	Assumes *CP*
2.62 $^{+0.28}_{-0.27}$	136	BEHR 66	HLBC	Assumes *CP*
3.26 ±0.77	18	ANDERSON 65	HBC	
1.4 ±0.4	14	FRANZINI 65	HBC	

[14] JAMES 72 is a final measurement and includes JAMES 71.

$\Gamma(\pi^\pm e^\mp \nu_e)$ Γ_1

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
7.92±0.04 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7.81±0.56	620	CHAN 71	HBC	
7.52$^{+0.85}_{-0.72}$		AUBERT 65	HLBC	$\Delta S=\Delta Q$,*CP* assumed

$\Gamma(\pi^\pm e^\mp \nu_e) + \Gamma(\pi^\pm \mu^\mp \nu_\mu)$ $(\Gamma_1+\Gamma_2)$

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
13.21±0.05 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
12.4 ±0.7	410	[15] BURGUN 72	HBC	$K^+ p \to K^0 p \pi^+$
8.47±1.69	126	[15] MANN 72	HBC	$K^- p \to n \overline{K}^0$
13.1 ±1.3	252	[15] WEBBER 71	HBC	$K^- p \to n \overline{K}^0$
11.6 ±0.9	393	[15,16] CHO 70	DBC	$K^+ n \to K^0 p$
10.3 ±0.8	335	[16] HILL 67	DBC	$K^+ n \to K^0 p$
9.85$^{+1.15}_{-1.05}$	109	[15] FRANZINI 65	HBC	

[15] Assumes $\Delta S = \Delta Q$ rule.

[16] CHO 70 includes events of HILL 67.

K^0_L BRANCHING RATIOS

Semileptonic modes

$\Gamma(\pi^\pm e^\mp \nu_e)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.4053±0.0015 OUR FIT Error includes scale factor of 2.1.			
0.4047±0.0028 OUR AVERAGE Error includes scale factor of 3.1.			
0.4007±0.0005±0.0015	13M	[17] AMBROSINO 06	KLOE
0.4067±0.0011		[18] ALEXOPOU... 04	KTEV

[17] There are correlations between these five KLOE measurements: B($K_L \to \pi e \nu$), B($K_L \to \pi \mu \nu$), B($K_L \to 3\pi^0$), B($K_L \to \pi^+ \pi^- \pi^0$), and τ_{K_L} measured in AMBROSINO 06. See the footnote for the τ_{K_L} measurement for the correlation matrix.

[18] ALEXOPOULOS 04 constrains $\sum_i$ B$_i$ = 0.9993 for the six major K_L branching fractions. The correlations among these branching fractions are taken into account in our fit. The correlation matrix is

$$\begin{array}{ccccccc} & K_{e3} & K_{\mu 3} & 3\pi^0 & \pi^+\pi^-\pi^0 & \pi^+\pi^- & \pi^0\pi^0 \\ K_{e3} & 1 & & & & & \\ K_{\mu 3} & 0.15 & 1 & & & & \\ 3\pi^0 & -0.77 & -0.62 & 1 & & & \\ \pi^+\pi^-\pi^0 & 0.18 & 0.08 & -0.54 & 1 & & \\ \pi^+\pi^- & 0.28 & 0.22 & -0.48 & 0.49 & 1 & \\ \pi^0\pi^0 & -0.72 & -0.54 & 0.89 & -0.46 & -0.39 & 1 \end{array}$$

$\Gamma(\pi^\pm \mu^\mp \nu_\mu)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
0.2702±0.0007 OUR FIT				
0.2700±0.0008 OUR AVERAGE				
0.2698±0.0005±0.0015	13M	[19] AMBROSINO	06	KLOE
0.2701±0.0009		[20] ALEXOPOU...	04	KTEV

[19] There are correlations between these five KLOE measurements: B($K_L \to \pi e \nu$), B($K_L \to \pi \mu \nu$), B($K_L \to 3\pi^0$), B($K_L \to \pi^+ \pi^- \pi^0$), and τ_{K_L} measured in AMBROSINO 06. See the footnote for the τ_{K_L} measurement for the correlation matrix.

[20] For correlations with other ALEXOPOULOS 04 measurements, see the footnote with their B($K_L \to \pi e \nu$) measurement.

$[\Gamma(\pi^\pm e^\mp \nu_e) + \Gamma(\pi^\pm \mu^\mp \nu_\mu)]/\Gamma_{\text{total}}$ $(\Gamma_1+\Gamma_2)/\Gamma$

VALUE	*DOCUMENT ID*
0.6755±0.0016 OUR FIT Error includes scale factor of 2.0.	

$\Gamma(\pi^\pm \mu^\mp \nu_\mu)/\Gamma(\pi^\pm e^\mp \nu_e)$ Γ_2/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.6668±0.0032 OUR FIT Error includes scale factor of 1.4.					
0.666 ±0.004 OUR AVERAGE Error includes scale factor of 1.6.					
0.6740±0.0059	13M	[21] AMBROSINO	06	KLOE	Not in fit
0.6640±0.0014±0.0022	394K	[22] ALEXOPOU...	04	KTEV	Not in fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.702 ±0.011	33k	CHO	80	HBC	
0.662 ±0.037	10k	WILLIAMS	74	ASPK	
0.741 ±0.044	6700	BRANDENB...	73	HBC	
0.662 ±0.030	1309	EVANS	73	HLBC	
0.68 ±0.08	3548	BASILE	70	OSPK	
0.71 ±0.05	770	BUDAGOV	68	HLBC	

[21] AMBROSINO 06 enters the fit via their separate measurements of these two modes.

[22] ALEXOPOULOS 04 enters the fit via their separate measurements of these two modes.

$\Gamma((\pi\mu\text{atom})\nu)/\Gamma(\pi^{\pm}\mu^{\mp}\nu_{\mu})$ — Γ_3/Γ_2

VALUE (units 10^{-7})	*EVTS*	*DOCUMENT ID*		*TECN*
3.90±0.39	155	[23] ARONSON	86	SPEC

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

VALUE (units 10^{-7})	*EVTS*	*DOCUMENT ID*		*TECN*
seen	18	COOMBES	76	WIRE

[23] ARONSON 86 quote theoretical value of $(4.31 \pm 0.08) \times 10^{-7}$.

$\Gamma(\pi^0\pi^{\pm}e^{\mp}\nu)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
5.20±0.11 OUR AVERAGE					
5.21±0.07±0.09		5402	BATLEY	04	NA48
5.16±0.20±0.22		729	MAKOFF	93	E731

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

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
6.2 ±2.0		16	CARROLL	80C	SPEC
< 220	90		[24] DONALDSON	74	SPEC

[24] DONALDSON 74 uses $K^0_L \rightarrow \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

——— Hadronic modes, ——— including Charge conjugation×Parity Violating (*CPV*) modes ———

$\Gamma(3\pi^0)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1956±0.0014 OUR FIT Error includes scale factor of 1.9.					
0.1969±0.0026 OUR AVERAGE Error includes scale factor of 2.0.					
0.1997±0.0003±0.0019	13M	[25] AMBROSINO	06	KLOE	Not fitted
0.1945±0.0018		[25] ALEXOPOU...	04	KTEV	Not fitted

[25] We exclude these $B(K_L \rightarrow 3\pi^0)$ measurements from our fit because the authors have constrained K_L branching fractions to sum to one. It enters our fit via the other measurements from the experiment and their correlations, along with our constraint that the fitted branching fractions sum to one.

$\Gamma(3\pi^0)/\Gamma(\pi^{\pm}e^{\mp}\nu_e)$ — Γ_5/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.483 ±0.005 OUR FIT Error includes scale factor of 2.1.					
0.4782±0.0014±0.0053	209K	[26] ALEXOPOU...	04	KTEV	Not in fit

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

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.545 ±0.004 ±0.009	38k	KREUTZ	95	NA31	

[26] This measurement enters the fit via their separate measurements of these two modes.

$\Gamma(3\pi^0)/[\Gamma(\pi^{\pm}e^{\mp}\nu_e)+\Gamma(\pi^{\pm}\mu^{\mp}\nu_{\mu})+\Gamma(\pi^+\pi^-\pi^0)]$ — $\Gamma_5/(\Gamma_1+\Gamma_2+\Gamma_6)$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.2441±0.0022 OUR FIT Error includes scale factor of 1.9.					

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

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.251 ±0.014	549	BUDAGOV	68	HLBC	ORSAY measur.
0.277 ±0.021	444	BUDAGOV	68	HLBC	Ecole polytec.meas
$0.31\ ^{+0.07}_{-0.06}$	29	KULYUKINA	68	CC	
0.24 ±0.08	24	ANIKINA	64	CC	

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_5/Γ_6

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.558±0.013 OUR FIT	Error includes scale factor of 1.3.			
1.582±0.027	13M	[27] AMBROSINO 06	KLOE	Not in fit
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.611±0.014±0.034	28k	KREUTZ 95	NA31	
1.65 ±0.07	883	BARMIN 72B	HLBC	Error statistical only
1.80 ±0.13	1010	BUDAGOV 68	HLBC	
2.0 ±0.6	188	ALEKSANYAN 64B	FBC	

[27] AMBROSINO 06 enters the fit via their separate measurements of these two modes.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.1256±0.0005 OUR FIT			
0.1255±0.0006 OUR AVERAGE			
0.1263±0.0004±0.0011	13M	[28] AMBROSINO 06	KLOE
0.1252±0.0007		[29] ALEXOPOU... 04	KTEV

[28] There are correlations between these five KLOE measurements: B($K_L \to \pi e \nu$), B($K_L \to \pi \mu \nu$), B($K_L \to 3\pi^0$), B($K_L \to \pi^+\pi^-\pi^0$), and τ_{K_L} measured in AMBROSINO 06. See the footnote for the τ_{K_L} measurement for the correlation matrix.

[29] For correlations with other ALEXOPOULOS 04 measurements, see the footnote with their B($K_L \to \pi e \nu$) measurement.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi^\pm e^\mp \nu_e)$ Γ_6/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.3098±0.0020 OUR FIT	Error includes scale factor of 1.4.			
0.3078±0.0005±0.0017	799K	[30] ALEXOPOU... 04	KTEV	Not in fit
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.336 ±0.003 ±0.007	28k	KREUTZ 95	NA31	

[30] This measurement enters the fit via their separate measurements for the two modes.

$\Gamma(\pi^+\pi^-\pi^0)/\left[\Gamma(\pi^\pm e^\mp \nu_e)+\Gamma(\pi^\pm \mu^\mp \nu_\mu)+\Gamma(\pi^+\pi^-\pi^0)\right]$ $\Gamma_6/(\Gamma_1+\Gamma_2+\Gamma_6)$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.1567±0.0007 OUR FIT	Error includes scale factor of 1.2.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.163 ±0.003	6499	CHO 77	HBC	
0.1605±0.0038	1590	ALEXANDER 73B	HBC	
0.146 ±0.004	3200	BRANDENB... 73	HBC	
0.159 ±0.010	558	EVANS 73	HLBC	
0.167 ±0.016	1402	KULYUKINA 68	CC	
0.161 ±0.005		HOPKINS 67	HBC	
0.162 ±0.015	126	HAWKINS 66	HBC	
0.159 ±0.015	326	ASTBURY 65B	CC	
0.178 ±0.017	566	GUIDONI 65	HBC	
0.144 ±0.004	1729	HOPKINS 65	HBC	See HOPKINS 67

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_7/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*
1.976±0.008 OUR FIT		
1.975±0.012	[31] ALEXOPOU... 04	KTEV

[31] For correlations with other ALEXOPOULOS 04 measurements, see the footnote with their B($K_L \rightarrow \pi e \nu$) measurement.

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^\pm e^\mp \nu_e)$ Γ_7/Γ_1

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
4.877±0.026 OUR FIT	Error includes scale factor of 1.2.			
4.856±0.017±0.023	84K	[32] ALEXOPOU... 04	KTEV	Not in fit

[32] This measurement enters the fit via their separate measurements for the two modes.

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^\pm \mu^\mp \nu_\mu)$ Γ_7/Γ_2

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*
7.314±0.035 OUR FIT			
7.275±0.042±0.054	45k	[33] AMBROSINO 06F	KLOE

[33] Fully inclusive. Taking B($K^0_L \rightarrow \pi \mu \nu$) from KLOE, AMBROSINO 06, B($K^0_L \rightarrow \pi^+\pi^-$) = $(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$ is obtained.

$\Gamma(\pi^+\pi^-)/\left[\Gamma(\pi^\pm e^\mp \nu_e)+\Gamma(\pi^\pm \mu^\mp \nu_\mu)\right]$ $\Gamma_7/(\Gamma_1+\Gamma_2)$

Violates *CP* conservation.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.926±0.014 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.13 ±0.14	1687	COUPAL 85	SPEC	η_{+-}=2.28 ± 0.06
3.04 ±0.14	2703	DEVOE 77	SPEC	η_{+-}=2.25 ± 0.05
2.51 ±0.23	309	[34] DEBOUARD 67	OSPK	η_{+-}=2.00 ± 0.09
2.35 ±0.19	525	[34] FITCH 67	OSPK	η_{+-}=1.94 ± 0.08

[34] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \rightarrow 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^\pm e^\mp \nu_e)/\Gamma(2\,\text{tracks})$ $\Gamma_1/(\Gamma_1+\Gamma_2+0.03508\Gamma_5+\Gamma_6+\Gamma_7)$

Γ(2 tracks) = $\Gamma(\pi^\pm e^\mp \nu_e)$ + $\Gamma(\pi^\pm \mu^\mp \nu_\mu)$ + 0.03508 $\Gamma(3\pi^0)$ + $\Gamma(\pi^+\pi^-\pi^0)$ + $\Gamma(\pi^+\pi^-)$ where 0.03508 is the fraction of $3\pi^0$ events with one Dalitz decay ($\pi^0 \rightarrow \gamma e^+ e^-$).

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.5004±0.0012 OUR FIT	Error includes scale factor of 1.6.		
0.4978±0.0035	6.8M	LAI 04B	NA48

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^\pm e^\mp \nu_e)+\Gamma(\pi^\pm \mu^\mp \nu_\mu)+\Gamma(\pi^+\pi^-\pi^0)]$ $\Gamma_7/(\Gamma_1+\Gamma_2+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.467±0.011 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.60 ±0.07	4200	[35] MESSNER 73	ASPK	$\eta_{+-} = 2.23 \pm 0.05$

[35] From same data as $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ MESSNER 73, but with different normalization.

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_7/Γ_6

Violates *CP* conservation.

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.574±0.009 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.64 ±0.04	4200	MESSNER 73	ASPK	$\eta_{+-} = 2.23$

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_8/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*
0.869±0.004 OUR FIT Error includes scale factor of 1.1.		
0.865±0.012	[36] ALEXOPOU... 04	KTEV

[36] For correlations with other ALEXOPOULOS 04 measurements, see the footnote with their B($K_L \to \pi e \nu$) measurement.

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^+\pi^-)$ Γ_8/Γ_7

Violates *CP* conservation.

VALUE	*DOCUMENT ID*	*COMMENT*
0.4395±0.0016 OUR FIT Error includes scale factor of 1.3.		
0.4391±0.0013	ETAFIT 06	S = 1.1

$\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$ Γ_8/Γ_5

Violates *CP* conservation.

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.444 ±0.004 OUR FIT Error includes scale factor of 1.9.				
0.4446±0.0016±0.0019	100K	[37] ALEXOPOU... 04	KTEV	Not in fit
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.37 ±0.08	29	BARMIN 70	HLBC	η_{00}=2.02 ± 0.23
0.32 ±0.15	30	BUDAGOV 70	HLBC	η_{00}=1.9 ± 0.5
0.46 ±0.11	57	BANNER 69	OSPK	η_{00}=2.2 ± 0.3

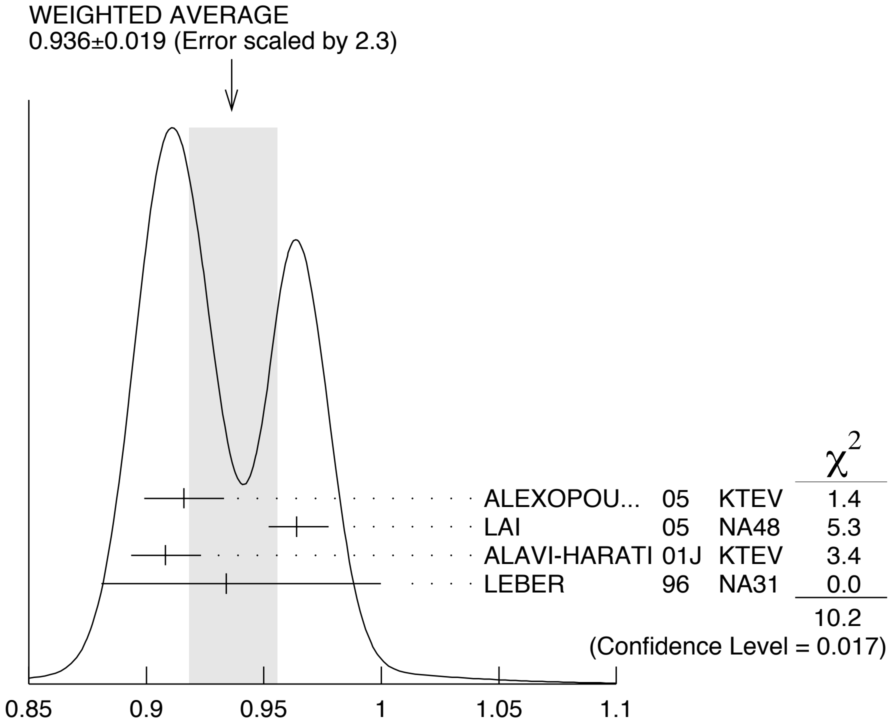
[37] This measurement enters the fit via their separate measurements for the two modes.

Semileptonic modes with photons

$\Gamma(\pi^\pm e^\mp \nu_e \gamma)/\Gamma(\pi^\pm e^\mp \nu_e)$ Γ_9/Γ_1

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.936±0.019 OUR AVERAGE Error includes scale factor of 2.3. See the ideogram below.				
0.916±0.017	4309	[38] ALEXOPOU... 05	KTEV	E^*_γ >30 MeV, $\theta^*_{e\gamma}$ >20°
$0.964\pm0.008^{+0.011}_{-0.009}$	19K	LAI 05	NA48	E^*_γ >30 MeV, $\theta^*_{e\gamma}$ >20°
$0.908\pm0.008^{+0.013}_{-0.012}$	15k	ALAVI-HARATI 01J	KTEV	$E^*_\gamma \geq 30$ MeV, $\theta^*_{e\gamma} \geq 20°$
$0.934\pm0.036^{+0.055}_{-0.039}$	1384	LEBER 96	NA31	$E^*_\gamma \geq 30$ MeV, $\theta^*_{e\gamma} \geq 20°$

[38] Also measured cut E^*_γ >10 MeV, $\theta^*_{e\gamma}$ >0° 14221 evts: $\Gamma(\pi^\pm e^\mp \nu_e \gamma)$ / $\Gamma(\pi^\pm e^\mp \nu_e)$ = (4.942 ± 0.062)%.



$\Gamma\left(\pi^\pm e^\mp \nu_e \gamma\right)/\Gamma\left(\pi^\pm e^\mp \nu_e\right)$ Γ_9/Γ_1

$\Gamma(\pi^\pm \mu^\mp \nu_\mu \gamma)/\Gamma(\pi^\pm \mu^\mp \nu_\mu)$ Γ_{10}/Γ_2

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.09±0.08 OUR AVERAGE					
2.09±0.09		[39] ALEXOPOU...	05	KTEV	E^*_γ > 30 MeV
$2.08\pm0.17^{+0.16}_{-0.21}$	252	BENDER	98	NA48	$E^*_\gamma \geq 30$ MeV

[39] Also measured cut E^*_γ >10 MeV, 1385 evts: $\Gamma(\pi^\pm \mu^\mp \nu_\mu \gamma)$ / $\Gamma(\pi^\pm \mu^\mp \nu_\mu)$ = (0.530 ± 0.014 ± 0.012)%.

——— Hadronic modes with photons or $\ell\overline{\ell}$ pairs ———

$\Gamma(\pi^0 \pi^0 \gamma)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
< 5.6			BARR	94	NA31
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<230	90	0	ROBERTS	94	E799

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{12}/Γ_6

For earlier limits see our 1992 edition Physical Review **D45,** 1 June, Part II (1992).

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.23±0.13	516	[40,41] CARROLL	80B	SPEC	E_γ >20 MeV
2.33±0.23	546	[40,42] CARROLL	80B	SPEC	
3.56±0.26	1062	[40,43] CARROLL	80B	SPEC	E_γ >20 MeV

[40] CARROLL 80B quotes B($\pi^+\pi^-\gamma$) using normalization B($\pi^+\pi^-\pi^0$) = 0.1239. We divide by this value to obtain their measured $\Gamma(\pi^+\pi^-\gamma)$ / $\Gamma(\pi^+\pi^-\pi^0)$.

[41] Internal Bremsstrahlung component only.

[42] Direct γ emission component only.

[43] Both IB and DE components.

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-)$ Γ_{12}/Γ_7

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.11±0.08 OUR AVERAGE	Error includes scale factor of 2.9.				
2.08±0.02±0.02	8669	[44] ALAVI-HARATI	01B	KTEV	E^*_γ >20 MeV
2.30±0.07	3136	[45] RAMBERG	93	E731	E_γ >20 MeV

[44] ALAVI-HARATI 01B includes both Direct Emission (DE) and Inner Bremsstrahlung (IB) processes. They also report DE/(DE+IB)= 0.683 ± 0.011. The paper reports results for ρ propagator, linear, and quadratic form factors.

[45] RAMBERG 93 finds that fraction of Direct Emission (DE) decays with E_γ >20 MeV is 0.685 ± 0.041.

$\Gamma(\pi^0 2\gamma)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE (units 10^{-6})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.49±0.08 OUR AVERAGE	Error includes scale factor of 2.0.					
1.45±0.05±0.01		2.5k	[46] LAI	02B	NA48	
1.68±0.07±0.08		884	[47] ALAVI-HARATI	99B	KTEV	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.7 ±0.2 ±0.2		63	[48] BARR	92	NA31	
1.86±0.60±0.60		60	PAPADIMITR...	91	E731	$m_{\gamma\gamma}$ > 280 MeV
<5.1	90		PAPADIMITR...	91	E731	$m_{\gamma\gamma}$ < 264 MeV
2.1 ±0.6		14	[49] BARR	90C	NA31	$m_{\gamma\gamma}$ > 280 MeV

[46] LAI 02B reports $(1.36 \pm 0.03 \pm 0.03) \times 10^{-6}$ for B($K^0_L \rightarrow \pi^0\pi^0$) = 9.27×10^{-4}. We rescale to our best value B($K^0_L \rightarrow \pi^0\pi^0$) = $(8.69 \pm 0.04) \times 10^{-4}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. They also find that B($\pi^0 2\gamma$, $m_{\gamma\gamma}$ <110 MeV) < 0.6×10^{-8}(90% CL).

[47] ALAVI-HARATI 99B finds that $\Gamma(\pi^0 2\gamma$, $m_{\gamma\gamma}$ <240 MeV)) / $\Gamma(\pi^0 2\gamma)$ = (17.3 ± 1.3 ± 1.5)%.

[48] BARR 92 find that $\Gamma(\pi^0 2\gamma$, $m_{\gamma\gamma}$ <240 MeV)/$\Gamma(\pi^0 2\gamma)$< 0.09 (90% CL).

[49] BARR 90C superseded by BARR 92.

$\Gamma(\pi^0 \gamma e^+ e^-)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE (units 10^{-8})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
2.34±0.35±0.13		44	ALAVI-HARATI	01E	KTEV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<71	90	0	MURAKAMI	99	SPEC

——— Other modes with photons or $\ell\overline{\ell}$ pairs ———

$\Gamma(2\gamma)/\Gamma_{\rm total}$ Γ_{15}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5.48±0.05 OUR FIT Error includes scale factor of 1.2.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.54±0.84		[50] BANNER	72B	OSPK	
4.5 ±1.0	23	ENSTROM	71	OSPK	K^0_L 1.5–9 GeV/c
5.0 ±1.0		[51] REPELLIN	71	OSPK	
5.5 ±1.1	90	KUNZ	68	OSPK	Norm.to 3 π(C+N)

[50] This value uses $(\eta_{00}/\eta_{+-})^2 = 1.05 \pm 0.14$. In general, $\Gamma(2\gamma)/\Gamma_{\rm total} = \left[(4.32 \pm 0.55) \times 10^{-4}\right]\left[(\eta_{00}/\eta_{+-})^2\right]$.

[51] Assumes regeneration amplitude in copper at 2 GeV is 22 mb. To evaluate for a given regeneration amplitude and error, multiply by (regeneration amplitude/22mb)^2.

$\Gamma(2\gamma)/\Gamma(3\pi^0)$ Γ_{15}/Γ_5

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.803±0.017 OUR FIT					
2.802±0.018 OUR AVERAGE					
2.79 ±0.02 ±0.02	27k	ADINOLFI	03	KLOE	
2.81 ±0.01 ±0.02		LAI	03	NA48	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.13 ±0.43	28	BARMIN	71	HLBC	
2.24 ±0.28	115	BANNER	69	OSPK	
2.5 ±0.7	16	ARNOLD	68B	HLBC	Vacuum decay

$\Gamma(2\gamma)/\Gamma(\pi^0\pi^0)$ Γ_{15}/Γ_8

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
0.631±0.006 OUR FIT Error includes scale factor of 1.3.				
0.632±0.004±0.008	110k	BURKHARDT	87	NA31

$\Gamma(3\gamma)/\Gamma_{\rm total}$ Γ_{16}/Γ

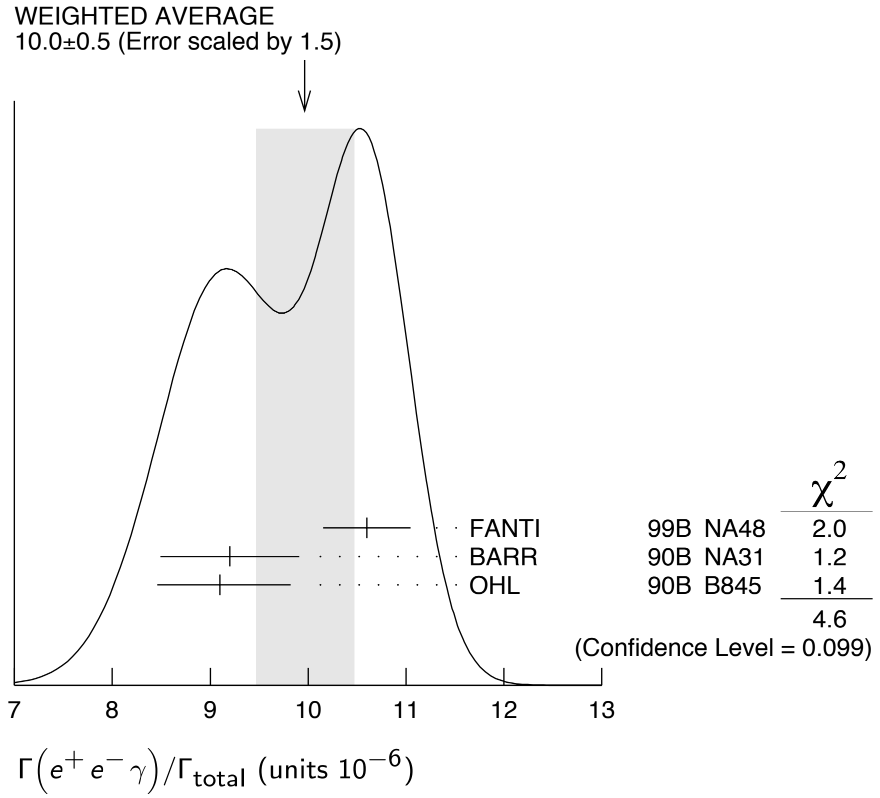
VALUE	*CL%*	*DOCUMENT ID*		*TECN*
$<2.4 \times 10^{-7}$	90	[52] BARR	95C	NA31

[52] Assumes a phase-space decay distribution.

$\Gamma(e^+ e^- \gamma)/\Gamma_{\rm total}$ Γ_{17}/Γ

VALUE (units 10^{-6})	*EVTS*	*DOCUMENT ID*		*TECN*
10.0±0.5 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
10.6±0.2±0.4	6864	[53] FANTI	99B	NA48
9.2±0.5±0.5	1053	BARR	90B	NA31
$9.1 \pm 0.4^{+0.6}_{-0.5}$	919	OHL	90B	B845

[53] For FANTI 99B, the ±0.4 systematic error includes for uncertainties in the calculation, primarily uncertainties in the $\pi^0 \to e^+ e^- \gamma$ and $K^0_L \to \pi^0 \pi^0$ branching ratios, evaluated using our 1999 Web edition values.



$\Gamma(\mu^+ \mu^- \gamma)/\Gamma_{\rm total}$ Γ_{18}/Γ

VALUE (units 10^{-7})	*EVTS*	*DOCUMENT ID*		*TECN*
3.59±0.11 OUR AVERAGE	Error includes scale factor of 1.3.			
3.62±0.04±0.08	9100	ALAVI-HARATI	01G	KTEV
3.4 ±0.6 ±0.4	45	FANTI	97	NA48
3.23±0.23±0.19	197	SPENCER	95	E799

$\Gamma(e^+ e^- \gamma\gamma)/\Gamma_{\rm total}$ Γ_{19}/Γ

VALUE (units 10^{-7})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5.95±0.33 OUR AVERAGE					
5.84±0.15±0.32	1543	ALAVI-HARATI	01F	KTEV	$E^*_\gamma > 5$ MeV
8.0 ±1.5 $^{+1.4}_{-1.2}$	40	SETZU	98	NA31	$E_\gamma > 5$ MeV
6.5 ±1.2 ±0.6	58	NAKAYA	94	E799	$E_\gamma > 5$ MeV
6.6 ±3.2		MORSE	92	B845	$E_\gamma > 5$ MeV

$\Gamma(\mu^+ \mu^- \gamma\gamma)/\Gamma_{\rm total}$ Γ_{20}/Γ

VALUE (units 10^{-9})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$10.4^{+7.5}_{-5.9}$±0.7	4	ALAVI-HARATI	00E	KTEV	$m_{\gamma\gamma} \geq 1$ MeV/c^2

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

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ Γ_{21}/Γ_7

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
3.48 ±0.05 OUR AVERAGE				
3.474±0.057	6210	AMBROSE 00	B871	
3.87 ±0.30	179	[54] AKAGI 95	SPEC	
3.38 ±0.17	707	HEINSON 95	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9 ±0.3 ±0.1	178	[55] AKAGI 91B	SPEC	In AKAGI 95
3.45 ±0.18 ±0.13	368	[56] HEINSON 91	SPEC	In HEINSON 95
4.1 ±0.5	54	INAGAKI 89	SPEC	In AKAGI 91B
2.8 ±0.3 ±0.2	87	MATHIAZHA...89B	SPEC	In HEINSON 91

[54] AKAGI 95 gives this number multiplied by the PDG 1992 average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$.

[55] AKAGI 91B give this number multiplied by the 1990 PDG average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$.

[56] HEINSON 91 give $\Gamma(K^0_L \to \mu\mu)/\Gamma_{\text{total}}$. We divide out the $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma_{\text{total}}$ PDG average which they used.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{22}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
$\mathbf{0.087^{+0.057}_{-0.041}}$		4	AMBROSE 98	B871
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.6	90	1	AKAGI 95	SPEC
<0.41	90	0	[57] ARISAKA 93B	B791

[57] ARISAKA 93B includes all events with <6 MeV radiated energy.

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ Γ_{23}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
3.11±0.19 OUR AVERAGE					
3.08±0.09±0.18		1125	[58] LAI 03C	NA48	
3.2 ±0.6 ±0.4		37	ADAMS 98	KTEV	
4.4 ±1.3 ±0.5		13	TAKEUCHI 98	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.6	90		NOMURA 97	SPEC	$m_{ee} > 4$ MeV

[58] LAI 03C second error is 0.15(syst)±0.10(norm) combined in quadrature. The normalization uses $\text{BR}(K_L \to \pi^+\pi^-\pi^0) * \text{BR}(\pi^0 \to e^+e^-) = (1.505 \pm 0.047) \times 10^{-3}$ from our 2000 Edition.

$\Gamma(\pi^0\pi^0e^+e^-)/\Gamma_{\text{total}}$ Γ_{24}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
<6.6	90	1	ALAVI-HARATI 02C	E799

$\Gamma(\mu^+\mu^-e^+e^-)/\Gamma_{\text{total}}$ Γ_{25}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.69±0.27 OUR AVERAGE						
2.69±0.24±0.12		131	[59] ALAVI-HARATI	03B	KTEV	
$2.9 \; {}^{+6.7}_{-2.4}$		1	GU	96	E799	

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

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.62±0.40±0.17		43	ALAVI-HARATI	01H	KTEV	Sup. by ALAVI-HARATI 03B
<4900	90		BALATS	83	SPEC	

[59] ALAVI-HARATI 03B also measures the linear slope $\alpha = -1.59 \pm 0.37$.

$\Gamma(e^+e^-e^+e^-)/\Gamma_{\text{total}}$ Γ_{26}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3.56±0.21 OUR AVERAGE					
3.30±0.24±0.25	200	[60] LAI	05B	NA48	
3.72±0.18±0.23	441	ALAVI-HARATI	01D	KTEV	
3.96±0.78±0.32	27	GU	94	E799	
3.07±1.25±0.26	6	VAGINS	93	B845	

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

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
6 ±2 ±1	18	[61] AKAGI	95	SPEC	m_{ee} >470 MeV
7 ±3 ±2	6	[61] AKAGI	95	SPEC	m_{ee} >470 MeV
10.4 ±3.7 ±1.1	8	[62] BARR	95	NA31	
6 ±2 ±1	18	AKAGI	93	CNTR	Sup. by AKAGI 95
4 ±3	2	BARR	91	NA31	Sup. by BARR 95

[60] LAI 05B uses 1998 and 1999 data. Data are normalized to the observed events of $K^0_L \to \pi^+\pi^-\pi^0$ (π^0 into Dalitz pair) and PDG 04 values are used for B($K^0_L \to \pi^+\pi^-\pi^0$) and B($\pi^0 \to e^+e^-\gamma$). The systematic error includes a normalization error of ±0.10.

[61] Values are for the total branching fraction, acceptance-corrected for the m_{ee} cuts shown.

[62] Distribution of angles between two e^+e^- pair planes favors $CP{=}-1$ for K^0_L.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{27}/Γ

Violates *CP* in leading order. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<0.38	90		ALAVI-HARATI	00D	KTEV

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

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<5.1	90	0	HARRIS	93	E799

$\Gamma(\pi^0e^+e^-)/\Gamma_{\text{total}}$ Γ_{28}/Γ

Violates *CP* in leading order. Direct and indirect *CP*-violating contributions are expected to be comparable and to dominate the *CP*-conserving part. LAI 02B result suggests that *CP*-violation effects dominate. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 2.8	90		[63] ALAVI-HARATI	04A	KTEV	combined result

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

$<$ 3.5	90		ALAVI-HARATI 04A	KTEV	
$0.0047^{+0.0022}_{-0.0018}$			[64] LAI 02B	NA48	*CP*-conserving part
$<$ 5.1	90	2	ALAVI-HARATI 01	KTEV	
0.01 to 0.02			ALAVI-HARATI 99B	KTEV	*CP*-conserving part
$<$ 43	90	0	HARRIS 93B	E799	
$<$ 75	90	0	BARKER 90	E731	
$<$ 55	90	0	OHL 90	B845	
$<$ 400	90		BARR 88	NA31	
$<$3200	90		JASTRZEM... 88	SPEC	

[63] Combined result of ALAVI-HARATI 04A 1999-2000 data set and ALAVI-HARATI 01 1997 data set.

[64] LAI 02B uses the absence of a signal in $K^0_L \rightarrow \pi^0\gamma\gamma$ with $m(\gamma\gamma)<m(\pi^0)$ and their a_V value to predict this value.

$\Gamma(\pi^0\nu\overline{\nu})/\Gamma_{\rm total}$ Γ_{29}/Γ

Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed. Test of $\Delta S = 1$ weak neutral current.

VALUE (units 10^{-5})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
< 0.059	90	0	ALAVI-HARATI 00	KTEV

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

$<$ 0.16	90	0	ADAMS 99	KTEV
$<$ 5.8	90	0	WEAVER 94	E799
$<$22	90	0	GRAHAM 92	CNTR

$\Gamma(e^\pm\mu^\mp)/\Gamma_{\rm total}$ Γ_{30}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-11})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
<0.47	90		AMBROSE 98B	B871

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

$<$9.4	90	0	AKAGI 95	SPEC
$<$3.9	90	0	ARISAKA 93	B791
$<$3.3	90	0	[65] ARISAKA 93	B791

[65] This is the combined result of ARISAKA 93 and MATHIAZHAGAN 89.

$\Gamma(e^\pm e^\pm\mu^\mp\mu^\mp)/\Gamma_{\rm total}$ Γ_{31}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-11})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 4.12	90	0	ALAVI-HARATI 03B	KTEV	

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

$<$ 12.3	90	0	[66] ALAVI-HARATI 01H	KTEV	Sup. by ALAVI-HARATI 03B
$<$610	90	0	[66] GU 96	E799	

[66] Assuming uniform phase space distribution.

$\Gamma(\pi^0 \mu^\pm e^\mp)/\Gamma_{\rm total}$ **Γ_{32}/Γ**

Test of lepton family number conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*
$<6.2 \times 10^{-9}$	90	ARISAKA	98	E799

V_{ud}, V_{us}, THE CABIBBO ANGLE, AND CKM UNITARITY

Written October 2005 by E. Blucher (Univ. of Chicago) and W.J. Marciano (BNL)

The Cabibbo-Kobayashi-Maskawa (CKM) [1,2] three-generation quark mixing matrix written in terms of the Wolfenstein parameters (λ, A, ρ, η) [3] nicely illustrates the orthonormality constraint of unitarity and central role played by λ.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (1)$$

That cornerstone is a carryover from the two-generation Cabibbo angle, $\lambda = sin(\theta_{\rm Cabibbo}) = V_{us}$. Its value is a critical ingredient in determinations of the other parameters and in tests of CKM unitarity.

Unfortunately, the precise value of λ has been somewhat controversial in the past, with kaon decays suggesting [4] $\lambda \simeq 0.220$ while hyperon decays [5] and indirect determinations via nuclear β-decays imply a somewhat larger $\lambda \simeq 0.225 - 0.230$. That discrepancy is often discussed in terms of a deviation from the unitarity requirement

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1. \quad (2)$$

For many years, using a value of V_{us} derived from $K \to \pi e \nu$ (K_{e3}) decays, that sum was consistently 2–2.5 sigma below unity, a potential signal [6] for new physics effects. Below, we discuss the current status of V_{ud}, V_{us}, and their associated unitarity test in Eq. (2). (Since $|V_{ub}|^2 \simeq 1 \times 10^{-5}$ is negligibly small, it is ignored in this discussion.)

V_{ud}

The value of V_{ud} has been obtained from superallowed nuclear, neutron, and pion decays. Currently, the most precise determination of V_{ud} comes from superallowed nuclear beta-decays [6] ($0^+ \to 0^+$ transitions). Measuring their half-lives, t, and Q values which give the decay rate factor, f, leads to a precise determination of V_{ud} via the master formula [7–9]

$$|V_{ud}|^2 = \frac{2984.48(5)\,\mathrm{sec}}{ft(1+\mathrm{RC})} \tag{3}$$

where RC denotes the entire effect of electroweak radiative corrections, nuclear structure, and isospin violating nuclear effects. RC is nucleus dependent, ranging from about +3.1% to +3.6% for the nine best measured superallowed decays. In Table 1, we give the ft values along with their implied V_{ud} for the nine best measured superallowed decays [6, 10]. They collectively give a weighted average (with errors combined in quadrature) of

$$V_{ud} = 0.97377(27) \text{ (superallowed)} \tag{4}$$

which, assuming unitarity, corresponds to $\lambda = 0.2275(12)$. We note, however, that a recent remeasurement [10] of the ^{46}V Q value has significantly affected its ft and V_{ud} values, with the latter now about 2.7 sigma below the average. That recent shift may point to a potential problem with the Q values and ft

values of the other superallowed beta decays. Remeasurement of all Q values using modern atomic trapping techniques is called for and in progress.

Table 1: Values of V_{ud} implied by various precisely measured superallowed nuclear beta decays. The ft values are taken from a recent update by Savard et al. [10]. Uncertainties in V_{ud} correspond to 1) nuclear structure and $Z^2\alpha^3$ uncertainties [6, 11] added in quadrature with the ft error, 2) a common error assigned to nuclear Coulomb distortion effects [11], and 3) a common uncertainty in the radiative corrections from quantum loop effects [9]. Only the first error is used to obtain the weighted average.

Nucleus	ft (sec)	V_{ud}
^{10}C	3039.5(47)	0.97381(77)(15)(19)
$^{14}0$	3043.3(19)	0.97368(39)(15)(19)
^{26}Al	3036.8(11)	0.97406(23)(15)(19)
^{34}Cl	3050.0(12)	0.97412(26)(15)(19)
^{38}K	3051.1(10)	0.97404(26)(15)(19)
^{42}Sc	3046.8(12)	0.97330(32)(15)(19)
^{46}V	3050.7(12)	0.97280(34)(15)(19)
^{50}Mn	3045.8(16)	0.97367(41)(15)(19)
^{54}Co	3048.4(11)	0.97373(40)(15)(19)
Weighted Ave.		0.97377(11)(15)(19)

Combined measurements of the neutron lifetime, τ_n, and the ratio of axial-vector/vector couplings, $g_A \equiv G_A/G_V$, via neutron decay asymmetries can also be used to determine V_{ud}:

$$|V_{ud}|^2 = \frac{4908.7(1.9)\mathrm{sec}}{\tau_n(1+3g_A^2)}, \tag{5}$$

where the error stems from uncertainties in the electroweak radiative corrections [8] due to hadronic loop effects. Those effects have been recently updated and their error was reduced by about a factor of 2 [9], leading to a ±0.0002 theoretical uncertainty in V_{ud} (common to all V_{ud} extractions). Using the world averages from this *Review*

$$\begin{aligned} \tau_n^{\text{ave}} &= 885.7(8)\text{sec} \\ g_A^{\text{ave}} &= 1.2695(29) \end{aligned} \tag{6}$$

leads to

$$V_{ud} = 0.9746(4)_{\tau_n}(18)_{g_A}(2)_{\text{RC}} \tag{7}$$

with the error dominated by g_A uncertainties (which have been expanded due to experimental inconsistencies). We note that a recent precise measurement [12] of $\tau_n = 878.5(7)(3)$ sec is also inconsistent with the world average from this *Review* and would lead to a considerably larger $V_{ud} = 0.9786(4)(18)(2)$. Future neutron studies are expected to resolve these inconsistencies and significantly reduce the uncertainties in g_A and τ_n, potentially making them the best way to determine V_{ud}.

The recently completed PIBETA experiment at PSI measured the very small ($\mathcal{O}(10^{-8})$) branching ratio for $\pi^+ \to \pi^o e^+ \nu_e$ with about ±1/2% precision. Their result gives [13]

$$V_{ud} = 0.9749(26) \left[\frac{BR(\pi^+ \to e^+\nu_e(\gamma))}{1.2352 \times 10^{-4}}\right]^{\frac{1}{2}} \tag{8}$$

which is normalized using the very precisely determined theoretical prediction for $BR(\pi^+ \to e^+\nu_e(\gamma)) = 1.2352(5) \times 10^{-4}$ [7] rather than the experimental branching ratio from this *Review* of $1.230(4)\times10^{-4}$ which would lower the value to $V_{ud} = 0.9728(30)$. Theoretical uncertainties in that determination are very small;

however, much higher statistics would be required to make this approach competitive with others.

V_{us}

$|V_{us}|$ may be determined from kaon decays, hyperon decays, and tau decays. Previous determinations have most often used $K\ell 3$ decays:

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell+\delta_{SU2})C^2\left|V_{us}\right|^2 f_+^2(0) I_K^\ell . \quad (9)$$

Here, ℓ refers to either e or μ, G_F is the Fermi constant, M_K is the kaon mass, S_{EW} is the short-distance radiative correction, δ_K^ℓ is the mode-dependent long-distance radiative correction, $f_+(0)$ is the calculated form factor at zero momentum transfer for the $\ell\nu$ system, and I_K^ℓ is the phase-space integral, which depends on measured semileptonic form factors. For charged kaon decays, δ_{SU2} is the deviation from one of the ratio of $f_+(0)$ for the charged to neutral kaon decay; it is zero for the neutral kaon. C^2 is 1 (1/2) for neutral (charged) kaon decays. Previous PDG determinations of $|V_{us}|$ have been based only on $K \to \pi e \nu$ decays; $K \to \pi \mu \nu$ decays have not been used because of large uncertainties in I_K^μ. The experimental measurements are the semileptonic decay widths (based on the semileptonic branching fractions and lifetime) and form factors (allowing calculation of the phase space integrals). Theory is needed for S_{EW}, δ_K^ℓ, δ_{SU2}, and $f_+(0)$. These experimental and theoretical inputs are discussed in the following paragraphs.

Branching Fractions. Recent measurements of the $K \to \pi e \nu$ branching fractions are significantly different from previous PDG averages, probably as a result of inadequate treatment of radiation in older experiments. We therefore choose to base averages on recent measurements where the treatment of radiation is clear.

For the K_L branching fractions, we consider the following experimental inputs:

- KTeV measured the following 5 partial width ratios [14, 15]:
  $\Gamma(K_L \to \pi^\pm \mu^\mp \nu)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$,
  $\Gamma(K_L \to \pi^+ \pi^- \pi^0)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$,
  $\Gamma(K_L \to \pi^0 \pi^0 \pi^0)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$,
  $\Gamma(K_L \to \pi^+ \pi^-)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$, and
  $\Gamma(K_L \to \pi^0 \pi^0)/\Gamma(K_L \to \pi^0 \pi^0 \pi^0)$. Since the six decay modes listed above account for more than 99.9% of the total decay rate, the five partial width ratios may be converted into measurements of the branching fractions for the six decay modes.
- KLOE uses a tagged K_L sample to measure the 4 largest K_L branching fractions [16].
- NA48 measures the following 2 ratios: $\Gamma_{Ke3}/\Gamma(2\ track)$ [17] and $\Gamma_{000}/\Gamma(K_S \to \pi^0 \pi^0)$ [18]. These ratios may be used to determine $B(K_{e3})$.

A fit to all of these measurements, accounting for correlations, gives the K_L semileptonic branching fractions in Table 2. Figure 1 shows a comparison of the new experimental measurements, the best fit values, and the 2002 PDG fit values [19]. Note that the new measurements are consistent with each other, but are shifted significantly from the PDG fit.

For $K_S \to \pi e \nu$, we use the new KLOE measurement [20]: $B(K_S \to \pi e \nu) = (7.06 \pm 0.06 \pm 0.04) \times 10^{-4}$.

For $K^\pm \to \pi^0 e^\pm \nu$, we use the BNL E865 [21] measurement of $B(K^\pm \to \pi^0 e^\pm \nu) = (5.13 \pm 0.1)\%$. Preliminary measurements from NA48, KLOE, and ISTRA+ are consistent with this result.

Table 2: Average K_L semileptonic branching fractions and widths based on fit to new measurements from KTeV, KLOE, and NA48. The partial width measurements use the average K_L lifetime quoted in Table 3.

Decay Mode	Branching fraction	Γ_i $(10^7 s^{-1})$
$K_L \to \pi^\pm e^\mp \nu$	0.4040 ± 0.0008	0.7908 ± 0.0032
$K_L \to \pi^\pm \mu^\mp \nu$	0.2699 ± 0.0008	0.5283 ± 0.0023

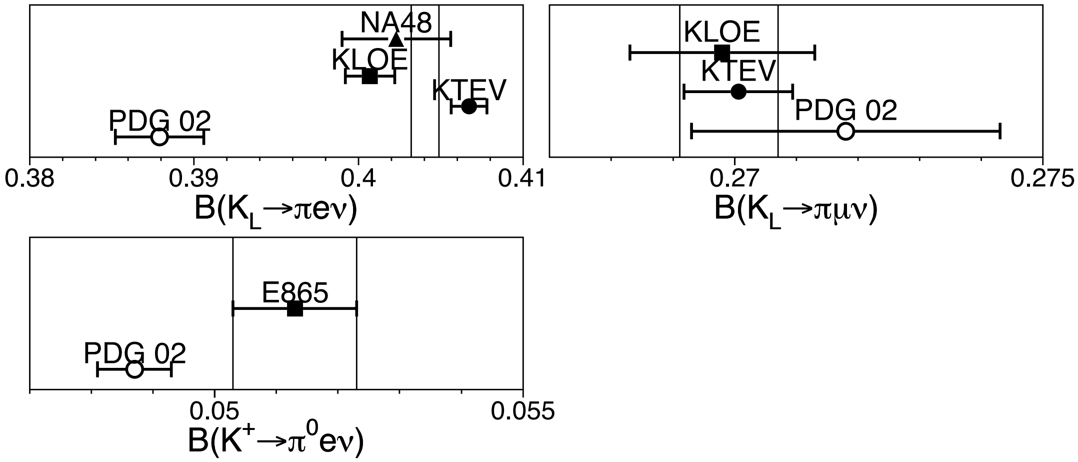


Figure 1: Recent $K_L \to \pi e \nu$, $K_L \to \pi \mu \nu$, and $K^\pm \to \pi^0 e^\pm \nu$ branching fraction measurements (solid points) compared to PDG 2002 fit (open circles). The vertical lines indicate the $\pm 1\sigma$ bounds from a fit to all recent measurements (from KTeV, KLOE, NA48, and E865).

Kaon Lifetime. KLOE has performed two new measurements of the K_L lifetime: one based on exploiting the lifetime dependence of the detector acceptance to find the K_L lifetime required to make the sum of branching fractions equal to 1 [16], and another based on the $K_L \to 3\pi^0$ decay distribution [22]. These new results and the old PDG average are listed in Table 3. The new average value, which we use for the results quoted below, is $\tau_L = (50.98 \pm 0.21) ns$.

Combining the K_L branching fractions with the new lifetime gives the partial decay widths quoted in Table 2. Note that correlations between the KLOE branching fractions and the "indirect" KLOE lifetime determination have been taken into account.

For the K_S and K^+ lifetimes, we use the PDG average values.

Table 3: K_L lifetime measurements.

Source	Lifetime (ns)
PDG 2004 Average	51.5 ± 0.4
KLOE (sum of branching fractions)	50.72 ± 0.37
KLOE ($3\pi^0$ distribution)	50.87 ± 0.31
New Average	50.98 ± 0.21

Phase Space Integrals. Recent experiments have also remeasured the semileptonic form factors needed to calculate the phase space integrals. These recent measurements of the semileptonic form factors are much more precise than previous averages, making it possible to use both the muon and electron decay modes for K_L.

We use the KTeV quadratic form factor results [23] for neutral kaon decays and the ISTRA+ quadratic form factor measurements [24] for charged kaons. For both charged and neutral decays, we include an additional 0.7% uncertainty in the phase space integrals, as suggested by KTeV [23], to account for differences between the quadratic and pole model form factor parametrizations, both of which give acceptable fits to the data. The resulting phase space integrals are $I^e_{K0} = 0.1535 \pm 0.0011$, $I^\mu_{K0} = 0.10165 \pm 0.0008$, and $I^e_{K+} = 0.1591 \pm 0.0012$.

Theoretical Inputs. We use the following theoretical inputs to calculate $f_+(0)|V_{us}|$ from Eq. (9).

- Short-distance radiative correction [7, 25]: $S_{EW} = 1.023$;
- Long-distance radiative corrections [26, 27]: $\delta^e_{K0} = 0.0104 \pm 0.002$, $\delta^\mu_{K0} = 0.019 \pm 0.003$, $\delta^e_{K+} = 0.0006 \pm 0.002$;
- SU2 breaking correction [26,28] $\delta_{SU2} = 0.046 \pm 0.004$.

$K_{\ell 3}$ results for $|V_{us}|$. Figure 2 shows a comparison of the PDG and the averages of recent measurements for $|V_{us}|f_+(0)$ for $K^\pm$, K_L, and K_S. The average of all recent measurements gives

$$f_+^{K^0\pi^-}(0)|V_{us}| = 0.2169 \pm 0.0009. \tag{10}$$

The figure also shows $f_+(0)(1 - |V_{ud}|^2 - |V_{ub}|^2)^{1/2}$, the expectation for $f_+(0)|V_{us}|$ assuming unitarity, based on $|V_{ud}| = 0.9738 \pm 0.0003$, $|V_{ub}| = (3.6 \pm 0.7) \times 10^{-3}$, and the Leutwyler-Roos calculation of $f_+(0) = 0.961 \pm 0.008$ [28]. Using the result in Eq. (10) with the Leutwyler-Roos calculation of $f_+(0)$ gives

$$|V_{us}| = \lambda = 0.2257 \pm 0.0021. \tag{11}$$

A similar result for $f_+(0)$ was recently obtained from a quenched lattice gauge theory calculation [29]. Other calculations of $f_+(0)$ result in $|V_{us}|$ values that differ by as much as 2% from the result in Eq. (11). For example, a recent chiral perturbation theory calculation [30, 31] gives $f_+(0) = 0.974 \pm 0.012$, which implies a lower value of $|V_{us}| = 0.2227 \pm 0.0029$ [32].

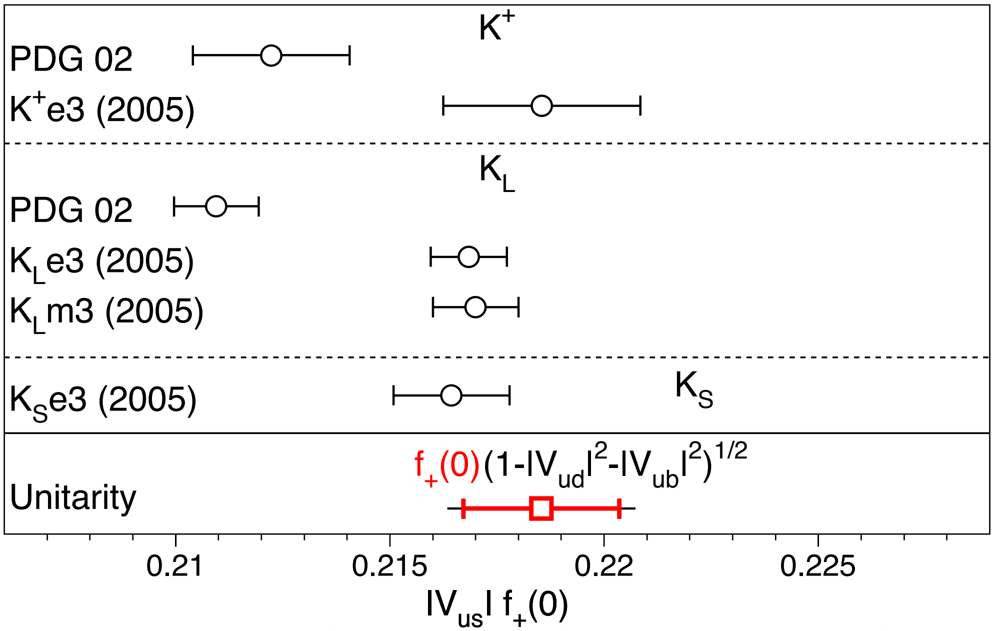


Figure 2: Comparison of determinations of $|V_{us}|f_+(0)$ from this review (labeled 2005), from the PDG 2002, and with the prediction from unitarity using $|V_{ud}|$ and the Leutwyler-Roos calculation of $f_+(0)$ [28]. For $f_+(0)(1-|V_{ud}|^2-|V_{ub}|^2)^{1/2}$, the inner error bars are from the quoted uncertainty in $f_+(0)$; the total uncertainties include the $|V_{ud}|$ and $|V_{ub}|$ errors. See full-color version on color pages at end of book.

A value of V_{us} can also be obtained from a comparison of the radiative inclusive decay rates for $K \to \mu\nu(\gamma)$ and $\pi \to \mu\nu(\gamma)$ combined with a lattice gauge theory calculation of f_K/f_π via [33]

$$\frac{|V_{us}|f_K}{|V_{ud}|f_\pi} = 0.2387(4)\left[\frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}\right]^{\frac{1}{2}} \tag{12}$$

with the small error coming from electroweak radiative corrections. Employing

$$\frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.3383(46), \tag{13}$$

which incorporates the KLOE result [34], $B(K \to \mu\nu(\gamma)) = 63.66(9)(15)\%$ and [35, 36]

$$f_K/f_\pi = 1.198(3)(+16/-5) \tag{14}$$

along with the value of V_{ud} in Eq. (4) leads to

$$|V_{us}| = 0.2245(5)(1.198 f_\pi/f_K). \tag{15}$$

It should be mentioned that hyperon decay fits suggest [5]

$$|V_{us}| = 0.2250(27) \text{ Hyperon Decays} \tag{16}$$

modulo SU(3) breaking effects that could shift that value up or down. We note that a recent representative effort [37] that incorporates SU(3) breaking found $V_{us} = 0.226(5)$. Similarly, strangeness changing tau decays give [38]

$$|V_{us}| = 0.2208(34) \text{ Tau Decays} \tag{17}$$

where the central value depends on the strange quark mass.

Employing the value of V_{ud} in Eq. (4) and V_{us} in Eq. (11) leads to the unitarity consistency check

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992(5)(9), \tag{18}$$

where the first error is the uncertainty from $|V_{ud}|^2$ and the second error is the uncertainty from $|V_{us}|^2$. The result is in good agreement with unitarity. Averaging the direct determination of λ (V_{us}) with the determination derived from unitarity and V_{ud} gives $\lambda = 0.227(1)$. Although unitarity now seems well established, issues regarding the Q values in superallowed nuclear

β-decays, $\tau_n, g_A, f_+(0)$ and f_K/f_π must still be resolved before a definitive confirmation is possible.

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ENERGY DEPENDENCE OF K^0_L DALITZ PLOT

For discussion, see note on Dalitz plot parameters in the $K^{\pm}$ section of the Particle Listings above. For definitions of a_v, a_t, a_u, and a_y, see the earlier version of the same note in the 1982 edition of this *Review* published in Physics Letters **111B** 70 (1982).

$\left|\text{matrix element}\right|^2 = 1 + gu + hu^2 + jv + kv^2 + fuv$
where $u = (s_3 - s_0) / m^2_{\pi}$ and $v = (s_2 - s_1) / m^2_{\pi}$

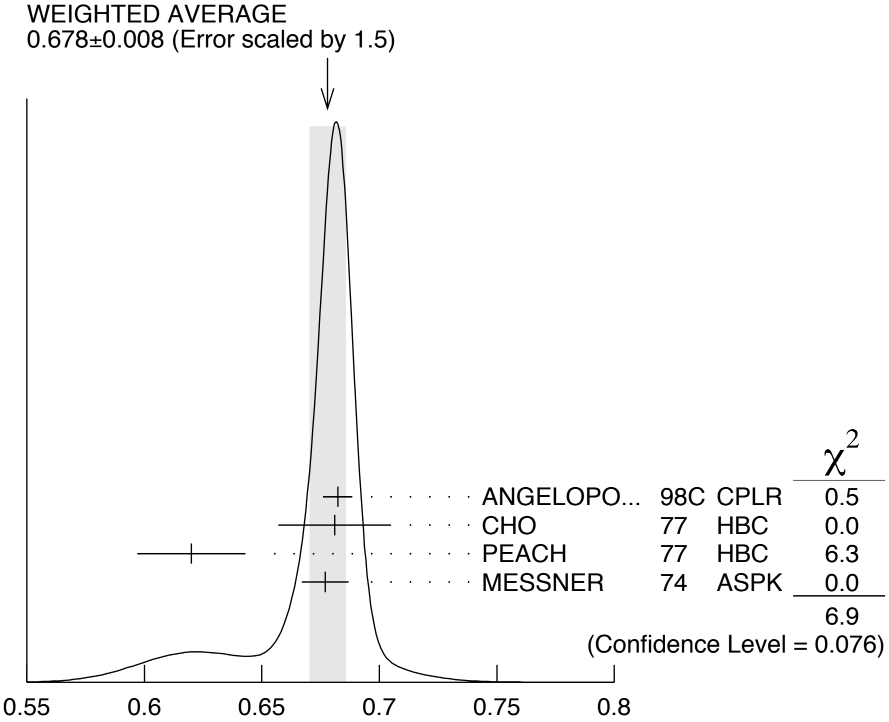
LINEAR COEFFICIENT g FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.678 ±0.008 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.		
0.6823±0.0044±0.0044	500k	ANGELOPO... 98C	CPLR	
0.681 ±0.024	6499	CHO 77	HBC	
0.620 ±0.023	4709	PEACH 77	HBC	
0.677 ±0.010	509k	MESSNER 74	ASPK	$a_y = -0.917 \pm 0.013$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.69 ±0.07	192	[67] BALDO-... 75	HLBC	
0.590 ±0.022	56k	[67] BUCHANAN 75	SPEC	$a_u = -0.277 \pm 0.010$
0.619 ±0.027	20k	[67,68] BISI 74	ASPK	$a_t = -0.282 \pm 0.011$
0.612 ±0.032		[67] ALEXANDER 73B	HBC	
0.73 ±0.04	3200	[67] BRANDENB... 73	HBC	
0.608 ±0.043	1486	[67] KRENZ 72	HLBC	$a_t = -0.277 \pm 0.018$
0.650 ±0.012	29k	[67] ALBROW 70	ASPK	$a_y = -0.858 \pm 0.015$
0.593 ±0.022	36k	[67,69] BUCHANAN 70	SPEC	$a_u = -0.278 \pm 0.010$
0.664 ±0.056	4400	[67] SMITH 70	OSPK	$a_t = -0.306 \pm 0.024$
0.400 ±0.045	2446	[67] BASILE 68B	OSPK	$a_t = -0.188 \pm 0.020$
0.649 ±0.044	1350	[67] HOPKINS 67	HBC	$a_t = -0.294 \pm 0.018$
0.428 ±0.055	1198	[67] NEFKENS 67	OSPK	$a_u = -0.204 \pm 0.025$

[67] Quadratic dependence required by some experiments. (See sections on "QUADRATIC COEFFICIENT *h*" and "QUADRATIC COEFFICIENT *k*" below.) Correlations prevent us from averaging results of fits not including *g*, *h*, and *k* terms.

[68] BISI 74 value comes from quadratic fit with quad. term consistent with zero. *g* error is thus larger than if linear fit were used.

[69] BUCHANAN 70 result revised by BUCHANAN 75 to include radiative correlations and to use more reliable K^0_L momentum spectrum of second experiment (had same beam).



Linear coeff. g for $K^0_L \rightarrow \pi^+\pi^-\pi^0$ matrix element squared

QUADRATIC COEFFICIENT h FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.076±0.006 OUR AVERAGE				
0.061±0.004±0.015	500k	ANGELOPO...	98C	CPLR
0.095±0.032	6499	CHO	77	HBC
0.048±0.036	4709	PEACH	77	HBC
0.079±0.007	509k	MESSNER	74	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.011±0.018	29k	[70] ALBROW	70	ASPK
0.043±0.052	4400	[70] SMITH	70	OSPK

See notes in section "LINEAR COEFFICIENT g FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ $|$MATRIX ELEMENT$|^2$" above.

[70] Quadratic coefficients h and k required by some experiments. (See section on "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

QUADRATIC COEFFICIENT k FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.0099±0.0015 OUR AVERAGE				
0.0104±0.0017±0.0024	500k	ANGELOPO...	98C	CPLR
0.024 ±0.010	6499	CHO	77	HBC
−0.008 ±0.012	4709	PEACH	77	HBC
0.0097±0.0018	509k	MESSNER	74	ASPK

LINEAR COEFFICIENT j FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ (CP-VIOLATING TERM)

Listed in CP-violation section below.

QUADRATIC COEFFICIENT *f* FOR $K^0_L \to \pi^+\pi^-\pi^0$ (*CP*-VIOLATING TERM)

Listed in *CP*-violation section below.

QUADRATIC COEFFICIENT *h* FOR $K^0_L \to \pi^0\pi^0\pi^0$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*
−5.0±1.4 OUR AVERAGE	Error includes scale factor of 1.7.			
$-6.1\pm0.9\pm0.5$	14.7M	LAI	01B	NA48
$-3.3\pm1.1\pm0.7$	5M	[71] SOMALWAR	92	E731

[71] SOMALWAR 92 chose m_{π^+} as normalization to make it compatible with the Particle Data Group $K^0_L \to \pi^+\pi^-\pi^0$ definitions.

K^0_L FORM FACTORS

For discussion, see note on form factors in the $K^\pm$ section of the Particle Listings above.

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.

f_S and f_T refer to the scalar and tensor term.

$f_0 = f_+ + f_-\ t/(m^2_{K^0} - m^2_{\pi^+})$.

t = momentum transfer to the π.

λ_+ and λ_0 are the linear expansion coefficients of f_+ and f_0:

$f_+(t) = f_+(0)\ (1 + \lambda_+ t\ /m^2_{\pi^+})$

For quadratic expansion

$f_+(t) = f_+(0)\ (1 + \lambda'_+ t\ /m^2_{\pi^+} + \frac{\lambda''_+}{2}\ t^2/m^4_{\pi^+}\ )$

as used by KTeV. If there is a non-vanishing quadratic term, then λ_+ represents an average slope, which is then different from λ'_+.

NA48 and ISTRA quadratic expansion coefficients are converted with

$\lambda'_+{}^{PDG} = \lambda_+{}^{NA48}$ and $\lambda''_+{}^{PDG} = 2\ \lambda'_+{}^{NA48}$

$\lambda'_+{}^{PDG} = (\frac{m_{\pi^+}}{m_{\pi^0}})^2\ \lambda_+{}^{ISTRA}$ and

$\lambda''_+{}^{PDG} = 2\ (\frac{m_{\pi^+}}{m_{\pi^0}})^4\ \lambda'_+{}^{ISTRA}$

ISTRA linear expansion coefficients are converted with

$\lambda_+{}^{PDG} = (\frac{m_{\pi^+}}{m_{\pi^0}})^2\ \lambda_+{}^{ISTRA}$ and $\lambda_0{}^{PDG} = (\frac{m_{\pi^+}}{m_{\pi^0}})^2\ \lambda_0{}^{ISTRA}$

The pole parametrization is

$$f_+(t) = f_+(0)\ (\frac{M_V^2}{M_V^2 - t}\ )$$

$$f_0(t) = f_0(0)\ (\frac{M_S^2}{M_S^2 - t}\ )$$

where M_V and M_S are the vector and scalar pole masses.

The following abbreviations are used:

DP = Dalitz plot analysis.

PI = π spectrum analysis.

MU = μ spectrum analysis.
POL= μ polarization analysis.
BR = $K^0_{\mu3}/K^0_{e3}$ branching ratio analysis.
E = positron or electron spectrum analysis.
RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K^0_{e3} DECAY)

For radiative correction of K^0_{e3} DP, see GINSBERG 67, BECHERRAWY 70, CIRIGLIANO 02, CIRIGLIANO 04, and ANDRE 04. Results labeled OUR FIT are discussed in the review "$K^{\pm}_{\ell3}$ and $K^0_{\ell3}$ Form Factors" in the $K^{\pm}$ Listings. For earlier, lower statistics results, see the 2004 edition of this review, Phys. Lett. B592, 1 (2004).

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.84 ±0.04 OUR FIT	Assuming μ-e universality			
2.85 ±0.04 OUR AVERAGE				
2.86 ±0.05 ±0.04	2M	AMBROSINO 06D	KLOE	
2.832±0.037±0.043	1.9M	ALEXOPOU... 04A	KTEV	PI, no $\mu = e$
2.88 ±0.04 ±0.11	5.6M	[72] LAI 04C	NA48	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.84 ±0.07 ±0.13	5.6M	[73] LAI 04C	NA48	DP
2.45 ±0.12 ±0.22	366k	APOSTOLA... 00	CPLR	DP
3.06 ±0.34	74k	BIRULEV 81	SPEC	DP
3.12 ±0.25	500k	GJESDAL 76	SPEC	DP
2.70 ±0.28	25k	BLUMENTHAL75	SPEC	DP

[72] Results from linear fit and assuming only vector and axial couplings.

[73] Results from linear fit with $|f_S/f_+|$ and $|f_T/f_+|$ free.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K^0_{\mu3}$ DECAY)

Results labeled OUR FIT are discussed in the review "$K^{\pm}_{\ell3}$ and $K^0_{\ell3}$ Form Factors" in the $K^{\pm}$ Listings. For earlier, lower statistics results, see the 2004 edition of this review, Phys. Lett. B592, 1 (2004).

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.84 ±0.04 OUR FIT	Assuming μ-e universality			
2.78 ±0.10 OUR FIT	Not assuming μ-e universality			
2.745±0.088±0.063	1.5M	ALEXOPOU... 04A	KTEV	DP, no $\mu = e$
2.813±0.051	3.4M	ALEXOPOU... 04A	KTEV	PI, DP, $\mu = e$
3.0 ±0.3	1.6M	DONALDSON 74B	SPEC	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.27 ±0.44	150k	BIRULEV 81	SPEC	DP

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^0_{\mu3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ^{μ}_+ and $d\xi(0)/d\lambda_+$. Results labeled OUR FIT are discussed in the review "$K^{\pm}_{\ell3}$ and $K^0_{\ell3}$ Form Factors" in the $K^{\pm}$ Listings. For earlier, lower statistics results, see the 2004 edition of this review, Phys. Lett. B592, 1 (2004).

VALUE (units 10^{-2})	*$d\lambda_0/d\lambda_+$*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.64 ±0.11 OUR FIT	Correlation is $d\lambda_0/d\lambda_+ = -0.82$. Assumes μ-e universality.				
1.67 ±0.12 OUR FIT	Correlation is $d\lambda_0/d\lambda_+ = -0.44$.				
1.657±0.125	−0.44	1.5M	[74] ALEXOPOU... 04A	KTEV	DP, no $\mu = e$

1.635±0.121	−0.85	3.4M	[75] ALEXOPOU...	04A	KTEV	PI, DP, $\mu = e$
+1.9 ±0.4	−0.47	1.6M	[76] DONALDSON	74B	SPEC	DP

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

3.41 ±0.67	unknown	150k	[77] BIRULEV	81	SPEC	DP

[74] ALEXOPOULOS 04A gives a correlation −0.38 between their λ_0 and λ_+ measurements. From it we calculate $d\lambda_0/d\lambda_+$.

[75] ALEXOPOULOS 04A gives a correlation −0.36 between their λ_0 and λ_+ measurements. From it we calculate $d\lambda_0/d\lambda_+$.

[76] DONALDSON 74B $d\lambda_0/d\lambda_+$ obtained from figure 18.

[77] BIRULEV 81 gives $d\lambda_0/d\lambda_+ = -1.5$, giving an unreasonably narrow error ellipse which dominates all other results. We use $d\lambda_0/d\lambda_+ = 0$.

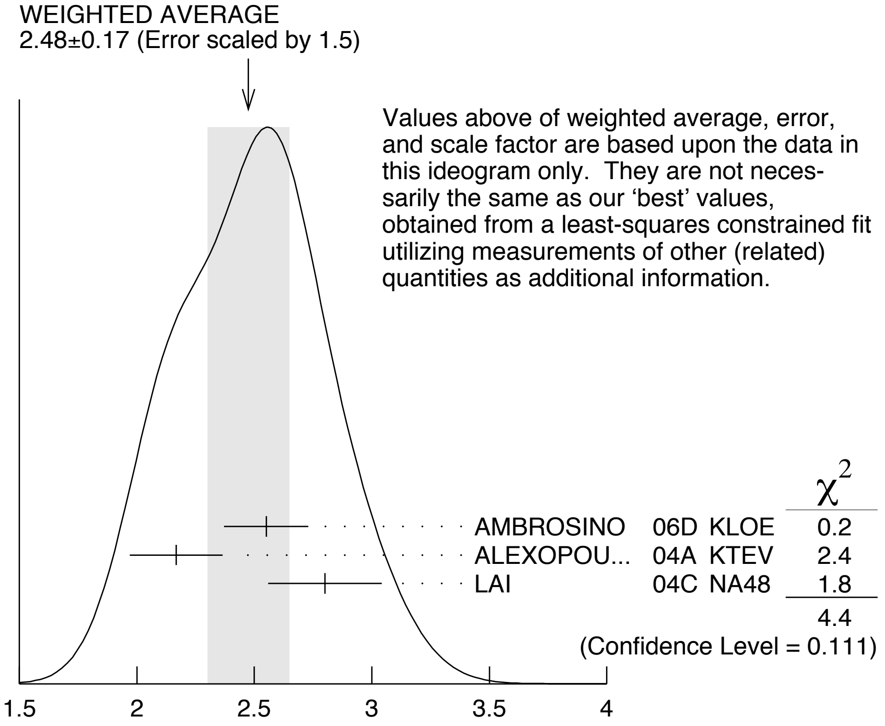
λ'_+(LINEAR K^0_{e3} FORM FACTOR FROM QUADRATIC FIT)

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.49 ±0.13		**OUR FIT**		Error includes scale factor of 1.1. Not assuming μ-e universality
2.42 ±0.14		**OUR FIT**		Error includes scale factor of 1.3. Assuming μ-e universality
2.48 ±0.17		**OUR AVERAGE**		Error includes scale factor of 1.5. See the ideogram below.
2.55 ±0.15 ±0.10	2M	[78] AMBROSINO 06D	KLOE	
2.167±0.137±0.143	1.9M	[79] ALEXOPOU... 04A	KTEV	PI, no $\mu = e$
2.80 ±0.19 ±0.15	5.6M	[80] LAI 04C	NA48	DP

[78] AMBROSINO 06D gives a correlation −0.95 between their λ'_+ and λ''_+.

[79] ALEXOPOULOS 04A gives a correlation −0.97 between their λ'_+ and λ''_+.

[80] For LAI 04C we calculate a correlation −0.88 between their λ'_+ and λ''_+.



λ'_+(LINEAR K^0_{e3} FORM FACTOR FROM QUADRATIC FIT)

λ''_+(QUADRATIC K^0_{e3} FORM FACTOR)

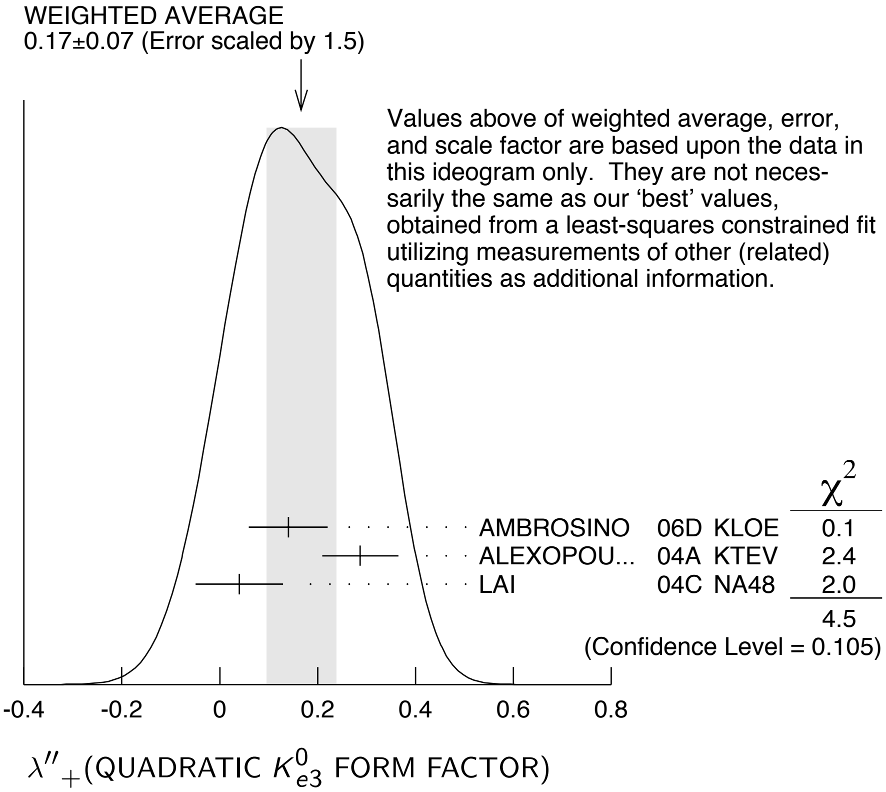
VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.18 ±0.05	**OUR FIT**			Error includes scale factor of 1.1. Assuming μ-e universality
0.16 ±0.05	**OUR FIT**			Error includes scale factor of 1.1. Not assuming μ-e universality
0.17 ±0.07	**OUR AVERAGE**			Error includes scale factor of 1.5. See the ideogram below.
0.14 ±0.07 ±0.04	2M	[81] AMBROSINO 06D	KLOE	
0.287±0.057±0.053	1.9M	[82] ALEXOPOU... 04A	KTEV	PI, no $\mu = e$
0.04 ±0.08 ±0.04	5.6M	[83,84] LAI 04C	NA48	DP

[81] AMBROSINO 06D gives a correlation -0.95 between their λ'_+ and λ''_+.

[82] ALEXOPOULOS 04A gives a correlation -0.97 between their λ'_+ and λ''_+.

[83] Values doubled to agree with PDG conventions described above.

[84] LAI 04C gives a correlation -0.88 between their λ'_+ and λ''_+.



λ'_+(LINEAR $K^0_{\mu3}$ FORM FACTOR FROM QUADRATIC FIT)

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.42 ±0.14	**OUR FIT**			Error includes scale factor of 1.3. Assuming μ-e universality
1.7 ±0.4	**OUR FIT**			Not assuming μ-e universality
1.703±0.319±0.177	1.5M	[85] ALEXOPOU... 04A	KTEV	DP, no $\mu = e$
2.064±0.175	3.4M	[85] ALEXOPOU... 04A	KTEV	PI, DP, $\mu = e$

[85] See section λ_0 below for correlations.

λ''_+(QUADRATIC $K^0_{\mu 3}$ FORM FACTOR)

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.18 ±0.05 OUR FIT				Error includes scale factor of 1.1. Assuming μ-*e* universality
0.44 ±0.15 OUR FIT				Not assuming μ-*e* universality
0.443±0.131±0.072	1.5M	[86] ALEXOPOU... 04A	KTEV	DP, no $\mu = e$
0.320±0.069	3.4M	[86] ALEXOPOU... 04A	KTEV	PI, DP, $\mu = e$

[86] See section λ_0 below for correlations.

λ_0(LINEAR f_0 $K^0_{\mu 3}$ FORM FACTOR FROM QUADRATIC FIT)

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.46 ±0.13 OUR FIT				Assuming μ-*e* universality
1.28 ±0.18 OUR FIT				Not assuming μ-*e* universality
1.281±0.136±0.122	1.5M	[87] ALEXOPOU... 04A	KTEV	DP, no $\mu = e$
1.372±0.131	3.4M	[88] ALEXOPOU... 04A	KTEV	PI, DP, $\mu = e$

[87] ALEXOPOULOS 04A, not assuming μ-*e* universality, gives a correlation matrix

$$\begin{array}{cccc} & \lambda'_+ & \lambda''_+ & \lambda_0 \\ \lambda'_+ & 1 & & \\ \lambda''_+ & -0.96 & 1 & \\ \lambda_0 & 0.65 & -0.75 & 1 \end{array}$$

[88] ALEXOPOULOS 04A, assuming μ-*e* universality, gives a correlation matrix

$$\begin{array}{cccc} & \lambda'_+ & \lambda''_+ & \lambda_0 \\ \lambda'_+ & 1 & & \\ \lambda''_+ & -0.97 & 1 & \\ \lambda_0 & 0.34 & -0.44 & 1 \end{array}$$

M^e_V (POLE MASS FOR K^0_{e3} DECAY)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
877 ± 5 OUR FIT				Error includes scale factor of 1.1. Assuming μ-*e* universality
875 ± 5 OUR AVERAGE				
870 ± 6 ±7	2M	AMBROSINO 06D	KLOE	
881.03± 5.12±4.94	1.9M	ALEXOPOU... 04A	KTEV	PI, no $\mu = e$
859 ±18	5.6M	LAI 04C	NA48	

M^{μ}_V (POLE MASS FOR $K^0_{\mu 3}$ DECAY)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
877 ± 5 OUR FIT				Error includes scale factor of 1.1. Assuming μ-*e* universality
889 ±16 OUR FIT				Not assuming μ-*e* universality
889.19±12.81±9.92	1.5M	[89] ALEXOPOU... 04A	KTEV	DP, no $\mu = e$
882.32± 6.54	3.4M	[89] ALEXOPOU... 04A	KTEV	PI, DP, $\mu = e$

[89] See section M^{μ}_S below for correlations.

M^{μ}_{S} (POLE MASS FOR $K^0_{\mu3}$ DECAY)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1167 ±40 OUR FIT				Not assuming μ-*e* universality
1187 ±50 OUR FIT				Error includes scale factor of 1.4. Assuming μ-*e* universality
1167.14±28.30±31.04	1.5M	[90] ALEXOPOU... 04A	KTEV	PI, no $\mu = e$
1173.80±39.47	3.4M	[91] ALEXOPOU... 04A	KTEV	PI, DP, $\mu = e$

[90] ALEXOPOULOS 04A gives a correlation −0.46 between their M^{μ}_{S} and M^{μ}_{V} and measurements, not assuming μ-*e* universality.

[91] ALEXOPOULOS 04A gives a correlation −0.40 between their M^{μ}_{S} and M^{μ}_{V} and measurements, assuming μ-*e* universality.

$|f_S/f_+|$ FOR K^0_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE (units 10^{-2})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{1.5^{+0.7}_{-1.0}\pm1.2}$		5.6M	[92] LAI 04C	NA48	

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

VALUE (units 10^{-2})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
<9.5	95	18k	HILL 78	STRC	
<7.	68	48k	BIRULEV 76	SPEC	See also BIRULEV 81
<4.	68	25k	BLUMENTHAL75	SPEC	

[92] Results from linear fit with $|f_S/f_+|$ and $|f_T/f_+|$ free.

$|f_T/f_+|$ FOR K^0_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE (units 10^{-2})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{5^{+3}_{-4}\pm3}$		5.6M	[93] LAI 04C	NA48	

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

VALUE (units 10^{-2})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
<40.	95	18k	HILL 78	STRC	
<34.	68	48k	BIRULEV 76	SPEC	See also BIRULEV 81
<23.	68	25k	BLUMENTHAL75	SPEC	

[93] Results from linear fit with $|f_S/f_+|$ and $|f_T/f_+|$ free.

$|f_T/f_+|$ FOR $K^0_{\mu3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE (units 10^{-2})	*DOCUMENT ID*	*TECN*
12.±12.	BIRULEV 81	SPEC

α_{K^*} DECAY FORM FACTOR FOR $K_L \to e^+e^-\gamma$

α_{K^*} is the constant in the model of BERGSTROM 83 which measures the relative strength of the vector-vector transition $K_L \to K^*\gamma$ with $K^* \to \rho, \omega, \phi \to \gamma^*$ and the pseudoscalar-pseudoscalar transition $K_L \to \pi, \eta, \eta' \to \gamma\gamma^*$.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
−0.33 ±0.05 OUR AVERAGE			
−0.36 ±0.06 ±0.02	6864	FANTI 99B	NA48
−0.28 ±0.13		BARR 90B	NA31
$-0.280^{+0.099}_{-0.090}$		OHL 90B	B845

α_{K^*} DECAY FORM FACTOR FOR $K_L \to \mu^+\mu^-\gamma$

α_{K^*} is the constant in the model of BERGSTROM 83 described in the previous section.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
$-$0.158±0.027 OUR AVERAGE			
$-0.160^{+0.026}_{-0.028}$	9100	ALAVI-HARATI 01G	KTEV
$-0.04\ ^{+0.24}_{-0.21}$		FANTI 97	NA48

$\alpha^{\text{eff}}_{K^*}$ DECAY FORM FACTOR FOR $K_L \to e^+e^-e^+e^-$

$\alpha^{\text{eff}}_{K^*}$ is the parameter describing the relative strength of an intermediate pseudoscalar decay amplitude and a vector meson decay amplitude in the model of BERGSTROM 83. It takes into account both the radiative effects and the form factor. Since there are two e^+e^- pairs here compared with one in $e^+e^-\gamma$ decays, a factorized expression is used for the $e^+e^-e^+e^-$ decay form factor.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
$-$0.14±0.16±0.15	441	ALAVI-HARATI 01D	KTEV

a_1/a_2 FORM FACTOR FOR M1 DIRECT EMISSION AMPLITUDE

Form factor $= \tilde{g}_{M1}\left[1+\frac{a_1/a_2}{(M_\rho^2-M_K^2)+2M_K E_\gamma^*}\right]$ as described in ALAVI-HARATI 00B.

VALUE (GeV^2)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$-$0.734±0.022 OUR AVERAGE				
$-0.81\ ^{+0.07}_{-0.13}\ \pm 0.02$		[94] LAI 03C	NA48	$\pi^+\pi^-e^+e^-$
$-0.737\pm0.026\pm0.022$		[95] ALAVI-HARATI 01B		$\pi^+\pi^-\gamma$
$-0.720\pm0.028\pm0.009$	1766	[96] ALAVI-HARATI 00B	KTEV	$\pi^+\pi^-e^+e^-$

[94] LAI 03C also measured $\widetilde{g}_{M1} = 0.99^{+0.28}_{-0.27} \pm 0.07$.

[95] ALAVI-HARATI 01B fit gives χ^2/DOF = 38.8/27. Linear and quadratic fits give χ^2/DOF = 43.2/27 and 37.6/26 respectively.

[96] ALAVI-HARATI 00B also measured $\widetilde{g}_{M1}=1.35^{+0.20}_{-0.17} \pm 0.04$.

$\overline{f}_S$ DECAY FORM FACTOR FOR $K^0_L \to \pi^\pm\pi^0e^\mp\nu_e$

VALUE	*DOCUMENT ID*	*TECN*
0.049±0.011 OUR AVERAGE	Error includes scale factor of 1.7.	
0.052±0.006±0.002	BATLEY 04	NA48
0.010±0.016±0.017	MAKOFF 93	E731

$\overline{f}_P$ DECAY FORM FACTOR FOR $K^0_L \to \pi^\pm\pi^0e^\mp\nu_e$

VALUE	*DOCUMENT ID*	*TECN*
$-$0.052±0.012 OUR AVERAGE		
$-$0.051±0.011±0.005	BATLEY 04	NA48
$-$0.079±0.049±0.022	MAKOFF 93	E731

λ_g DECAY FORM FACTOR FOR $K^0_L \to \pi^\pm\pi^0e^\mp\nu_e$

VALUE	*DOCUMENT ID*	*TECN*
0.085±0.020 OUR AVERAGE		
0.087±0.019±0.006	BATLEY 04	NA48
0.014±0.087±0.070	MAKOFF 93	E731

$\overline{h}$ DECAY FORM FACTOR FOR $K^0_L \to \pi^\pm \pi^0 e^\mp \nu_e$

VALUE	*DOCUMENT ID*		*TECN*
−0.30±0.13 OUR AVERAGE			
−0.32±0.12±0.07	BATLEY	04	NA48
−0.07±0.31±0.31	MAKOFF	93	E731

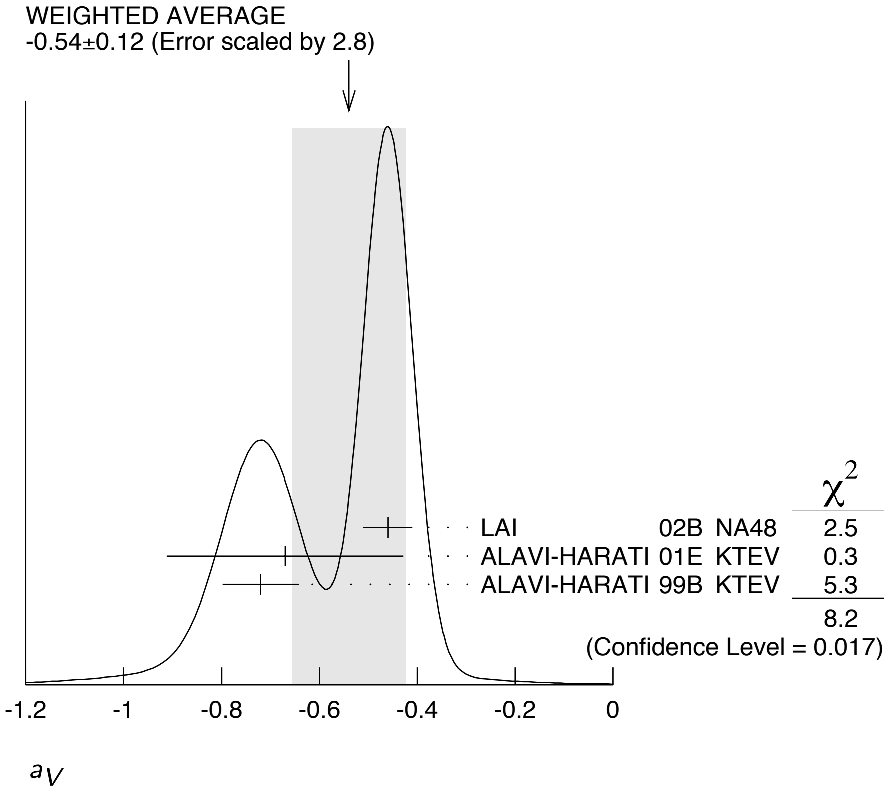
L_3 CHIRAL PERT. THEO. PARAM. FOR $K^0_L \to \pi^\pm \pi^0 e^\mp \nu_e$

VALUE (units 10^{-3})	*DOCUMENT ID*		*TECN*
−3.96±0.28 OUR AVERAGE	Error includes scale factor of 1.6.		
−4.1 ±0.2	BATLEY	04	NA48
−3.4 ±0.4	[97] MAKOFF	93	E731

[97] MAKOFF 93 sign has been changed to negative to agree with the sign convention used in BATLEY 04.

a_V, VECTOR MESON EXCHANGE CONTRIBUTION

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.54±0.12 OUR AVERAGE	Error includes scale factor of 2.8.			See the ideogram below.
−0.46±0.03±0.04	LAI	02B	NA48	$K^0_L \to \pi^0 2\gamma$
−0.67±0.21±0.12	ALAVI-HARATI	01E	KTEV	$K^0_L \to \pi^0 e^+ e^- \gamma$
−0.72±0.05±0.06	ALAVI-HARATI	99B	KTEV	$K^0_L \to \pi^0 2\gamma$



CP VIOLATION IN K_L DECAYS

Revised May 2006 by L. Wolfenstein (Carnegie-Mellon University) and T.G. Trippe (LBNL).

The symmetries C (particle-antiparticle interchange) and P (space inversion) hold for strong and electromagnetic interactions. After the discovery of large C and P violation in the weak interactions, it appeared that the product CP was a good symmetry. In 1964 CP violation was observed in K^0 decays at a level given by the parameter $\epsilon \approx 2.3 \times 10^{-3}$.

A unified treatment of CP violation in K, D, B, and B_s mesons is given in "CP Violation in Meson Decays" by D. Kirkby and Y. Nir in this *Review.* A more detailed review including a thorough discussion of the experimental techniques used to determine CP violation parameters is given in a book by K. Kleinknecht [1]. Here we give a concise summary of the formalism needed to define the parameters of CP violation in K_L decays and a description of our fits for the best values of these parameters.

1. Formalism for CP violation in Kaon decay:

CP violation has been observed in the semi-leptonic decays $K_L^0 \rightarrow \pi^{\mp}\ell^{\pm}\nu$ and in the nonleptonic decay $K_L^0 \rightarrow 2\pi$. The experimental numbers that have been measured are

$$A_L = \frac{\Gamma(K_L^0 \rightarrow \pi^-\ell^+\nu) - \Gamma(K_L^0 \rightarrow \pi^+\ell^-\nu)}{\Gamma(K_L^0 \rightarrow \pi^-\ell^+\nu) + \Gamma(K_L^0 \rightarrow \pi^+\ell^-\nu)} \tag{1a}$$

$$\begin{aligned}\eta_{+-} &= A(K_L^0 \rightarrow \pi^+\pi^-)/A(K_S^0 \rightarrow \pi^+\pi^-) \\ &= |\eta_{+-}|\, e^{i\phi_{+-}} \qquad (1b)\\ \eta_{00} &= A(K_L^0 \rightarrow \pi^0\pi^0)/A(K_S^0 \rightarrow \pi^0\pi^0) \\ &= |\eta_{00}|\, e^{i\phi_{00}} \ . \qquad (1c)\end{aligned}$$

CP violation can occur either in the K^0–$\overline{K}^0$ mixing or in the decay amplitudes. Assuming CPT invariance, the mass eigenstates of the K^0–$\overline{K}^0$ system can be written

$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle \ , \qquad |K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle \ . \tag{2}$$

If CP invariance held, we would have $q = p$ so that K_S would be CP even and K_L CP odd. (We define $|\overline{K}^0\rangle$ as CP $|K^0\rangle$). CP violation in K^0–$\overline{K}^0$ mixing is then given by the parameter $\widetilde{\epsilon}$ where

$$\frac{p}{q} = \frac{(1+\widetilde{\epsilon})}{(1-\widetilde{\epsilon})} \ . \tag{3}$$

CP violation can also occur in the decay amplitudes

$$A(K^0 \to \pi\pi(I)) = A_I e^{i\delta_I} \ , \qquad A(\overline{K}^0 \to \pi\pi(I)) = A_I^* e^{i\delta_I} \ , \tag{4}$$

where I is the isospin of $\pi\pi$, δ_I is the final-state phase shift, and A_I would be real if CP invariance held. The CP-violating observables are usually expressed in terms of ϵ and ϵ' defined by

$$\eta_{+-} = \epsilon + \epsilon' \ , \qquad \eta_{00} = \epsilon - 2\epsilon' \ , \tag{5a}$$

One can then show [2]

$$\epsilon = \widetilde{\epsilon} + i \ \ (\text{Im}\ A_0/\text{Re}\ A_0) \ , \tag{5b}$$

$$\sqrt{2}\epsilon' = ie^{i(\delta_2-\delta_0)}(\text{Re}\,A_2/\text{Re}\,A_0) \ \ (\text{Im}\,A_2/\text{Re}\,A_2 - \text{Im}\,A_0/\text{Re}\ A_0) \ , \tag{5c}$$

$$A_L = 2\text{Re}\ \epsilon/(1+|\epsilon|^2) \approx 2\text{Re}\ \epsilon \ . \tag{5d}$$

In Eqs. (5a) small corrections [3] of order $\epsilon' \times$ Re (A_2/A_0) are neglected and Eq. (5d) assumes the $\Delta S = \Delta Q$ rule.

The quantities Im A_0, Im A_2, and Im $\widetilde{\epsilon}$ depend on the choice of phase convention since one can change the phases of K^0 and $\overline{K}^0$ by a transformation of the strange quark state $|s\rangle \to |s\rangle\ e^{i\alpha}$; of course, observables are unchanged. It is possible by a choice of phase convention to set $\text{Im}\,A_0$ or $\text{Im}\,A_2$ or $\text{Im}\,\widetilde{\epsilon}$ to zero, but none of these is zero with the usual phase conventions in the Standard Model. The choice $\text{Im}\,A_0 = 0$ is called the Wu-Yang phase convention [4] in which case $\epsilon = \widetilde{\epsilon}$. The value of ϵ' is independent of phase convention and a nonzero value demonstrates CP violation in the decay amplitudes, referred to as direct CP violation. The possibility that direct CP violation is essentially zero and that CP violation occurs only in the mixing matrix was referred to as the superweak theory [5].

By applying CPT invariance and unitarity the phase of ϵ is given approximately by

$$\phi_\epsilon \approx \tan^{-1}\frac{2(m_{K_L}-m_{K_S})}{\Gamma_{K_S}-\Gamma_{K_L}} \approx 43.51\pm 0.05^\circ \qquad (6a)$$

while Eq. $(5c)$ gives the phase of ϵ' to be

$$\phi_{\epsilon'} = \delta_2-\delta_0+\frac{\pi}{2} \approx 42.3\pm 1.5^\circ\ , \qquad (6b)$$

where the numerical value is based on an analysis of π–π scattering using chiral perturbation theory [6]. The approximation in Eq. $(6a)$ depends on the assumption that direct CP violation is very small in all K^0 decays. This is expected to be good to a few tenths of a degree as indicated by the small value of ϵ' and of η_{+-0} and η_{000}, the CP-violation parameters in the decays $K_S \to \pi^+\pi^-\pi^0$ [7] and $K_S\to\pi^0\pi^0\pi^0$ [8]. The relation in Eq. $(6a)$ is exact in the superweak theory so this is sometimes called the superweak phase $\phi_{\rm SW}$. An important point for the analysis is that $\cos(\phi_{\epsilon'}-\phi_\epsilon)\simeq 1$. The consequence is that only two real quantities need be measured, the magnitude of ϵ and the value of (ϵ'/ϵ) including its sign. The measured quantity $|\eta_{00}/\eta_{+-}|^2$ is very close to unity so that we can write

$$|\eta_{00}/\eta_{+-}|^2 \approx 1-6\mathrm{Re}\,(\epsilon'/\epsilon)\approx 1-6\epsilon'/\epsilon\ . \qquad (7a)$$

$$\mathrm{Re}(\epsilon'/\epsilon)\approx \tfrac{1}{3}(1-|\eta_{00}/\eta_{+-}|)\ . \qquad (7b)$$

From the experimental measurements in this Edition of the *Review of Particle Physics* and the fits discussed in the next section, one finds

$$|\epsilon| = (2.232\pm 0.007)\times 10^{-3}\ , \qquad (8a)$$

$$\phi_\epsilon = (43.5 \pm 0.7)^\circ \;, \tag{8b}$$

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \epsilon'/\epsilon = (1.66 \pm 0.26) \times 10^{-3} \;, \tag{8c}$$

$$\phi_{+-} = (43.4 \pm 0.7)^\circ \;, \tag{8d}$$

$$\phi_{00} - \phi_{+-} = (0.2 \pm 0.4)^\circ \;, \tag{8e}$$

$$A_L = (3.32 \pm 0.06) \times 10^{-3} \;. \tag{8f}$$

Direct CP violation, as indicated by ϵ'/ϵ, is expected in the Standard Model. However the numerical value cannot be reliably predicted because of theoretical uncertainties [9]. The value of A_L agrees with Eq. (5d). The values of ϕ_{+-} and $\phi_{00} - \phi_{+-}$ are used to set limits on CPT violation. [See Tests of Conservation Laws.]

2. Fits for K_L^0 CP-violation parameters:

In recent years, K_L^0 CP-violation experiments have improved our knowledge of CP-violation parameters and their consistency with the expectations of CPT invariance and unitarity. To determine the best values of the CP-violation parameters in $K_L^0 \to \pi^+\pi^-$ and $\pi^0\pi^0$ decay, we make two types of fits, one for the phases ϕ_{+-} and ϕ_{00} jointly with Δm and τ_S, and the other for the amplitudes $|\eta_{+-}|$ and $|\eta_{00}|$ jointly with the $K_L^0 \to \pi\pi$ branching fractions.

Fits to ϕ_{+-}, ϕ_{00}, $\Delta\phi$, Δm, and τ_S data: These are joint fits to the data on ϕ_{+-}, ϕ_{00}, the phase difference $\Delta\phi = \phi_{00} - \phi_{+-}$, the K_L^0–K_S^0 mass difference Δm, and the K_S^0 mean life τ_S, including the effects of correlations.

Measurements of ϕ_{+-} and ϕ_{00} are highly correlated with Δm and τ_S. Some measurements of τ_S are correlated with Δm. The correlations are given in the footnotes of the ϕ_{+-} and ϕ_{00} sections of the K_L^0 Particle Listings and the τ_S section of the K_S^0 Particle listings.

In most cases, the correlations are quoted as 100%, *i.e.*with the value and error of ϕ_{+-} or ϕ_{00} given at a fixed value of Δm and τ_S with additional terms specifying the dependence of the value on Δm and τ_S. These cases lead to diagonal bands in Figs. [1] and [2]. The KTeV experiment [10] quotes its results as values of ϕ_{+-}, Δm, and τ_S with correlations, leading to the ellipses labeled "b".

Table 1: References, Document ID's, and sources corresponding to the letter labels in the figures. The data are given in the ϕ_{+-} and Δm sections of the K_L Particle Listings, and the τ_S section of the K_S Particle Listings.

Label	Source	PDG Document ID	Ref.
a	this review	OUR FIT	
b	FNAL KTeV	ALAVI-HARATI 03	[10]
c	CERN CPLEAR	APOSTOLAKIS 99C	[11]
d	FNAL E773	SCHWINGENHEUER 95	[12]
e	FNAL E731	GIBBONS 93,93C	[13,14]
f	CERN	GEWENIGER 74B,74C	[15,16]
g	CERN NA31	CAROSI 90	[17]
h	CERN NA48	LAI 02C	[18]
i	CERN NA31	BERTANZA 97	[19]
j	this review	SUPERWEAK 04	

The data on τ_S, Δm, and ϕ_{+-} shown in Figs. [1] and [2]. are combined with data on ϕ_{00} and $\phi_{00} - \phi_{+-}$ in two fits, one without assuming *CPT* and the other with this assumption. The results without assuming *CPT* are shown as ellipses labeled

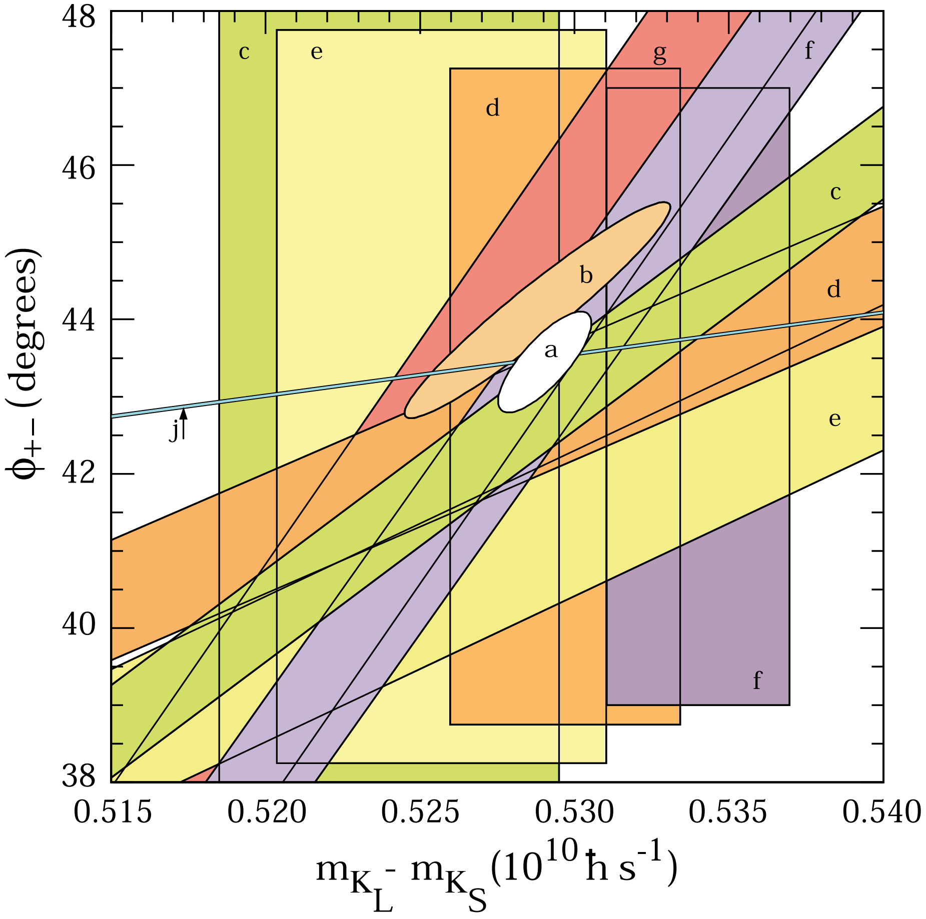


Figure 1: ϕ_{+-} vs Δm for experiments which do not assume CPT invariance. Δm measurements appear as vertical bands spanning $\Delta m \pm 1\sigma$, cut near the top and bottom to aid the eye. Most ϕ_{+-} measurements appear as diagonal bands spanning $\phi_{+-} \pm \sigma_\phi$. Data are labeled by letters: "b"–FNAL KTeV, "c"–CERN CPLEAR, "d"–FNAL E773, "e"–FNAL E731, "f"–CERN, "g"–CERN NA31, and are cited in Table 1. The narrow band "j" shows $\phi_{\rm SW}$. The ellipse "a" shows the $\chi^2 = 1$ contour of the fit result. See full-color version on color pages at end of book.

"a". These ellipses are seen to be in good agreement with the superweak phase

$$\phi_{\mathrm{SW}} = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right) = \tan^{-1}\left(\frac{2\Delta m \tau_S \tau_L}{\hbar(\tau_L - \tau_S)}\right) \ . \tag{9}$$

In Figs. [1] and [2], ϕ_{SW} is shown as narrow bands labeled "j".

Table 2 column 2, "Fit w/o CPT," gives the resulting fitted parameters, while Table 3 gives the correlation matrix for this fit. The white ellipses labeled "a" in Fig. 1 and Fig. 2 are the $\chi^2 = 1$ contours for this fit.

For experiments which have dependencies on unseen fit parameters, that is, parameters other than those shown on the x or y axis of the figure, their band positions are evaluated using the fit results and their band widths include the fitted uncertainty in the unseen parameters. This is also true for the ϕ_{SW} bands.

If CPT invariance and unitarity are assumed, then by Eq. (6*a*), the phase of ϵ is constrained to be approximately equal to

$$\phi_{\mathrm{SW}} = (43.507 \pm 0.0004)^\circ + 54(\Delta m - 0.5290)^\circ + 32(\tau_S - 0.8958) \tag{10}$$

where we have linearized the Δm and τ_S dependence of Eq. (9). The error ±0.0004 is due to the uncertainty in τ_L. Here Δm has units $10^{10}\,\hbar\,\mathrm{s}^{-1}$ and τ_S has units 10^{-10} s.

If in addition we use the observation that $Re(\epsilon'/\epsilon) \ll 1$ and $cos(\phi_{\epsilon'} - \phi_\epsilon) \simeq 1$, as well as the numerical value of $\phi_{\epsilon'} - \phi_\epsilon$ given in Eq. (6*b*), then Eqs. (5a), which are sketched in Fig. 3, lead to the constraint

$$\begin{aligned} \phi_{00} - \phi_{+-} &\approx -3\ \mathrm{Im}\left(\frac{\epsilon'}{\epsilon}\right) \\ &\approx -3\ \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)\tan(\phi_{\epsilon'} - \phi_\epsilon) \\ &\approx -0.023^\circ \pm 0.020^\circ \end{aligned} \tag{11}$$

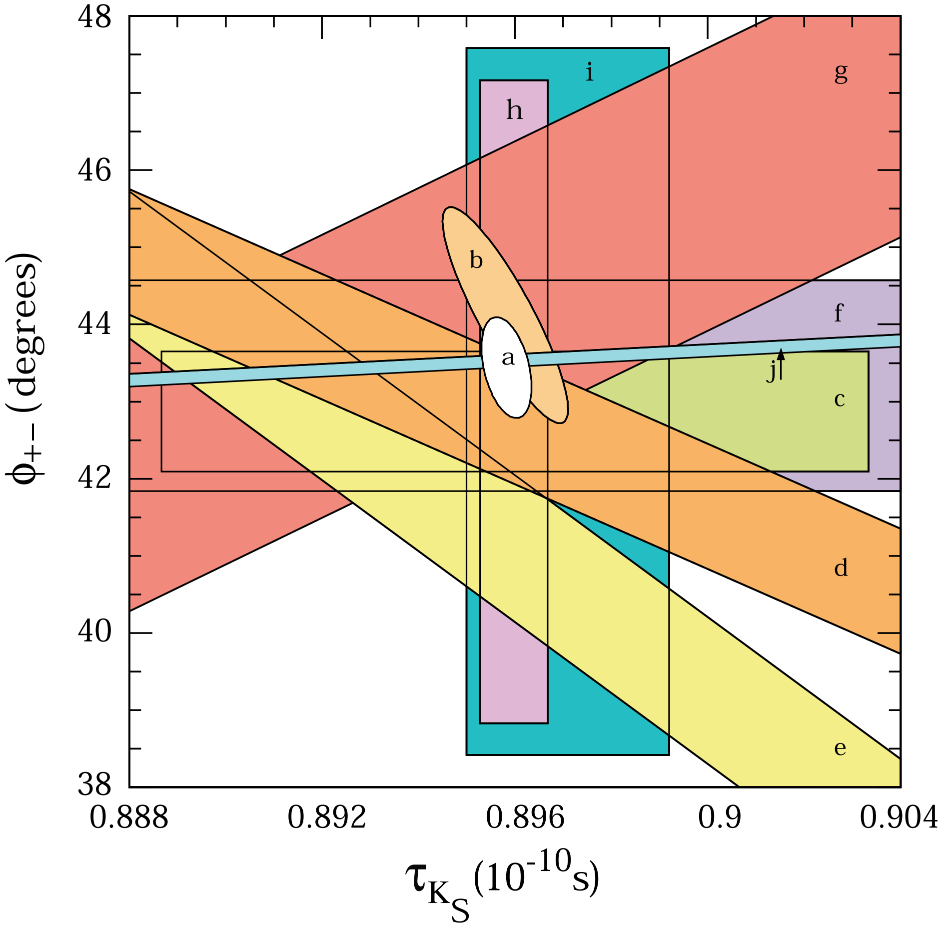


Figure 2: ϕ_{+-} vs τ_S. τ_S measurements appear as vertical bands spanning $\tau_S \pm 1\sigma$, some of which are cut near the top and bottom to aid the eye. Most ϕ_{+-} measurements appear as diagonal or horizontal bands spanning $\phi_{+-} \pm \sigma_\phi$. Data are labeled by letters: "b"–FNAL KTeV, "c"–CERN CPLEAR, "d"–FNAL E773, "e"–FNAL E731, "f"–CERN, "g"–CERN NA31, "h"–CERN NA48, "i"–CERN NA31, and are cited in Table 1. The narrow band "j" shows $\phi_{\rm SW}$. The ellipse "a" shows the fit result's $\chi^2 = 1$ contour. Color version at end of book.

so that $\phi_{+-} \approx \phi_{00} \approx \phi_\epsilon \approx \phi_{\rm SW}$.

In the fit assuming CPT we constrain $\phi_\epsilon = \phi_{\rm SW}$ using the linear expression in Eq. (10) and constrain $\phi_{00} - \phi_{+-}$ using

Eq. (11). These constraints are inserted into the Data Listings with the Document ID of SUPERWEAK 04. Some additional data for which the authors assumed CPT are added to this fit or substitute for other less precise data for which the authors did not make this assumption. See the data listings for details.

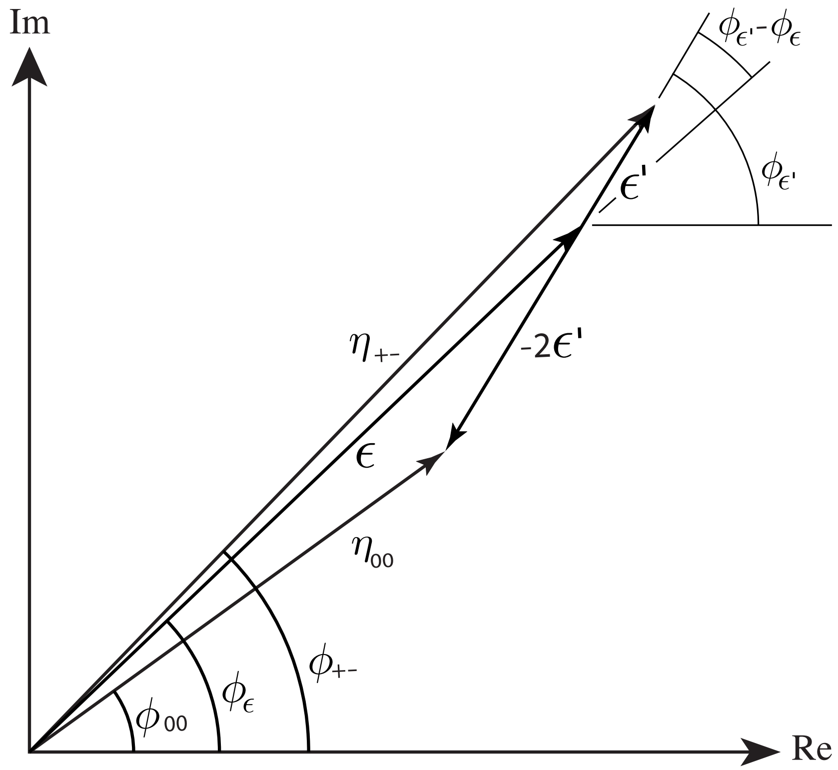


Figure 3: Sketch of Eqs. (5a). Not to scale.

The results of this fit are shown in Table 2, column 3, "Fit w/CPT," and the correlation matrix is shown in Table 4. The Δm precision is improved by the CPT assumption.

Table 2: Fit results for ϕ_{+-}, Δm, τ_S, ϕ_{00}, $\Delta\phi = \phi_{00} - \phi_{+-}$, and ϕ_ϵ without and with the CPT assumption.

Quantity(units)	Fit w/o CPT	Fit w/ CPT
$\phi_{+-}(^\circ)$	43.4 ± 0.7 (S=1.3)	43.52 ± 0.05 (S=1.2)
$\Delta m(10^{10}\hbar\ \mathrm{s}^{-1})$	0.5290 ± 0.0015 (S=1.1)	0.5292 ± 0.0009 (S=1.2)
$\tau_S(10^{-10}\mathrm{s})$	0.8958 ± 0.0005	0.8953 ± 0.0005 (S=1.1)
$\phi_{00}(^\circ)$	43.7 ± 0.8 (S=1.2)	43.50 ± 0.06 (S=1.2)
$\Delta\phi(^\circ)$	0.2 ± 0.4	-0.02 ± 0.04 (S=2.1)
$\phi_\epsilon(^\circ)$	43.5 ± 0.7 (S=1.3)	43.51 ± 0.05 (S=1.1)
χ^2	17.3	21.8
# Deg. Free.	13	17

Table 3: Correlation matrix for the results of the fit without the CPT assumption

	ϕ_{+-}	Δm	τ_S	ϕ_{00}	$\Delta\phi$	ϕ_ϵ
ϕ_{+-}	1.000	0.778	−0.391	0.837	−0.002	0.977
Δm	0.778	1.000	−0.424	0.665	0.024	0.766
τ_S	−0.391	−0.424	1.000	−0.327	0.001	−0.328
ϕ_{00}	0.837	0.665	−0.327	1.000	0.546	0.934
$\Delta\phi$	−0.002	0.024	0.001	0.546	1.000	0.211
ϕ_ϵ	0.977	0.766	−0.328	0.934	0.211	1.000

Fits for ϵ'/ϵ, $|\eta_{+-}|$, $|\eta_{00}|$, and B($K_L \to \pi\pi$)

We list measurements of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$ and ϵ'/ϵ. Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained

Table 4: Correlation matrix for the results of the fit with the CPT assumption

	ϕ_{+-}	Δm	τ_S	ϕ_{00}	$\Delta\phi$	ϕ_ϵ
ϕ_{+-}	1.000	0.924	0.054	0.711	−0.283	0.964
Δm	0.924	1.000	−0.231	0.834	−0.020	0.958
τ_S	0.054	−0.231	1.000	0.056	0.009	0.059
ϕ_{00}	0.711	0.834	0.056	1.000	0.473	0.873
$\Delta\phi$	−0.283	−0.020	0.009	0.473	1.000	−0.018
ϕ_ϵ	0.964	0.958	0.059	0.873	−0.018	1.000

from measurements of the K_L^0 and K_S^0 lifetimes (τ_L, τ_S) and branching ratios (B) to $\pi\pi$, using the relations

$$|\eta_{+-}| = \left[\frac{\mathrm{B}(K_L^0 \to \pi^+\pi^-)}{\tau_L}\ \frac{\tau_S}{\mathrm{B}(K_S^0 \to \pi^+\pi^-)}\right]^{1/2} , \quad (12a)$$

$$|\eta_{00}| = \left[\frac{\mathrm{B}(K_L^0 \to \pi^0\pi^0)}{\tau_L}\ \frac{\tau_S}{\mathrm{B}(K_S^0 \to \pi^0\pi^0)}\right]^{1/2} . \quad (12b)$$

For historical reasons the branching ratio fits and the CP-violation fits are done separately, but we want to include the influence of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and ϵ'/ϵ measurements on $\mathrm{B}(K_L^0 \to \pi^+\pi^-)$ and $\mathrm{B}(K_L^0 \to \pi^0\pi^0)$ and vice versa. We approximate a global fit to all of these measurements by first performing two independent fits: 1) BRFIT, a fit to the K_L^0 branching ratios, rates, and mean life, and 2) ETAFIT, a fit to the $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{+-}/\eta_{00}|$, and ϵ'/ϵ measurements. The results from fit 1, along with the K_S^0 values from this edition are used to compute values of $|\eta_{+-}|$ and $|\eta_{00}|$ which are included as measurements in the $|\eta_{00}|$ and $|\eta_{+-}|$ sections with a document ID of BRFIT 06. Thus the fit values of $|\eta_{+-}|$ and $|\eta_{00}|$ given in this edition include both the direct measurements and the results from the branching ratio fit.

The process is reversed in order to include the direct $|\eta|$ measurements in the branching ratio fit. The results from fit 2 above (before including BRFIT 06 values) are used along with the K^0_L and K^0_S mean lives and the $K^0_S \to \pi\pi$ branching fractions to compute the K^0_L branching ratio $\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(K^0_L \to \pi^+\pi^-)$. This branching ratio value is included as a measurement in the branching ratio section with a document ID of ETAFIT 06. Thus the K^0_L branching ratio fit values in this edition include the results of the direct measurement of $|\eta_{00}/\eta_{+-}|$ and ϵ'/ϵ. Most individual measurements of $|\eta_{+-}|$ and $|\eta_{00}|$ enter our fits directly via the corresponding measurements of $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$ and $\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(\text{total})$ and those that do not have too large errors to have any influence on the fitted values of these branching ratios. A more detailed discussion of these fits is given in the 1990 edition of this *Review* [20].

In this 2006 edition of the *Review of Particle Physics*, the values of $|\epsilon|$, $|\eta_{+-}|$, and $|\eta_{00}|$ decrease significantly as a result of the high precision measurements of K^0_L branching ratios from KTeV, KLOE, and NA48. These measurements reduce the branching ratio $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$ by 5.5 percent, a 4.6σ decrease relative to the 2004 edition [21]. The resulting BRFIT 06 value of $|\eta_{+-}|$ reduces the fitted value of $|\eta_{+-}|$ by 3.7σ. Earlier high precision measurements of ϵ'/ϵ constrain $|\eta_{00}|$ to be nearly equal to $|\eta_{+-}|$ and ∼100% correlated with it. Since to a very good approximation

$$|\epsilon| = \frac{2}{3}|\eta_{+-}| + \frac{1}{3}|\eta_{00}|\,, \tag{13}$$

then $|\epsilon|$, $|\eta_{+-}|$, and $|\eta_{00}|$ are all approximately equal and ~100% correlated with each other. Therefore they are all reduced by 3.7σ.

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CP-VIOLATION PARAMETERS IN K_L^0 DECAYS

CHARGE ASYMMETRY IN $K^0_{\ell 3}$ DECAYS

Such asymmetry violates *CP*. It is related to Re(ϵ).

A_L = weighted average of $A_L(\mu)$ and $A_L(e)$

In previous editions and in the literature the symbol used for this asymmetry was δ_L or δ. We use A_L for consistency with B^0 asymmetry notation and with recent K_S^0 notation.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.332±0.006 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.			
0.333±0.050	33M	WILLIAMS 73	ASPK	$K_{\mu 3}$ + K_{e3}

$A_L(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \overline{\nu}_\mu)]$/SUM

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*
The data in this block is included in the average printed for a previous datablock.			
0.304±0.025 OUR AVERAGE			
0.313±0.029	15M	GEWENIGER 74	ASPK
0.278±0.051	7.7M	PICCIONI 72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.60 ±0.14	4.1M	MCCARTHY 73	CNTR
0.57 ±0.17	1M	[98] PACIOTTI 69	OSPK
0.403±0.134	1M	[98] DORFAN 67	OSPK

[98] PACIOTTI 69 is a reanalysis of DORFAN 67 and is corrected for $\mu^+ \mu^-$ range difference in MCCARTHY 72.

$A_L(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \overline{\nu}_e)]/\text{SUM}$

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*
The data in this block is included in the average printed for a previous datablock.			
0.334 ±0.007 OUR AVERAGE			
0.3322±0.0058±0.0047	298M	ALAVI-HARATI 02	
0.341 ±0.018	34M	GEWENIGER 74	ASPK
0.318 ±0.038	40M	FITCH 73	ASPK
0.346 ±0.033	10M	MARX 70	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.36 ±0.18	600k	ASHFORD 72	ASPK
0.246 ±0.059	10M	[99] SAAL 69	CNTR
0.224 ±0.036	10M	[99] BENNETT 67	CNTR

[99] SAAL 69 is a reanalysis of BENNETT 67.

PARAMETERS FOR $K^0_L \rightarrow 2\pi$ DECAY

$\eta_{+-} = \text{A}(K^0_L \rightarrow \pi^+\pi^-) \,/\, \text{A}(K^0_S \rightarrow \pi^+\pi^-)$

$\eta_{00} = \text{A}(K^0_L \rightarrow \pi^0\pi^0) \,/\, \text{A}(K^0_S \rightarrow \pi^0\pi^0)$

The fitted values of $|\eta_{+-}|$ and $|\eta_{00}|$ given below are the results of a fit to $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and $\text{Re}(\epsilon'/\epsilon)$. Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from the fitted values of the $K^0_L \rightarrow \pi\pi$ and $K^0_S \rightarrow \pi\pi$ branching ratios and the K^0_L and K^0_S lifetimes. This information is included as data in the $|\eta_{+-}|$ and $|\eta_{00}|$ sections with a Document ID "BRFIT." See the note "*CP* violation in K_L decays" above for details.

$|\eta_{00}| = |\text{A}(K^0_L \rightarrow 2\pi^0) \,/\, \text{A}(K^0_S \rightarrow 2\pi^0)|$

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*	*COMMENT*
2.225±0.007 OUR FIT			
2.239±0.017	BRFIT 06		S = 1.5
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.47 ±0.31 ±0.24	ANGELOPO... 98	CPLR	
2.49 ±0.40	[100] ADLER 96B	CPLR	Sup. by ANGELOPOULOS 98
2.33 ±0.18	CHRISTENS... 79	ASPK	
2.71 ±0.37	[101] WOLFF 71	OSPK	Cu reg., 4γ's
2.95 ±0.63	[101] CHOLLET 70	OSPK	Cu reg., 4γ's

[100] Error is statistical only.

[101] CHOLLET 70 gives $|\eta_{00}|$ = (1.23 ± 0.24)×(regeneration amplitude, 2 GeV/c Cu)/10000mb. WOLFF 71 gives $|\eta_{00}|$ = (1.13 ± 0.12)×(regeneration amplitude, 2 GeV/c Cu)/10000mb. We compute both $|\eta_{00}|$ values for (regeneration amplitude, 2 GeV/c Cu) = 24 ± 2mb. This regeneration amplitude results from averaging over FAISSNER 69, extrapolated using optical-model calculations of Bohm et al., Physics Letters **27B** 594 (1968) and the data of BALATS 71. (From H. Faissner, private communication).

$|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-) / A(K^0_S \to \pi^+\pi^-)|$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.236 ± 0.007 OUR FIT				
2.233 ± 0.008		BRFIT 06		$S = 1.2$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.219 ± 0.013		[102] AMBROSINO 06F	KLOE	
2.228 ± 0.010		[103] ALEXOPOU... 04	KTEV	
$2.286 \pm 0.023 \pm 0.026$	70M	[104] APOSTOLA... 99C	CPLR	K^0-$\overline{K}^0$ asymmetry
$2.310 \pm 0.043 \pm 0.031$		[105] ADLER 95B	CPLR	K^0-$\overline{K}^0$ asymmetry
$2.32 \pm 0.14 \pm 0.03$	10^5	ADLER 92B	CPLR	K^0-$\overline{K}^0$ asymmetry
2.30 ± 0.035		GEWENIGER 74B	ASPK	

[102] AMBROSINO 06F uses KLOE branching ratios and τ_L together with τ_S from PDG 04. Their $|\eta_{+-}|$ value is not directly used in our fit, but enters the fit via their branching ratio and lifetime measurements.

[103] ALEXOPOULOS 04 $|\eta_{+-}|$ uses their $K^0_L \to \pi\pi$ branching fractions, $\tau_S = (0.8963 \pm 0.0005) \times 10^{-10}$ s from the average of KTeV and NA48 τ_S measurements, and assumes that $\Gamma(K^0_S \to \pi \ell \nu_\ell) = \Gamma(K^0_L \to \pi \ell \nu_\ell)$ giving $\mathrm{B}(K^0_S \to \pi \ell \nu_\ell) = 0.118\%$. Their η_{+-} is not directly used in our fit, but enters our fit via their branching ratio measurements.

[104] APOSTOLAKIS 99C report $(2.264 \pm 0.023 \pm 0.026 + 9.1[\tau_S - 0.8934]) \times 10^{-3}$. We evaluate for our 2006 best value $\tau_S = (0.8958 \pm 0.0005) \times 10^{-10}$ s.

[105] ADLER 95B report $(2.312 \pm 0.043 \pm 0.030 - 1[\Delta m - 0.5274] + 9.1[\tau_S - 0.8926]) \times 10^{-3}$. We evaluate for our 1996 best values $\Delta m = (0.5304 \pm 0.0014) \times 10^{-10}\ \hbar \mathrm{s}^{-1}$ and $\tau_S = (0.8927 \pm 0.0009) \times 10^{-10}$ s. Superseded by APOSTOLAKIS 99C.

$|\epsilon| = (2|\eta_{+-}| + |\eta_{00}|)/3$

This expression is a very good approximation, good to about one part in 10^{-4} because of the small measured value of $\phi_{00} - \phi_{+-}$ and small theoretical ambiguities.

VALUE (units 10^{-3})	*DOCUMENT ID*
2.232 ± 0.007 OUR FIT	

$|\eta_{00}/\eta_{+-}|$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*
0.9950 ± 0.0008 OUR FIT Error includes scale factor of 1.6.			
0.9930 ± 0.0020 OUR AVERAGE			
0.9931 ± 0.0020		[106,107] BARR 93D	NA31
$0.9904 \pm 0.0084 \pm 0.0036$		[108] WOODS 88	E731
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.9939 \pm 0.0013 \pm 0.0015$	1M	[106] BARR 93D	NA31
$0.9899 \pm 0.0020 \pm 0.0025$		[106] BURKHARDT 88	NA31

[106] This is the square root of the ratio R given by BURKHARDT 88 and BARR 93D.

[107] This is the combined results from BARR 93D and BURKHARDT 88, taking into account a common systematic uncertainty of 0.0014.

[108] We calculate $|\eta_{00}/\eta_{+-}| = 1 - 3(\epsilon'/\epsilon)$ from WOODS 88 (ϵ'/ϵ) value.

$\mathrm{Re}(\epsilon'/\epsilon) = (1-|\eta_{00}/\eta_{+-}|)/3$

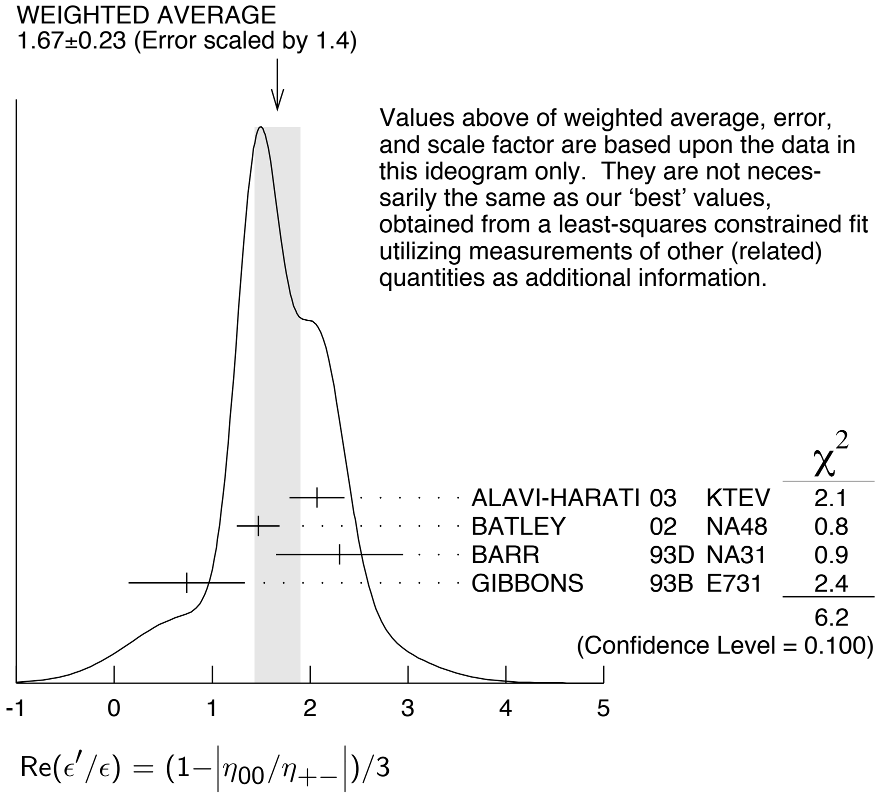
We have neglected terms of order $\omega \cdot \mathrm{Re}(\epsilon'/\epsilon)$, where $\omega = \mathrm{Re}(A_2)/\mathrm{Re}(A_0) \simeq 1/22$. If included, this correction would lower $\mathrm{Re}(\epsilon'/\epsilon)$ by about 0.04×10^{-3}. See SOZZI 04.

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*	*COMMENT*
1.66±0.26 OUR FIT Error includes scale factor of 1.6.			
1.67±0.23 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.			
2.07±0.28	ALAVI-HARATI 03	KTEV	
1.47±0.22	BATLEY 02	NA48	
2.3 ±0.65	[109,110] BARR 93D	NA31	
0.74±0.52±0.29	GIBBONS 93B	E731	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.53±0.26	LAI 01C	NA48	Incl. in BATLEY 02
2.80±0.30±0.28	ALAVI-HARATI 99D	KTEV	In ALAVI-HARATI 03
1.85±0.45±0.58	FANTI 99C	NA48	In LAI 01C
2.0 ±0.7	[111] BARR 93D	NA31	
−0.4 ±1.4 ±0.6	PATTERSON 90	E731	in GIBBONS 93B
3.3 ±1.1	[111] BURKHARDT 88	NA31	
3.2 ±2.8 ±1.2	[109] WOODS 88	E731	

[109] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements. They enter the average in this section but enter the fit via the $|\eta_{00}/\eta_{+-}|$ only.

[110] This is the combined results from BARR 93D and BURKHARDT 88, taking into account their common systematic uncertainty.

[111] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

ϕ_{+-}, PHASE of η_{+-}

The dependence of the phase on Δm and τ_S is given for each experiment in the comments below, where Δm is the $K_L^0 - K_S^0$ mass difference in units 10^{10} $\hbar s^{-1}$ and τ_s is the K_S mean life in units 10^{-10} s. We also give the regeneration phase ϕ_f in the comments below.

OUR FIT is described in the note on "*CP* violation in K_L decays" in the K_L^0 Particle Listings. Most experiments in this section are included in both the "Not Assuming *CPT*" and "Assuming *CPT*" fits. In the latter fit, they have little direct influence on ϕ_{+-} because their errors are large compared to that assuming *CPT*, but they influence Δm and τ_s through their dependencies on these parameters, which are given in the footnotes. Only ALAVI-HARATI 03 is excluded from the "Assuming *CPT*" fit because we explicitly include their Δm and τ_s measurements which assume *CPT*.

VALUE (°)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
43.52±0.05 OUR FIT	Error includes scale factor of 1.2. Assuming *CPT*			
43.4 ±0.7 OUR FIT	Error includes scale factor of 1.3. Not assuming *CPT*			
44.12±0.72±1.20		[112] ALAVI-HARATI 03	KTEV	Not assuming *CPT*
42.9 ±0.6 ±0.3	70M	[113] APOSTOLA... 99C	CPLR	K^0-$\overline{K}^0$ asymmetry
43.0 ±0.8 ±0.2		[114,115] SCHWINGEN...95	E773	$CH_{1.1}$ regenerator
41.4 ±0.9 ±0.3		[115,116] GIBBONS 93	E731	B_4C regenerator
44.4 ±1.6 ±0.6		[117] CAROSI 90	NA31	Vacuum regen.
43.3 ±1.0 ±0.5		[118] GEWENIGER 74B	ASPK	Vacuum regen.

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

VALUE (°)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
42.5 ±0.4 ±0.3		[119,120] ADLER 96C	RVUE	
43.4 ±1.1 ±0.3		[121] ADLER 95B	CPLR	K^0-$\overline{K}^0$ asymmetry
42.3 ±4.4 ±1.4	10^5	[122] ADLER 92B	CPLR	K^0-$\overline{K}^0$ asymmetry
47.7 ±2.0 ±0.9		[115,123] KARLSSON 90	E731	
44.3 ±2.8 ±0.2		[124] CARITHERS 75	SPEC	C regenerator

[112] ALAVI-HARATI 03 ϕ_{+-} is correlated with their $\Delta m = m_{K_L^0} - m_{K_S^0}$ and τ_{K_S} measurements in the K_L^0 and K_S^0 sections respectively. The correlation coefficients are $\rho(\phi_{+-},\Delta m)$=+0.955, $\rho(\phi_{+-},\tau_S)$=−0.871, and $\rho(\tau_S,\Delta m)$=−0.840. *CPT* is not assumed. Uses scintillator Pb regenerator.

[113] APOSTOLAKIS 99C measures $\phi_{+-} = (43.19 \pm 0.53 \pm 0.28) + 300\,[\Delta m - 0.5301]$ (°). We have adjusted the measurement to use our best values of ($\Delta m = 0.5292 \pm 0.0009$) ($10^{10}$ $\hbar$ s^{-1}). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[114] SCHWINGENHEUER 95 measures $\phi_{+-} = (43.53 \pm 0.76) + 173\,[\Delta m - 0.5282] - 275\,[\tau_S - 0.8926]$ (°). We have adjusted the measurement to use our best values of ($\Delta m = 0.5292 \pm 0.0009$) ($10^{10}$ $\hbar$ s^{-1}), ($\tau_s = 0.8953 \pm 0.0005$) ($10^{-10}$ s). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[115] These experiments measure ϕ_{+-}−ϕ_f and calculate the regeneration phase from the power law momentum dependence of the regeneration amplitude using analyticity and dispersion relations. SCHWINGENHEUER 95 [GIBBONS 93] includes a systematic error of 0.35° [0.5°] for uncertainties in their modeling of the regeneration amplitude.

[116] GIBBONS 93 measures $\phi_{+-} = (42.21 \pm 0.9) + 189\,[\Delta m - 0.5257] - 460\,[\tau_S - 0.8922]$ (°). We have adjusted the measurement to use our best values of ($\Delta m = 0.5292 \pm 0.0009$) ($10^{10}$ $\hbar$ s^{-1}), ($\tau_s = 0.8953 \pm 0.0005$) ($10^{-10}$ s). Our first error is their experiment's error and our second error is the systematic error from using our best values. This is actually reported in SCHWINGENHEUER 95, footnote 8. GIBBONS 93 reports ϕ_{+-} $(42.2 \pm 1.4)°$. They measure ϕ_+−ϕ_f and calculate the regeneration phase

ϕ_f from the power law momentum dependence of the regeneration amplitude using analyticity. An error of 0.6° is included for possible uncertainties in the regeneration phase.

[117] CAROSI 90 measures ϕ_{+-} = (46.9 ± 1.4 ± 0.7) + 579 [$\Delta m -$ 0.5351] + 303 [$\tau_s -$ 0.8922] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}), (τ_s = 0.8953 ± 0.0005) (10^{-10} s). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[118] GEWENIGER 74B measures ϕ_{+-} = (49.4 ± 1.0) + 565 [$\Delta m -$ 0.540] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[119] ADLER 96C measures ϕ_{+-} = (43.82 ± 0.41) + 339 [$\Delta m -$ 0.5307] − 252 [$\tau_s -$ 0.8922] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}), (τ_s = 0.8953 ± 0.0005) (10^{-10} s). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[120] ADLER 96C is the result of a fit which includes nearly the same data as entered into the "OUR FIT" value in the 1996 edition of this Review (Physical Review **D54** 1 (1996)).

[121] ADLER 95B measures ϕ_{+-} = (42.7 ± 0.9 ± 0.6) + 316 [$\Delta m -$ 0.5274] + 30 [$\tau_s -$ 0.8926] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}), (τ_s = 0.8953 ± 0.0005) (10^{-10} s). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[122] ADLER 92B quote separately two systematic errors: ±0.4 from their experiment and ±1.0 degrees due to the uncertainty in the value of Δm.

[123] KARLSSON 90 systematic error does not include regeneration phase uncertainty.

[124] CARITHERS 75 measures ϕ_{+-} = (45.5 ± 2.8) + 224 [$\Delta m -$ 0.5348] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}). Our first error is their experiment's error and our second error is the systematic error from using our best values. $\phi_f = -40.9 \pm 2.6°$.

ϕ_{00}, PHASE OF η_{00}

See comment in ϕ_{+-} header above for treatment of Δm and τ_s dependence, as well as for the inclusion of data in both the "Assuming *CPT*" and "Not Assuming *CPT*" fits.

OUR FIT is described in the note on "*CP* violation in K_L decays" in the K^0_L Particle Listings.

VALUE (°)	*DOCUMENT ID*	*TECN*	*COMMENT*
43.50±0.06 OUR FIT	Error includes scale factor of 1.2. Assuming *CPT*		
43.7 ±0.8 OUR FIT	Error includes scale factor of 1.2. Not assuming *CPT*		
44.5 ±2.3 ±0.6	[125] CAROSI 90	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
41.6 ±5.9 ±0.2	[126] ANGELOPO... 98	CPLR	
50.8 ±7.1 ±1.7	[127] ADLER 96B	CPLR	Sup. by ANGELOPOULOS 98
47.4 ±1.4 ±0.9	[128] KARLSSON 90	E731	

[125] CAROSI 90 measures ϕ_{00} = (47.1 ± 2.1 ± 1.0) + 579 [Δm − 0.5351] + 252 [τ_S − 0.8922] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}), (τ_S = 0.8953 ± 0.0005) (10^{-10} s). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[126] ANGELOPOULOS 98 measures ϕ_{00} = (42.0 ± 5.6 ± 1.9) + 240 [Δm − 0.5307] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}). Our first error is their experiment's error and our second error is the systematic error from using our best values. The τ_S dependence is negligible.

[127] ADLER 96B identified initial neutral kaon individually as being a K^0 or a $\overline{K}^0$. The systematic uncertainty is ±1.5° combined in quadrature with ±0.8° due to Δm.

[128] KARLSSON 90 systematic error does not include regeneration phase uncertainty.

$\phi_\epsilon = (2\phi_{+-} + \phi_{00})/3$

This expression is a very good approximation, good to about 10^{-3} degrees because of the small measured values of $\phi_{00} - \phi_{+-}$ and Re ϵ'/ϵ, and small theoretical ambiguities.

VALUE (°)			*DOCUMENT ID*		*COMMENT*
43.51	**±0.05**	**OUR FIT**	Error includes scale factor of 1.1. Assuming *CPT*		
43.5	**±0.7**	**OUR FIT**	Error includes scale factor of 1.3. Not assuming *CPT*		
43.5105±0.0004±0.0533			[129] SUPERWEAK	04	Assuming *CPT*

[129] SUPERWEAK 04 is a fake measurement used to impose the *CPT* or Superweak constraint $\phi_{+-} = \phi_{SW} = 2\,\frac{\Delta m}{\hbar}\,(\frac{\tau_S \tau_L}{\tau_L - \tau_S})$. This "measurement" is linearized using values near the RPP 2004 edition values of Δm, τ_S and τ_L, and then adjusted to our current values as described in the following "measurement". SUPERWEAK 04 measures ϕ_ϵ = (43.5131 ± 0.0004) + 54 [Δm − 0.5290] + 32 [τ_S − 0.8958] (°). We have adjusted the measurement to use our best values of (Δm = 0.5292 ± 0.0009) (10^{10} $\hbar$ s^{-1}), (τ_S = 0.8953 ± 0.0005) (10^{-10} s). Our first error is their experiment's error and our second error is the systematic error from using our best values.

DECAY-PLANE ASYMMETRY IN $\pi^+\pi^- e^+ e^-$ DECAYS

This is the *CP*-violating asymmetry

$$A = \frac{N_{\sin\phi\cos\phi>0.0} - N_{\sin\phi\cos\phi<0.0}}{N_{\sin\phi\cos\phi>0.0} + N_{\sin\phi\cos\phi<0.0}}$$

where ϕ is the angle between the $e^+ e^-$ and $\pi^+\pi^-$ planes in the K_L^0 rest frame.

CP ASYMMETRY *A* in $K_L^0 \to \pi^+\pi^- e^+ e^-$

VALUE (%)	*DOCUMENT ID*		*TECN*
13.7±1.5 OUR AVERAGE			
13.6±1.4±1.5	ABOUZAID	06	KTEV
14.2±3.0±1.9	LAI	03C	NA48
13.6±2.5±1.2	ALAVI-HARATI	00B	KTEV

PARAMETERS FOR $e^+ e^- e^+ e^-$ DECAYS

These are the *CP*-violating parameters in the ϕ distribution, where ϕ is the angle between the planes of the two $e^+ e^-$ paris in the kaon rest frame:

$$d\Gamma/d\phi \;\propto\; 1 + \beta_{CP} \cos(2\phi) + \gamma_{CP} \sin(2\phi)$$

β_{CP} from $K^0_L \to e^+ e^- e^+ e^-$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.19±0.07 OUR AVERAGE					
−0.13±0.10±0.03	200	[130] LAI	05B	NA48	
−0.23±0.09±0.02	441	ALAVI-HARATI	01D	KTEV	M_{ee} >8 MeV/c^2

[130] LAI 05B obtains $\beta_{CP} = -0.13 \pm 0.10$ (stat) if $\gamma_{CP} = 0$ is assumed.

γ_{CP} from $K^0_L \to e^+ e^- e^+ e^-$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.01±0.11 OUR AVERAGE	Error includes scale factor of 1.6.				
+0.13±0.10±0.03	200	LAI	05B	NA48	
−0.09±0.09±0.02	441	ALAVI-HARATI	01D	KTEV	M_{ee} >8 MeV/c^2

CHARGE ASYMMETRY IN $\pi^+\pi^-\pi^0$ DECAYS

These are *CP*-violating charge-asymmetry parameters, defined at beginning of section "LINEAR COEFFICIENT *g* FOR $K^0_L \to \pi^+\pi^-\pi^0$ above. See also note on Dalitz plot parameters in $K^\pm$ section and note on "*CP* violation in K_L decays" above.

LINEAR COEFFICIENT *j* FOR $K^0_L \to \pi^+\pi^-\pi^0$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
0.0012±0.0008 OUR AVERAGE				
0.0010±0.0024±0.0030	500k	ANGELOPO...	98C	CPLR
−0.001 ±0.011	6499	CHO	77	
0.001 ±0.003	4709	PEACH	77	
0.0013±0.0009	3M	SCRIBANO	70	
0.0 ±0.017	4400	SMITH	70	OSPK
0.001 ±0.004	238k	BLANPIED	68	

QUADRATIC COEFFICIENT *f* FOR $K^0_L \to \pi^+\pi^-\pi^0$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
0.0045±0.0024±0.0059	500k	ANGELOPO...	98C	CPLR

PARAMETERS for $K^0_L \to \pi^+\pi^-\gamma$ DECAY

$|\eta_{+-\gamma}| = |\mathrm{A}(K^0_L \to \pi^+\pi^-\gamma$, *CP* violating$)/\mathrm{A}(K^0_S \to \pi^+\pi^-\gamma)|$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*
2.35 ±0.07 OUR AVERAGE				
2.359±0.062±0.040	9045	MATTHEWS	95	E773
2.15 ±0.26 ±0.20	3671	RAMBERG	93B	E731

$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$

VALUE (°)	*EVTS*	*DOCUMENT ID*		*TECN*
44 ± 4 OUR AVERAGE				
43.8± 3.5± 1.9	9045	MATTHEWS	95	E773
72 ±23 ±17	3671	RAMBERG	93B	E731

$|\epsilon'_{+-\gamma}|/\epsilon$ for $K^0_L \rightarrow \pi^+\pi^-\gamma$

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<0.3	90	3671	[131] RAMBERG	93B	E731

[131] RAMBERG 93B limit on $|\epsilon'_{+-\gamma}|/\epsilon$ assumes than any difference between η_{+-} and $\eta_{+-\gamma}$ is due to direct *CP* violation.

T VIOLATION TESTS IN K^0_L DECAYS

Im(ξ) in $K^0_{\mu3}$ DECAY (from transverse μ pol.)

Test of *T* reversal invariance.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.007±0.026 OUR AVERAGE					
0.009±0.030	12M	MORSE	80	CNTR	Polarization
0.35 ±0.30	207k	[132] CLARK	77	SPEC	POL, t=0
−0.085±0.064	2.2M	[133] SANDWEISS	73	CNTR	POL, t=0
−0.02 ±0.08		LONGO	69	CNTR	POL, t=3.3
−0.2 ±0.6		ABRAMS	68B	OSPK	Polarization
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.012±0.026		SCHMIDT	79	CNTR	Repl. by MORSE 80

[132] CLARK 77 value has additional $\xi(0)$ dependence $+0.21\mathrm{Re}\left[\xi(0)\right]$.

[133] SANDWEISS 73 value corrected from value quoted in their paper due to new value of Re(ξ). See footnote 4 of SCHMIDT 79.

CPT-INVARIANCE TESTS IN K^0_L DECAYS

PHASE DIFFERENCE $\phi_{00} - \phi_{+-}$

Test of *CPT*.

OUR FIT is described in the note on "*CP* violation in K_L decays" in the K^0_L Particle Listings.

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.02 ±0.04 OUR FIT Error includes scale factor of 2.1. Assuming *CPT*				
0.2 ±0.4 OUR FIT Not assuming *CPT*				
−0.023±0.020	[134] SUPERWEAK	04		Assuming *CPT*
0.39 ±0.22 ±0.45	[135] ALAVI-HARATI	03	KTEV	
−0.30 ±0.88	[136] SCHWINGEN...	95		Combined E731, E773
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.62 ±0.71 ±0.75	SCHWINGEN...	95	E773	
−1.6 ±1.2	[137] GIBBONS	93	E731	
0.2 ±2.6 ±1.2	[138] CAROSI	90	NA31	
−0.3 ±2.4 ±1.2	KARLSSON	90	E731	

[134] SUPERWEAK 04 is a fake experiment to constrain ϕ_{00}-ϕ_{+-} to a small value as described in the note "*CP* violation in K_L decays."

[135] ALAVI-HARATI 03 fit Re(ϵ'/ϵ), Im(ϵ'/ϵ), Δm, τ_S, and ϕ_{+-} simultaneously, not assuming *CPT*. Phase difference is obtained from $\phi_{00} - \phi_{+-} \approx -3\mathrm{Im}(\epsilon'/\epsilon)$ for small $|\epsilon'/\epsilon|$.

[136] This SCHWINGENHEUER 95 values is the combined result of SCHWINGENHEUER 95 and GIBBONS 93, accounting for correlated systematic errors.

[137] GIBBONS 93 give detailed dependence of systematic error on lifetime (see the section on the K^0_S mean life) and mass difference (see the section on $m_{K^0_L} - m_{K^0_S}$).

[138] CAROSI 90 is excluded from the fit because it it is not independent of ϕ_{+-} and ϕ_{00} values.

PHASE DIFFERENCE $\phi_{+-} - \phi_{SW}$

Test of *CPT*. The Superweak phase $\phi_{SW} \equiv \tan^{-1}(2\Delta m/\Delta\Gamma)$ where $\Delta m = m_{K^0_L} - m_{K^0_S}$ and $\Delta\Gamma = \hbar(\tau_L - \tau_S)/(\tau_L\tau_S)$.

VALUE (°)	*DOCUMENT ID*	*TECN*
0.61±0.62±1.01	[139] ALAVI-HARATI 03	KTEV

[139] ALAVI-HARATI 03 fit is the same as their ϕ_{+-}, τ_{K_S}, Δm fit, except that the parameter $\phi_{+-} - \phi_{SW}$ is used in place of ϕ.

Re($\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}$)$-\frac{\delta_L}{2}$

Test of *CPT*

VALUE (units 10^{-6})	*DOCUMENT ID*	*TECN*	*COMMENT*
−3±35	[140] ALAVI-HARATI 02	E799	Uses δ_L from K_{e3} decays

[140] ALAVI-HARATI 02 uses PDG 00 values of η_{+-} and η_{00}.

$\Delta S = \Delta Q$ IN K^0 DECAYS

The relative amount of $\Delta S \neq \Delta Q$ component present is measured by the parameter x, defined as

$$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu) \ .$$

We list Re$\{x\}$ and Im$\{x\}$ for K_{e3} and $K_{\mu3}$ combined.

$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu) = A(\Delta S{=}{-}\Delta Q)/A(\Delta S{=}\Delta Q)$

REAL PART OF x

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.0018±0.0041±0.0045		ANGELOPO... 98D	CPLR	K_{e3} from K^0

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

$0.10^{+0.18}_{-0.19}$	79	SMITH 75B	WIRE	$\pi^- p \rightarrow K^0 \Lambda$
0.04 ± 0.03	4724	NIEBERGALL 74	ASPK	$K^+ p \rightarrow K^0 p \pi^+$
-0.008 ± 0.044	1757	FACKLER 73	OSPK	K_{e3} from K^0
-0.03 ± 0.07	1367	HART 73	OSPK	K_{e3} from $K^0 \Lambda$
-0.070 ± 0.036	1079	MALLARY 73	OSPK	K_{e3} from $K^0 \Lambda X$
0.03 ± 0.06	410	[141] BURGUN 72	HBC	$K^+ p \rightarrow K^0 p \pi^+$
$0.04^{+0.10}_{-0.13}$	100	[142] GRAHAM 72	OSPK	$K_{\mu3}$ from $K^0 \Lambda$
-0.05 ± 0.09	442	[142] GRAHAM 72	OSPK	$\pi^- p \rightarrow K^0 \Lambda$
$0.26^{+0.10}_{-0.14}$	126	MANN 72	HBC	$K^- p \rightarrow n \overline{K}^0$
-0.13 ± 0.11	342	[142] MANTSCH 72	OSPK	K_{e3} from $K^0 \Lambda$
$0.04^{+0.07}_{-0.08}$	222	[141] BURGUN 71	HBC	$K^+ p \rightarrow K^0 p \pi^+$
$0.25^{+0.07}_{-0.09}$	252	WEBBER 71	HBC	$K^- p \rightarrow n \overline{K}^0$
0.12 ± 0.09	215	[143] CHO 70	DBC	$K^+ d \rightarrow K^0 p p$
-0.020 ± 0.025		[144] BENNETT 69	CNTR	Charge asym+ Cu regen.
$0.09^{+0.14}_{-0.16}$	686	LITTENBERG 69	OSPK	$K^+ n \rightarrow K^0 p$
0.03 ± 0.03		[144] BENNETT 68	CNTR	
$0.09^{+0.07}_{-0.09}$	121	JAMES 68	HBC	$\overline{p} p$
$0.17^{+0.16}_{-0.35}$	116	FELDMAN 67B	OSPK	$\pi^- p \rightarrow K^0 \Lambda$
0.17 ± 0.10	335	[143] HILL 67	DBC	$K^+ d \rightarrow K^0 p p$
$0.035^{+0.11}_{-0.13}$	196	AUBERT 65	HLBC	K^+ charge exchange
$0.06^{+0.18}_{-0.44}$	152	[145] BALDO-... 65	HLBC	K^+ charge exchange
$-0.08^{+0.16}_{-0.28}$	109	[146] FRANZINI 65	HBC	$\overline{p} p$

[141] BURGUN 72 is a final result which includes BURGUN 71.

[142] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.

[143] CHO 70 is analysis of unambiguous events in new data and HILL 67.

[144] BENNETT 69 is a reanalysis of BENNETT 68.

[145] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).

[146] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.

IMAGINARY PART OF *x*

Assumes $m_{K^0_L} - m_{K^0_S}$ positive. See Listings above.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0012±0.0019±0.0009	640k	ANGELOPO... 01B	CPLR	K_{e3} from K^0

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

0.0012	±0.0019	640k	[147] ANGELOPO...	98E	CPLR	K_{e3} from K^0
−0.10	$^{+0.16}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \rightarrow K^0 \Lambda$
−0.06	±0.05	4724	NIEBERGALL	74	ASPK	$K^+ p \rightarrow K^0 p \pi^+$
−0.017	±0.060	1757	FACKLER	73	OSPK	K_{e3} from K^0
0.09	±0.07	1367	HART	73	OSPK	K_{e3} from $K^0 \Lambda$
0.107	$^{+0.092}_{-0.074}$	1079	MALLARY	73	OSPK	K_{e3} from $K^0 \Lambda X$
0.07	$^{+0.06}_{-0.07}$	410	[148] BURGUN	72	HBC	$K^+ p \rightarrow K^0 p \pi^+$
0.12	$^{+0.17}_{-0.16}$	100	[149] GRAHAM	72	OSPK	$K_{\mu 3}$ from $K^0 \Lambda$
0.05	±0.13	442	[149] GRAHAM	72	OSPK	$\pi^- p \rightarrow K^0 \Lambda$
0.21	$^{+0.15}_{-0.12}$	126	MANN	72	HBC	$K^- p \rightarrow n \overline{K}^0$
−0.04	±0.16	342	[149] MANTSCH	72	OSPK	K_{e3} from $K^0 \Lambda$
0.12	$^{+0.08}_{-0.09}$	222	[148] BURGUN	71	HBC	$K^+ p \rightarrow K^0 p \pi^+$
0.0	±0.08	252	WEBBER	71	HBC	$K^- p \rightarrow n \overline{K}^0$
−0.08	±0.07	215	[150] CHO	70	DBC	$K^+ d \rightarrow K^0 p p$
−0.11	$^{+0.10}_{-0.11}$	686	LITTENBERG	69	OSPK	$K^+ n \rightarrow K^0 p$
+0.22	$^{+0.37}_{-0.29}$	121	JAMES	68	HBC	$\overline{p} p$
0.0	±0.25	116	FELDMAN	67B	OSPK	$\pi^- p \rightarrow K^0 \Lambda$
−0.20	±0.10	335	[150] HILL	67	DBC	$K^+ d \rightarrow K^0 p p$
−0.21	$^{+0.11}_{-0.15}$	196	AUBERT	65	HLBC	K^+ charge exchange
−0.44	$^{+0.32}_{-0.19}$	152	[151] BALDO-...	65	HLBC	K^+ charge exchange
+0.24	$^{+0.40}_{-0.30}$	109	[152] FRANZINI	65	HBC	$\overline{p} p$

[147] Superseded by ANGELOPOULOS 01B.

[148] BURGUN 72 is a final result which includes BURGUN 71.

[149] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.

[150] Footnote 10 of HILL 67 should read +0.58, not −0.58 (private communication) CHO 70 is analysis of unambiguous events in new data and HILL 67.

[151] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).

[152] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.

K^0_L REFERENCES

ABOUZAID	06	PRL 96 101801	E. Abouzaid *et al.*	(KTEV Collab.)
AMBROSINO	06	PL B632 43	F. Ambrosino *et al.*	(KLOE Collab.)
AMBROSINO	06D	PL B636 166	F. Ambrosino *et al.*	(KLOE Collab.)
AMBROSINO	06F	hep-ex/0603041 To appear in PL B	F. Ambrosino *et al.*	(KLOE Collab.)
BRFIT	06	RPP 2006 edition	T.G. Trippe	(PDG Collab.)
ETAFIT	06	RPP 2006 edition	T.G. Trippe	(PDG Collab.)
ALEXOPOU...	05	PR D71 012001	T. Alexopoulos *et al.*	(FNAL KTeV Collab.)
AMBROSINO	05C	PL B626 15	F. Ambrosino *et al.*	(KLOE Collab.)
LAI	05	PL B605 247	A. Lai *et al.*	(CERN NA48 Collab.)

LAI	05B	PL B615 31	A. Lai *et al.*	(CERN NA48 Collab.)
ALAVI-HARATI	04A	PRL 93 021805	A. Alavi-Harati *et al.*	(FNAL KTeV/E799 Collab.)
ALEXOPOU...	04	PR D70 092006	T. Alexopoulos *et al.*	(FNAL KTeV Collab.)
ALEXOPOU...	04A	PR D70 092007	T. Alexopoulos *et al.*	(FNAL KTeV Collab.)
ANDRE	04	hep-ph/0406006	T. Andre	(EFI)
BATLEY	04	PL B595 75	J.R. Batley *et al.*	(CERN NA48 Collab.)
CIRIGLIANO	04	EPJ C35 53	V. Cirigliano, H. Neufeld, H. Pichl	(CIT, VALE+)
LAI	04B	PL B602 41	A. Lai *et al.*	(CERN NA48 Collab.)
LAI	04C	PL B604 1	A. Lai *et al.*	(CERN NA48 Collab.)
PDG	04	PL B592 1	S. Eidelman *et al.*	
SOZZI	04	EPJ C36 37	M. Sozzi	(PISA)
SUPERWEAK	04	RPP 2004 edition	T.G. Trippe	(PDG Collab.)
CP violation in K_L decays				
ADINOLFI	03	PL B566 61	M. Adinolfi *et al.*	(KLOE Collab.)
ALAVI-HARATI	03	PR D67 012005	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
Also		PR D70 079904 (erratum)	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	03B	PRL 90 141801	A. ALavi-Harati *et al.*	(FNAL KTeV Collab.)
LAI	03	PL B551 7	A. Lai *et al.*	(CERN NA48 Collab.)
LAI	03C	EPJ C30 33	A. Lai *et al.*	(CERN NA48 Collab.)
ALAVI-HARATI	02	PRL 88 181601	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	02C	PRL 89 211801	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
BATLEY	02	PL B544 97	J.R. Batley *et al.*	(CERN NA48 Collab.)
CIRIGLIANO	02	EPJ C23 121	V. Cirigliano *et al.*	(VIEN, VALE, MARS)
LAI	02B	PL B536 229	A. Lai *et al.*	(CERN NA48 Collab.)
ALAVI-HARATI	01	PRL 86 397	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01B	PRL 86 761	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01D	PRL 86 5425	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01E	PRL 87 021801	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01F	PR D64 012003	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01G	PRL 87 071801	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01H	PRL 87 111802	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	01J	PR D64 112004	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ANGELOPO...	01	PL B503 49	A. Angelopoulos *et al.*	(CPLEAR Collab.)
ANGELOPO...	01B	EPJ C22 55	A. Angelopoulos *et al.*	(CPLEAR Collab.)
LAI	01B	PL B515 261	A. Lai *et al.*	(CERN NA48 Collab.)
LAI	01C	EPJ C22 231	A. Lai *et al.*	(CERN NA48 Collab.)
ALAVI-HARATI	00	PR D61 072006	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	00B	PRL 84 408	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	00D	PRL 84 5279	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	00E	PR D62 112001	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
AMBROSE	00	PRL 84 1389	D. Ambrose *et al.*	(BNL E871 Collab.)
APOSTOLA...	00	PL B473 186	A. Apostolakis *et al.*	(CPLEAR Collab.)
PDG	00	EPJ C15 1	D.E. Groom *et al.*	
ADAMS	99	PL B447 240	J. Adams *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	99B	PRL 83 917	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
ALAVI-HARATI	99D	PRL 83 22	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
APOSTOLA...	99C	PL B458 545	A. Apostolakis *et al.*	(CPLEAR Collab.)
Also		EPJ C18 41	A. Apostolakis *et al.*	(CPLEAR Collab.)
FANTI	99B	PL B458 553	V. Fanti *et al.*	(CERN NA48 Collab.)
FANTI	99C	PL B465 335	V. Fanti *et al.*	(CERN NA48 Collab.)
MURAKAMI	99	PL B463 333	K. Murakami *et al.*	(KEK E162 Collab.)
ADAMS	98	PRL 80 4123	J. Adams *et al.*	(FNAL KTeV Collab.)
AMBROSE	98	PRL 81 4309	D. Ambrose *et al.*	(BNL E871 Collab.)
AMBROSE	98B	PRL 81 5734	D. Ambrose *et al.*	(BNL E871 Collab.)
ANGELOPO...	98	PL B420 191	A. Angelopoulos *et al.*	(CPLEAR Collab.)
ANGELOPO...	98C	EPJ C5 389	A. Angelopoulos *et al.*	(CPLEAR Collab.)
ANGELOPO...	98D	PL B444 38	A. Angelopoulos *et al.*	(CPLEAR Collab.)
Also		EPJ C22 55	A. Angelopoulos *et al.*	(CPLEAR Collab.)
ANGELOPO...	98E	PL B444 43	A. Angelopoulos *et al.*	(CPLEAR Collab.)
ARISAKA	98	PL B432 230	K. Arisaka *et al.*	(FNAL E799 Collab.)
BENDER	98	PL B418 411	M. Bender *et al.*	(CERN NA48 Collab.)
SETZU	98	PL B420 205	M.G. Setzu *et al.*	
TAKEUCHI	98	PL B443 409	Y. Takeuchi *et al.*	(KYOT, KEK, HIRO)
FANTI	97	ZPHY C76 653	V. Fanti *et al.*	(CERN NA48 Collab.)
NOMURA	97	PL B408 445	T. Nomura *et al.*	(KYOT, KEK, HIRO)
ADLER	96B	ZPHY C70 211	R. Adler *et al.*	(CPLEAR Collab.)
ADLER	96C	PL B369 367	R. Adler *et al.*	(CPLEAR Collab.)
GU	96	PRL 76 4312	P. Gu *et al.*	(RUTG, UCLA, EFI, COLO+)
LEBER	96	PL B369 69	F. Leber *et al.*	(MANZ, CERN, EDIN, ORSAY+)
PDG	96	PR D54 1	R. M. Barnett *et al.*	
ADLER	95	PL B363 237	R. Adler *et al.*	(CPLEAR Collab.)

ADLER	95B	PL B363 243	R. Adler *et al.*	(CPLEAR Collab.)
AKAGI	95	PR D51 2061	T. Akagi *et al.*	(TOHOK, TOKY, KYOT, KEK)
BARR	95	ZPHY C65 361	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
BARR	95C	PL B358 399	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
HEINSON	95	PR D51 985	A.P. Heinson *et al.*	(BNL E791 Collab.)
KREUTZ	95	ZPHY C65 67	A. Kreutz *et al.*	(SIEG, EDIN, MANZ, ORSAY+)
MATTHEWS	95	PRL 75 2803	J.N. Matthews *et al.*	(RUTG, EFI, ELMT+)
SCHWINGEN...	95	PRL 74 4376	B. Schwingenheuer *et al.*	(EFI, CHIC+)
SPENCER	95	PRL 74 3323	M.B. Spencer *et al.*	(UCLA, EFI, COLO+)
BARR	94	PL B328 528	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
GU	94	PRL 72 3000	P. Gu *et al.*	(RUTG, UCLA, EFI, COLO+)
NAKAYA	94	PRL 73 2169	T. Nakaya *et al.*	(OSAK, UCLA, EFI, COLU+)
ROBERTS	94	PR D50 1874	D. Roberts *et al.*	(UCLA, EFI, COLU+)
WEAVER	94	PRL 72 3758	M. Weaver *et al.*	(UCLA, EFI, COLU, ELMT+)
AKAGI	93	PR D47 R2644	T. Akagi *et al.*	(TOHOK, TOKY, KYOT, KEK)
ARISAKA	93	PRL 70 1049	K. Arisaka *et al.*	(BNL E791 Collab.)
ARISAKA	93B	PRL 71 3910	K. Arisaka *et al.*	(BNL E791 Collab.)
BARR	93D	PL B317 233	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
GIBBONS	93	PRL 70 1199	L.K. Gibbons *et al.*	(FNAL E731 Collab.)
Also		PR D55 6625	L.K. Gibbons *et al.*	(FNAL E731 Collab.)
GIBBONS	93B	PRL 70 1203	L.K. Gibbons *et al.*	(FNAL E731 Collab.)
GIBBONS	93C	Thesis RX-1487	L.K. Gibbons	(CHIC)
Also		PR D55 6625	L.K. Gibbons *et al.*	(FNAL E731 Collab.)
HARRIS	93	PRL 71 3914	D.A. Harris *et al.*	(EFI, UCLA, COLO+)
HARRIS	93B	PRL 71 3918	D.A. Harris *et al.*	(EFI, UCLA, COLO+)
MAKOFF	93	PRL 70 1591	G. Makoff *et al.*	(FNAL E731 Collab.)
Also		PRL 75 2069 (erratum)	G. Makoff *et al.*	
RAMBERG	93	PRL 70 2525	E. Ramberg *et al.*	(FNAL E731 Collab.)
RAMBERG	93B	PRL 70 2529	E.J. Ramberg *et al.*	(FNAL E731 Collab.)
VAGINS	93	PRL 71 35	M.R. Vagins *et al.*	(BNL E845 Collab.)
ADLER	92B	PL B286 180	R. Adler *et al.*	(CPLEAR Collab.)
Also		SJNP 55 840	R. Adler *et al.*	(CPLEAR Collab.)
BARR	92	PL B284 440	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
GRAHAM	92	PL B295 169	G.E. Graham *et al.*	(FNAL E731 Collab.)
MORSE	92	PR D45 36	W.M. Morse *et al.*	(BNL, YALE, VASS)
PDG	92	PR D45, 1 June, Part II	K. Hikasa *et al.*	(KEK, LBL, BOST+)
SOMALWAR	92	PRL 68 2580	S.V. Somalwar *et al.*	(FNAL E731 Collab.)
AKAGI	91B	PRL 67 2618	T. Akagi *et al.*	(TOHOK, TOKY, KYOT, KEK)
BARR	91	PL B259 389	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
HEINSON	91	PR D44 R1	A.P. Heinson *et al.*	(UCI, UCLA, LANL+)
PAPADIMITR...	91	PR D44 R573	V. Papadimitriou *et al.*	(FNAL E731 Collab.)
BARKER	90	PR D41 3546	A.R. Barker *et al.*	(FNAL E731 Collab.)
Also		PRL 61 2661	L.K. Gibbons *et al.*	(FNAL E731 Collab.)
BARR	90B	PL B240 283	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
BARR	90C	PL B242 523	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
CAROSI	90	PL B237 303	R. Carosi *et al.*	(CERN, EDIN, MANZ, LALO+)
KARLSSON	90	PRL 64 2976	M. Karlsson *et al.*	(FNAL E731 Collab.)
OHL	90	PRL 64 2755	K.E. Ohl *et al.*	(BNL E845 Collab.)
OHL	90B	PRL 65 1407	K.E. Ohl *et al.*	(BNL E845 Collab.)
PATTERSON	90	PRL 64 1491	J.R. Patterson *et al.*	(FNAL E731 Collab.)
INAGAKI	89	PR D40 1712	T. Inagaki *et al.*	(KEK, TOKY, KYOT)
MATHIAZHA...	89	PRL 63 2181	C. Mathiazhagan *et al.*	(UCI, UCLA, LANL+)
MATHIAZHA...	89B	PRL 63 2185	C. Mathiazhagan *et al.*	(UCI, UCLA, LANL+)
WAHL	89	CERN-EP/89-86	H. Wahl	(CERN)
BARR	88	PL B214 303	G.D. Barr *et al.*	(CERN, EDIN, MANZ, LALO+)
BURKHARDT	88	PL B206 169	H. Burkhardt *et al.*	(CERN, EDIN, MANZ+)
JASTRZEM...	88	PRL 61 2300	E. Jastrzembski *et al.*	(BNL, YALE)
WOODS	88	PRL 60 1695	M. Woods *et al.*	(FNAL E731 Collab.)
BURKHARDT	87	PL B199 139	H. Burkhardt *et al.*	(CERN, EDIN, MANZ+)
ARONSON	86	PR D33 3180	S.H. Aronson *et al.*	(BNL, CHIC, STAN+)
Also		PRL 48 1078	S.H. Aronson *et al.*	(BNL, CHIC, STAN+)
PDG	86C	PL 170B 132	M. Aguilar-Benitez *et al.*	(CERN, CIT+)
COUPAL	85	PRL 55 566	D.P. Coupal *et al.*	(CHIC, SACL)
BALATS	83	SJNP 38 556	M.Y. Balats *et al.*	(ITEP)
		Translated from YAF 38 927.		
BERGSTROM	83	PL 131B 229	L. Bergstrom, E. Masso, P. Singer	(CERN)
ARONSON	82	PRL 48 1078	S.H. Aronson *et al.*	(BNL, CHIC, STAN+)
ARONSON	82B	PRL 48 1306	S.H. Aronson *et al.*	(BNL, CHIC, PURD)
Also		PL 116B 73	E. Fischbach *et al.*	(PURD, BNL, CHIC)
Also		PR D28 476	S.H. Aronson *et al.*	(BNL, CHIC, PURD)
Also		PR D28 495	S.H. Aronson *et al.*	(BNL, CHIC, PURD)

PDG	82B	PL 111B 70	M. Roos *et al.*	(HELS, CIT, CERN)
BIRULEV	81	NP B182 1	V.K. Birulev *et al.*	(JINR)
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CARROLL	80B	PRL 44 529	A.S. Carroll *et al.*	(BNL, ROCH)
CARROLL	80C	PL 96B 407	A.S. Carroll *et al.*	(BNL, ROCH)
CHO	80	PR D22 2688	Y. Cho *et al.*	(ANL, CMU)
MORSE	80	PR D21 1750	W.M. Morse *et al.*	(BNL, YALE)
CHRISTENS...	79	PRL 43 1209	J.H. Christenson *et al.*	(NYU)
SCHMIDT	79	PRL 43 556	M.P. Schmidt *et al.*	(YALE, BNL)
HILL	78	PL 73B 483	D.G. Hill *et al.*	(BNL, SLAC, SBER)
CHO	77	PR D15 587	Y. Cho *et al.*	(ANL, CMU)
CLARK	77	PR D15 553	A.R. Clark *et al.*	(LBL)
Also		Thesis LBL-4275	G. Shen	(LBL)
DEVOE	77	PR D16 565	R. Devoe *et al.*	(EFI, ANL)
PEACH	77	NP B127 399	K.J. Peach *et al.*	(BGNA, EDIN, GLAS+)
BIRULEV	76	SJNP 24 178	V.K. Birulev *et al.*	(JINR)
		Translated from YAF 24 340.		
COOMBES	76	PRL 37 249	R.W. Coombes *et al.*	(STAN, NYU)
GJESDAL	76	NP B109 118	G. Gjesdal *et al.*	(CERN, HEIDH)
BALDO-...	75	NC 25A 688	M. Baldo-Ceolin *et al.*	(PADO, WISC)
BLUMENTHAL	75	PRL 34 164	R.B. Blumenthal *et al.*	(PENN, CHIC, TEMP)
BUCHANAN	75	PR D11 457	C.D. Buchanan *et al.*	(UCLA, SLAC, JHU)
CARITHERS	75	PRL 34 1244	W.C.J. Carithers *et al.*	(COLU, NYU)
SMITH	75B	Thesis UCSD unpub.	J.G. Smith	(UCSD)
BISI	74	PL 50B 504	V. Bisi, M.I. Ferrero	(TORI)
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DONALDSON	74B	PR D9 2960	G. Donaldson *et al.*	(SLAC, UCSC)
Also		PRL 31 337	G. Donaldson *et al.*	(SLAC, UCSC)
GEWENIGER	74	PL 48B 483	C. Geweniger *et al.*	(CERN, HEIDH)
Also		Thesis CERN Int. 74-4	V. Luth	(CERN)
GEWENIGER	74B	PL 48B 487	C. Geweniger *et al.*	(CERN, HEIDH)
Also		PL 52B 119	S. Gjesdal *et al.*	(CERN, HEIDH)
GEWENIGER	74C	PL 52B 108	C. Geweniger *et al.*	(CERN, HEIDH)
GJESDAL	74	PL 52B 113	S. Gjesdal *et al.*	(CERN, HEIDH)
MESSNER	74	PRL 33 1458	R. Messner *et al.*	(COLO, SLAC, UCSC)
NIEBERGALL	74	PL 49B 103	F. Niebergall *et al.*	(CERN, ORSAY, VIEN)
WILLIAMS	74	PRL 33 240	H.H. Williams *et al.*	(BNL, YALE)
ALEXANDER	73B	NP B65 301	G. Alexander *et al.*	(TELA, HEID)
BRANDENB...	73	PR D8 1978	G.W. Brandenburg *et al.*	(SLAC)
EVANS	73	PR D7 36	G.R. Evans *et al.*	(EDIN, CERN)
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FACKLER	73	PRL 31 847	O. Fackler *et al.*	(MIT)
FITCH	73	PRL 31 1524	V.L. Fitch *et al.*	(PRIN)
Also		Thesis COO-3072-13	R.C. Webb	(PRIN)
HART	73	NP B66 317	J.C. Hart *et al.*	(CAVE, RHEL)
MALLARY	73	PR D7 1953	M.L. Mallary *et al.*	(CIT)
Also		PRL 25 1214	F.J. Sciulli *et al.*	(CIT)
MCCARTHY	73	PR D7 687	R.L. McCarthy *et al.*	(LBL)
Also		PL 42B 291	R.L. McCarthy *et al.*	(LBL)
Also		Thesis LBL-550	R.L. McCarthy	(LBL)
MESSNER	73	PRL 30 876	R. Messner *et al.*	(COLO, SLAC, UCSC)
SANDWEISS	73	PRL 30 1002	J. Sandweiss *et al.*	(YALE, ANL)
WILLIAMS	73	PRL 31 1521	H.H. Williams *et al.*	(BNL, YALE)
ASHFORD	72	PL 38B 47	V.A. Ashford *et al.*	(UCSD)
BANNER	72B	PRL 29 237	M. Banner *et al.*	(PRIN)
BARMIN	72B	SJNP 15 638	V.V. Barmin *et al.*	(ITEP)
		Translated from YAF 15 1152.		
BURGUN	72	NP B50 194	G. Burgun *et al.*	(SACL, CERN, OSLO)
GRAHAM	72	NC 9A 166	M.F. Graham *et al.*	(ILL, NEAS)
JAMES	72	NP B49 1	F. James *et al.*	(CERN, SACL, OSLO)
KRENZ	72	LNC 4 213	W. Krenz *et al.*	(AACH, CERN, EDIN)
MANN	72	PR D6 137	W.A. Mann *et al.*	(MASA, BNL, YALE)
MANTSCH	72	NC 9A 160	P.M. Mantsch *et al.*	(ILL, NEAS)
MCCARTHY	72	PL 42B 291	R.L. McCarthy *et al.*	(LBL)
PICCIONI	72	PRL 29 1412	R. Piccioni *et al.*	(SLAC)
Also		PR D9 2939	R. Piccioni *et al.*	(SLAC, UCSC, COLO)
VOSBURGH	72	PR D6 1834	K.G. Vosburgh *et al.*	(RUTG, MASA)
Also		PRL 26 866	K.G. Vosburgh *et al.*	(RUTG, MASA)
BALATS	71	SJNP 13 53	M.Y. Balats *et al.*	(ITEP)
		Translated from YAF 13 93.		

BARMIN	71	PL 35B 604	V.V. Barmin *et al.*	(ITEP)
BURGUN	71	LNC 2 1169	G. Burgun *et al.*	(SACL, CERN, OSLO)
CARNEGIE	71	PR D4 1	R.K. Carnegie *et al.*	(PRIN)
CHAN	71	Thesis LBL-350	J.H.S. Chan	(LBL)
CHO	71	PR D3 1557	Y. Cho *et al.*	(CMU, BNL, CASE)
ENSTROM	71	PR D4 2629	J. Enstrom *et al.*	(SLAC, STAN)
Also		Thesis SLAC-0125	J.E. Enstrom	(STAN)
JAMES	71	PL 35B 265	F. James *et al.*	(CERN, SACL, OSLO)
MEISNER	71	PR D3 59	G.W. Meisner *et al.*	(MASA, BNL, YALE)
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ALBROW	70	PL 33B 516	M.G. Albrow *et al.*	(MCHS, DARE)
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BASILE	70	PR D2 78	P. Basile *et al.*	(SACL)
BECHERRAWY	70	PR D1 1452	T. Becherrawy	(ROCH)
BUCHANAN	70	PL 33B 623	C.D. Buchanan *et al.*	(SLAC, JHU, UCLA)
Also		Private Comm.	A.J. Cox	
BUDAGOV	70	PR D2 815	I.A. Budagov *et al.*	(CERN, ORSAY, EPOL)
Also		PL 28B 215	I.A. Budagov *et al.*	(CERN, ORSAY, EPOL)
CHO	70	PR D1 3031	Y. Cho *et al.*	(CMU, BNL, CASE)
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CULLEN	70	PL 32B 523	M. Cullen *et al.*	(AACH, CERN, TORI)
MARX	70	PL 32B 219	J. Marx *et al.*	(COLU, HARV, CERN)
Also		Thesis Nevis 179	J. Marx	(COLU)
SCRIBANO	70	PL 32B 224	A. Scribano *et al.*	(PISA, COLU, HARV)
SMITH	70	PL 32B 133	R.C. Smith *et al.*	(UMD, BNL)
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BENNETT	68	PL 27B 244	S. Bennett *et al.*	(COLU, CERN)
BLANPIED	68	PRL 21 1650	W.A. Blanpied *et al.*	(CASE, HARV, MCGI)
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Also		PL 15 58	X. de Bouard *et al.*	(CERN, ORSAY, MPIM)
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