# $K^0_L$

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

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

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 "Fits for $K^0_L$ *CP*-Violation Parameters" in the $K^0_L$ Particle Listings.

| *VALUE* ($10^{10}$ $\hbar$ s$^{-1}$) | | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **0.5303±0.0009** | **OUR FIT** | Assuming *CPT* | | | |
| **0.5301±0.0016** | **OUR FIT** | Not assuming *CPT* | | | |
| **0.5308±0.0014** | **OUR AVERAGE** | Error includes scale factor of 1.1. | | | |
| 0.5343±0.0063 | ±0.0025 | [1] ANGELOPO... | 01 | CPLR | |
| 0.5240±0.0044 | ±0.0033 | APOSTOLA... | 99C | CPLR | $K^0$-$\overline{K}^0$ to $\pi^+\pi^-$ |
| 0.5295±0.0020 | ±0.0003 | [2] ANGELOPO... | 98D | CPLR | |
| 0.5297±0.0030 | ±0.0022 | [3] SCHWINGEN... | 95 | E773 | 20–160 GeV $K$ beams |
| 0.5257±0.0049 | ±0.0021 | [3] GIBBONS | 93C | E731 | 20–160 GeV $K$ beams |
| 0.5340±0.00255 | ±0.0015 | [4] GEWENIGER | 74C | SPEC | Gap method |
| 0.5334±0.0040 | ±0.0015 | [4] GJESDAL | 74 | SPEC | Charge asymmetry in $K^0_{\ell 3}$ |
| 0.542 | ±0.006 | CULLEN | 70 | CNTR | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.5307±0.0013 | | [5] ADLER | 96C | RVUE | |
| 0.5274±0.0029 | ±0.0005 | [2] ADLER | 95 | CPLR | Sup. by ANGELOPOULOS 98D |
| 0.5286±0.0028 | | [6] GIBBONS | 93 | E731 | 20–160 GeV $K$ beams |
| 0.482 | ±0.014 | [7] ARONSON | 82B | SPEC | $E$=30–110 GeV |
| 0.534 | ±0.007 | [8] CARNEGIE | 71 | ASPK | Gap method |
| 0.542 | ±0.006 | [8] ARONSON | 70 | ASPK | Gap method |

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

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

[3] Fits $\Delta m$ and $\phi_{+-}$ simultaneously. GIBBONS 93C systematic error is from B. Winstein via private communtication.

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

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

[6] GIBBONS 93 value assume $\phi_{+-} = \phi_{00} = \phi_{SW} = (43.7 \pm 0.2)^\circ$.

[7] ARONSON 82 find that $\Delta m$ may depend on the kaon energy.

[8] 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 $\eta_{+-}$.

## $K_L^0$ MEAN LIFE

| *VALUE* ($10^{-8}$ s) | *EVTS* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| **5.17 ±0.04 OUR FIT** Error includes scale factor of 1.1. | | | | |
| **5.15 ±0.04 OUR AVERAGE** | | | | |
| 5.154±0.044 | 0.4M | VOSBURGH | 72 | CNTR |
| 5.15 ±0.14 | | DEVLIN | 67 | CNTR |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 5.0 ±0.5 | | [9] LOWYS | 67 | HLBC |
| $6.1\ ^{+1.5}_{-1.2}$ | 1700 | ASTBURY | 65C | CNTR |
| 5.3 ±0.6 | | FUJII | 64 | OSPK |
| $5.1\ ^{+2.4}_{-1.3}$ | 15 | DARMON | 62 | FBC |
| $8.1\ ^{+3.2}_{-2.4}$ | 34 | BARDON | 58 | CNTR |

[9] Sum of partial decay rates.

## $K_L^0$ DECAY MODES

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Scale factor/ Confidence level |
|---|---|---|---|---|
| | **Semileptonic modes** | | | |
| $\Gamma_1$ | $\pi^\pm e^\mp \nu_e$ | [a] | (38.79 ±0.27 ) % | S=1.1 |
| | Called $K^0_{e3}$. | | | |
| $\Gamma_2$ | $\pi^- e^+ \nu_e$ | | | |
| $\Gamma_3$ | $\pi^+ e^- \overline{\nu}_e$ | | | |
| $\Gamma_4$ | $\pi^\pm \mu^\mp \nu_\mu$ | [a] | (27.18 ±0.25 ) % | S=1.1 |
| | Called $K^0_{\mu 3}$. | | | |
| $\Gamma_5$ | $\pi^- \mu^+ \nu_\mu$ | | | |
| $\Gamma_6$ | $\pi^+ \mu^- \overline{\nu}_\mu$ | | | |
| $\Gamma_7$ | $(\pi\mu\text{atom})\nu$ | | ( 1.06 ±0.11 ) × $10^{-7}$ | |
| $\Gamma_8$ | $\pi^0 \pi^\pm e^\mp \nu$ | [a] | ( 5.18 ±0.29 ) × $10^{-5}$ | |
| | **Hadronic modes, including Charge conjugation × Parity Violating (*CPV*) modes** | | | |
| $\Gamma_9$ | $3\pi^0$ | | (21.08 ±0.27 ) % | S=1.1 |
| $\Gamma_{10}$ | $\pi^+ \pi^- \pi^0$ | | (12.58 ±0.19 ) % | S=1.7 |
| $\Gamma_{11}$ | $\pi^+ \pi^-$ | *CPV* | ( 2.084±0.032) × $10^{-3}$ | S=1.1 |
| $\Gamma_{12}$ | $\pi^0 \pi^0$ | *CPV* | ( 9.42 ±0.19 ) × $10^{-4}$ | S=1.1 |
| | **Semileptonic modes with photons** | | | |
| $\Gamma_{13}$ | $\pi^\pm e^\mp \nu_e \gamma$ | [a,b,c] | ( 3.53 ±0.06 ) × $10^{-3}$ | |
| $\Gamma_{14}$ | $\pi^\pm \mu^\mp \nu_\mu \gamma$ | | ( $5.7\ ^{+0.6}_{-0.7}$ ) × $10^{-4}$ | |

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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\Gamma_{15}$ | $\pi^0\pi^0\gamma$ | | $<$ | 5.6 | | $\times 10^{-6}$ | |
| $\Gamma_{16}$ | $\pi^+\pi^-\gamma$ | [b,c] | ( | 4.38 | $\pm 0.13$ ) | $\times 10^{-5}$ | S=1.8 |
| $\Gamma_{17}$ | $\pi^0 2\gamma$ | [c] | ( | 1.68 | $\pm 0.10$ ) | $\times 10^{-6}$ | |
| $\Gamma_{18}$ | $\pi^0\gamma e^+e^-$ | | ( | 2.3 | $\pm 0.4$ ) | $\times 10^{-8}$ | |

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

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\Gamma_{19}$ | $2\gamma$ | | ( | 5.96 | $\pm 0.15$ ) | $\times 10^{-4}$ | |
| $\Gamma_{20}$ | $3\gamma$ | | $<$ | 2.4 | | $\times 10^{-7}$ | CL=90% |
| $\Gamma_{21}$ | $e^+e^-\gamma$ | | ( | 10.0 | $\pm 0.5$ ) | $\times 10^{-6}$ | S=1.5 |
| $\Gamma_{22}$ | $\mu^+\mu^-\gamma$ | | ( | 3.59 | $\pm 0.11$ ) | $\times 10^{-7}$ | S=1.3 |
| $\Gamma_{23}$ | $e^+e^-\gamma\gamma$ | [c] | ( | 5.95 | $\pm 0.33$ ) | $\times 10^{-7}$ | |
| $\Gamma_{24}$ | $\mu^+\mu^-\gamma\gamma$ | [c] | ( | 1.0 | $^{+0.8}_{-0.6}$ ) | $\times 10^{-8}$ | |

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

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\Gamma_{25}$ | $\mu^+\mu^-$ | *S1* | | ( | 7.25 | $\pm 0.16$ ) | $\times 10^{-9}$ | |
| $\Gamma_{26}$ | $e^+e^-$ | *S1* | | ( | 9 | $^{+6}_{-4}$ ) | $\times 10^{-12}$ | |
| $\Gamma_{27}$ | $\pi^+\pi^-e^+e^-$ | *S1* | [c] | ( | 3.5 | $\pm 0.6$ ) | $\times 10^{-7}$ | |
| $\Gamma_{28}$ | $\mu^+\mu^-e^+e^-$ | *S1* | | ( | 2.6 | $\pm 0.4$ ) | $\times 10^{-9}$ | |
| $\Gamma_{29}$ | $e^+e^-e^+e^-$ | *S1* | | ( | 3.75 | $\pm 0.27$ ) | $\times 10^{-8}$ | |
| $\Gamma_{30}$ | $\pi^0\mu^+\mu^-$ | *CP,S1* | [d] | $<$ | 3.8 | | $\times 10^{-10}$ | CL=90% |
| $\Gamma_{31}$ | $\pi^0 e^+e^-$ | *CP,S1* | [d] | $<$ | 5.1 | | $\times 10^{-10}$ | CL=90% |
| $\Gamma_{32}$ | $\pi^0\nu\overline{\nu}$ | *CP,S1* | [e] | $<$ | 5.9 | | $\times 10^{-7}$ | CL=90% |
| $\Gamma_{33}$ | $e^\pm\mu^\mp$ | *LF* | [a] | $<$ | 4.7 | | $\times 10^{-12}$ | CL=90% |
| $\Gamma_{34}$ | $e^\pm e^\pm\mu^\mp\mu^\mp$ | *LF* | [a] | $<$ | 1.23 | | $\times 10^{-10}$ | CL=90% |
| $\Gamma_{35}$ | $\pi^0\mu^\pm e^\mp$ | *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 $\gamma$ part, is also included in the parent mode listed without $\gamma$'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, 3 decay rate, and 14 branching ratios uses 48 measurements and one constraint to determine 9 parameters. The overall fit has a $\chi^2 = 43.6$ for 40 degrees of freedom.

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

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $x_4$ | −36 | | | | | | | |
| $x_9$ | −49 | −37 | | | | | | |
| $x_{10}$ | −28 | −28 | −19 | | | | | |
| $x_{11}$ | −7 | −8 | −12 | 33 | | | | |
| $x_{12}$ | −6 | −6 | −9 | 25 | 77 | | | |
| $x_{16}$ | −3 | −4 | −5 | 15 | 45 | 35 | | |
| $x_{19}$ | −5 | −5 | −7 | 21 | 63 | 82 | 28 | |
| $\Gamma$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $x_1$ | $x_4$ | $x_9$ | $x_{10}$ | $x_{11}$ | $x_{12}$ | $x_{16}$ | $x_{19}$ |

| | Mode | | Rate ($10^8$ s$^{-1}$) | Scale factor |
|---|---|---|---|---|
| $\Gamma_1$ | $\pi^\pm e^\mp \nu_e$ Called $K^0_{e3}$. | [a] | 0.0750 ± 0.0008 | 1.1 |
| $\Gamma_4$ | $\pi^\pm \mu^\mp \nu_\mu$ Called $K^0_{\mu 3}$. | [a] | 0.0525 ± 0.0007 | 1.1 |
| $\Gamma_9$ | $3\pi^0$ | | 0.0407 ± 0.0006 | |
| $\Gamma_{10}$ | $\pi^+\pi^-\pi^0$ | | 0.0243 ± 0.0004 | 1.5 |
| $\Gamma_{11}$ | $\pi^+\pi^-$ | | (4.03 ± 0.07 ) × $10^{-4}$ | 1.1 |
| $\Gamma_{12}$ | $\pi^0\pi^0$ | | (1.82 ± 0.04 ) × $10^{-4}$ | 1.1 |
| $\Gamma_{16}$ | $\pi^+\pi^-\gamma$ | [b,c] | (8.46 ± 0.26 ) × $10^{-6}$ | 1.7 |
| $\Gamma_{19}$ | $2\gamma$ | | (1.151 ± 0.030 ) × $10^{-4}$ | 1.1 |

## $K^0_L$ DECAY RATES

### $\Gamma(\pi^+\pi^-\pi^0)$ $\Gamma_{10}$

| *VALUE* ($10^6$ s$^{-1}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **2.43±0.04 OUR FIT** Error includes scale factor of 1.5. | | | | | |
| **2.38±0.09 OUR AVERAGE** | | | | | |
| $2.32^{+0.13}_{-0.15}$ | 192 | BALDO-... | 75 | HLBC | Assumes *CP* |
| 2.35±0.20 | 180 | [10] JAMES | 72 | HBC | Assumes *CP* |
| 2.71±0.28 | 99 | CHO | 71 | DBC | Assumes *CP* |

| | | | | | |
|---|---|---|---|---|---|
| $2.12 \pm 0.33$ | 50 | MEISNER | 71 | HBC | Assumes *CP* |
| $2.20 \pm 0.35$ | 53 | WEBBER | 70 | HBC | Assumes *CP* |
| $2.62^{+0.28}_{-0.27}$ | 136 | BEHR | 66 | HLBC | Assumes *CP* |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $2.5 \pm 0.3$ | 98 | [10] JAMES | 71 | HBC | Assumes *CP* |
| $3.26 \pm 0.77$ | 18 | ANDERSON | 65 | HBC | |
| $1.4 \pm 0.4$ | 14 | FRANZINI | 65 | HBC | |

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

### $\Gamma(\pi^\pm e^\mp \nu_e)$ $\Gamma_1$

| *VALUE* ($10^6$ s$^{-1}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$7.50 \pm 0.08$ OUR FIT** | Error includes scale factor of 1.1. | | | | |
| **$7.7 \pm 0.5$ OUR AVERAGE** | | | | | |
| $7.81 \pm 0.56$ | 620 | CHAN | 71 | HBC | |
| $7.52^{+0.85}_{-0.72}$ | | AUBERT | 65 | HLBC | $\Delta S = \Delta Q$, *CP* assumed |

### $\Gamma(\pi^\pm e^\mp \nu_e) + \Gamma(\pi^\pm \mu^\mp \nu_\mu)$ $(\Gamma_1+\Gamma_4)$

| *VALUE* ($10^6$ s$^{-1}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$12.75 \pm 0.12$ OUR FIT** | Error includes scale factor of 1.1. | | | | |
| **$11.9 \pm 0.6$ OUR AVERAGE** | Error includes scale factor of 1.2. | | | | |
| $12.4 \pm 0.7$ | 410 | [11] BURGUN | 72 | HBC | $K^+ p \to K^0 p \pi^+$ |
| $13.1 \pm 1.3$ | 252 | [11] WEBBER | 71 | HBC | $K^- p \to n \overline{K}^0$ |
| $11.6 \pm 0.9$ | 393 | [11,12] CHO | 70 | DBC | $K^+ n \to K^0 p$ |
| $9.85^{+1.15}_{-1.05}$ | 109 | [11] FRANZINI | 65 | HBC | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $8.47 \pm 1.69$ | 126 | [11] MANN | 72 | HBC | $K^- p \to n \overline{K}^0$ |
| $10.3 \pm 0.8$ | 335 | [12] HILL | 67 | DBC | $K^+ n \to K^0 p$ |

[11] Assumes $\Delta S = \Delta Q$ rule.
[12] CHO 70 includes events of HILL 67.

## $K_L^0$ BRANCHING RATIOS

### Semileptonic modes

### $\left[\Gamma(\pi^\pm e^\mp \nu_e) + \Gamma(\pi^\pm \mu^\mp \nu_\mu)\right] / \Gamma_{\text{total}}$ $(\Gamma_1+\Gamma_4)/\Gamma$

| *VALUE* | *DOCUMENT ID* |
|---|---|
| **$0.6597 \pm 0.0030$ OUR FIT** | Error includes scale factor of 1.2. |

### $\Gamma(\pi^\pm \mu^\mp \nu_\mu) / \Gamma(\pi^\pm e^\mp \nu_e)$ $\Gamma_4/\Gamma_1$

| *VALUE* | *EVTS* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| **$0.701 \pm 0.009$ OUR FIT** | | | | |
| **$0.697^{+0.010}_{-0.009}$ OUR AVERAGE** | | | | |
| $0.702 \pm 0.011$ | 33k | CHO | 80 | HBC |
| $0.662 \pm 0.037$ | 10k | WILLIAMS | 74 | ASPK |
| $0.741 \pm 0.044$ | 6700 | BRANDENB... | 73 | HBC |
| $0.662 \pm 0.030$ | 1309 | EVANS | 73 | HLBC |
| $0.71 \pm 0.05$ | 770 | BUDAGOV | 68 | HLBC |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $0.68 \pm 0.08$ | 3548 | BASILE | 70 | OSPK |

### $\Gamma((\pi\mu\text{atom})\nu)/\Gamma(\pi^{\pm}\mu^{\mp}\nu_{\mu})$ $\Gamma_7/\Gamma_4$

| VALUE (units $10^{-7}$) | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **3.90±0.39** | 155 | [13] ARONSON | 86 | SPEC |

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

| | | | | |
|---|---|---|---|---|
| seen | 18 | COOMBES | 76 | WIRE |

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

### $\Gamma(\pi^0\pi^{\pm}e^{\mp}\nu)/\Gamma_{\text{total}}$ $\Gamma_8/\Gamma$

| VALUE (units $10^{-5}$) | CL% | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|---|
| **5.18±0.29 OUR AVERAGE** | | | | | |
| 5.16±0.20±0.22 | | 729 | MAKOFF | 93 | E731 |
| 6.2 ±2.0 | | 16 | CARROLL | 80C | SPEC |

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

| | | | | | |
|---|---|---|---|---|---|
| <220 | 90 | [14] DONALDSON | 74 | SPEC | |

[14] DONALDSON 74 uses $K_L^0 \to \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.126.

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

### $\Gamma(3\pi^0)/\Gamma_{\text{total}}$ $\Gamma_9/\Gamma$

| VALUE | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **0.2108±0.0027 OUR FIT** Error includes scale factor of 1.1. | | | | |
| **0.2105±0.0028** | 38k | [15] KREUTZ | 95 | NA31 |

[15] KREUTZ 95 measure $3\pi^0$, $\pi^+\pi^-\pi^0$, and $\pi e\nu_e$ modes. They assume PDG 1992 values for $\pi\mu\nu_\mu$, $2\pi$, and $2\gamma$ modes.

### $\Gamma(3\pi^0)/\Gamma(\pi^{\pm}e^{\mp}\nu_e)$ $\Gamma_9/\Gamma_1$

| VALUE | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **0.543±0.009 OUR FIT** Error includes scale factor of 1.1. | | | | |
| **0.545±0.004±0.009** | 38k | [16] KREUTZ | 95 | NA31 |

[16] KREUTZ 95 measurement excluded from fit because it is not independent of their $\Gamma(3\pi^0)/\Gamma_{\text{total}}$ measurement, which is in the fit.

### $\Gamma(3\pi^0)/[\Gamma(\pi^{\pm}e^{\mp}\nu_e)+\Gamma(\pi^{\pm}\mu^{\mp}\nu_\mu)+\Gamma(\pi^+\pi^-\pi^0)]$ $\Gamma_9/(\Gamma_1+\Gamma_4+\Gamma_{10})$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.268±0.004 OUR FIT** Error includes scale factor of 1.1. | | | | | |
| **0.260±0.011 OUR AVERAGE** | | | | | |
| 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 | |

## $\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ $\Gamma_9/\Gamma_{10}$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **1.68 ±0.04 OUR FIT** | Error includes scale factor of 1.3. | | | | |
| **1.63 ±0.05 OUR AVERAGE** | Error includes scale factor of 1.4. | | | | |
| 1.611±0.014±0.034 | 38k | [17] KREUTZ | 95 | NA31 | |
| 1.80 ±0.13 | 1010 | BUDAGOV | 68 | HLBC | |
| 2.0 ±0.6 | 188 | ALEKSANYAN | 64B | FBC | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 1.65 ±0.07 | 883 | BARMIN | 72B | HLBC | Error statistical only |

[17] KREUTZ 95 excluded from fit because it is not independent of their $\Gamma(3\pi^0)/\Gamma_{total}$ measurement, which is in the fit.

## $\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ $\Gamma_{10}/\Gamma$

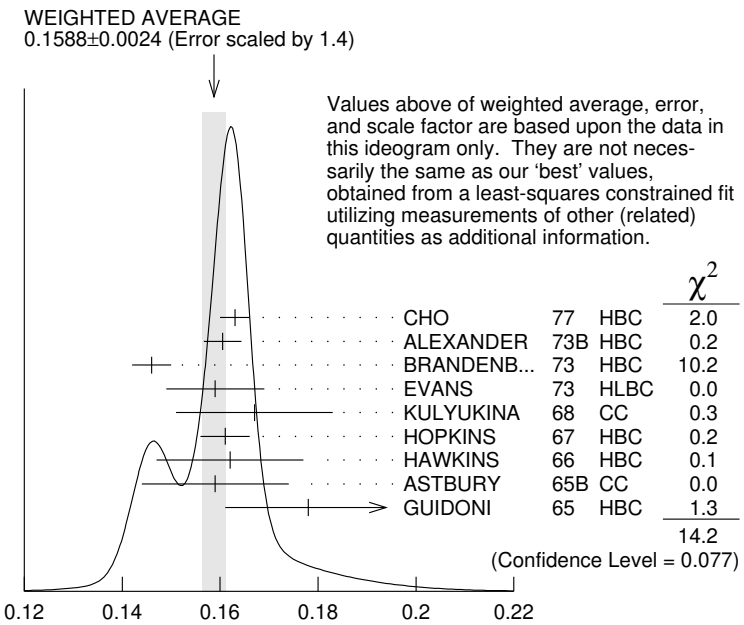
| VALUE | DOCUMENT ID |
|---|---|
| **0.1258±0.0019 OUR FIT** | Error includes scale factor of 1.7. |

## $\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi^\pm e^\mp \nu_e)$ $\Gamma_{10}/\Gamma_1$

| VALUE | EVTS | DOCUMENT ID | TECN |
|---|---|---|---|
| **0.324±0.006 OUR FIT** | Error includes scale factor of 1.6. | | |
| **0.336±0.003±0.007** | 28k | KREUTZ | 95 NA31 |

## $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^\pm e^\mp \nu_e)+\Gamma(\pi^\pm \mu^\mp \nu_\mu)+\Gamma(\pi^+\pi^-\pi^0)]$ $\Gamma_{10}/(\Gamma_1+\Gamma_4+\Gamma_{10})$

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.1601±0.0024 OUR FIT** | Error includes scale factor of 1.7. | | | | |
| **0.1588±0.0024 OUR AVERAGE** | Error includes scale factor of 1.4. See the ideogram below. | | | | |
| 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 | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.144 ±0.004 | 1729 | HOPKINS | 65 | HBC | See HOPKINS 67 |




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

## $\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ $\Gamma_{11}/\Gamma$

Violates $CP$ conservation.

| *VALUE* (units $10^{-3}$) | *DOCUMENT ID* | |
|---|---|---|
| **2.084±0.032 OUR FIT** | Error includes scale factor of 1.1. | |
| **2.075±0.049** | [18] ETAFIT | 02 |

[18] This ETAFIT value is computed from fitted values of $|\eta_{+-}|$, the $K_L^0$ and $K_S^0$ lifetimes, and the $K_S^0 \to \pi^+\pi^-$ branching fraction. See the discussion in the note "Fits for $K_L^0$ $CP$-Violation Parameters."

## $\Gamma(\pi^+\pi^-)/\left[\Gamma(\pi^\pm e^\mp \nu_e)+\Gamma(\pi^\pm \mu^\mp \nu_\mu)\right]$ $\Gamma_{11}/(\Gamma_1+\Gamma_4)$

Violates $CP$ conservation.

| *VALUE* (units $10^{-3}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **3.16±0.05 OUR FIT** | Error includes scale factor of 1.2. | | | | |
| **3.08±0.10 OUR AVERAGE** | | | | | |
| 3.13±0.14 | 1687 | COUPAL | 85 | SPEC | $\eta_{+-}$=2.28 ± 0.06 |
| 3.04±0.14 | 2703 | DEVOE | 77 | SPEC | $\eta_{+-}$=2.25 ± 0.05 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 2.51±0.23 | 309 | [19] DEBOUARD | 67 | OSPK | $\eta_{+-}$=2.00 ± 0.09 |
| 2.35±0.19 | 525 | [19] FITCH | 67 | OSPK | $\eta_{+-}$=1.94 ± 0.08 |

[19] Old experiments excluded from fit. See subsection on $\eta_{+-}$ in section on "PARAMETERS FOR $K_L^0 \to 2\pi$ DECAY" below for average $\eta_{+-}$ of these experiments and for note on discrepancy.

### $\Gamma(\pi^+\pi^-)/[\Gamma(\pi^\pm e^\mp \nu_e)+\Gamma(\pi^\pm \mu^\mp \nu_\mu)+\Gamma(\pi^+\pi^-\pi^0)]$ $\Gamma_{11}/(\Gamma_1+\Gamma_4+\Gamma_{10})$

Violates $CP$ conservation.

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **2.65±0.04 OUR FIT** | Error includes scale factor of 1.1. | | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 2.60±0.07 | 4200 | [20] MESSNER | 73 | ASPK | $\eta_{+-} = 2.23 \pm 0.05$ |

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

### $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ $\Gamma_{11}/\Gamma_{10}$

Violates $CP$ conservation.

| VALUE (units $10^{-2}$) | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| **1.657±0.030 OUR FIT** | Error includes scale factor of 1.2. | | | |
| **1.64 ±0.04** | 4200 | MESSNER | 73 ASPK | $\eta_{+-} = 2.23$ |

### $\Gamma(\pi^0\pi^0)/\Gamma_{total}$ $\Gamma_{12}/\Gamma$

Violates $CP$ conservation.

| VALUE (units $10^{-3}$) | DOCUMENT ID |
|---|---|
| **0.942±0.019 OUR FIT** | Error includes scale factor of 1.1. |

### $\Gamma(\pi^0\pi^0)/\Gamma(\pi^+\pi^-)$ $\Gamma_{12}/\Gamma_{11}$

Violates $CP$ conservation.

| VALUE | DOCUMENT ID | | |
|---|---|---|---|
| **0.452 ±0.006 OUR FIT** | | | |
| **0.4528±0.0058** | [21] ETAFIT | 02 | |

[21] This ETAFIT value is computed from fitted values of $|\eta_{00}\ /\ \eta_{+-}|$ and the $\Gamma(K_S^0 \to \pi^+\pi^-)\ /\ \Gamma(K_S^0 \to \pi^0\pi^0)$ branching fraction. See the discussion in the note "Fits for $K_L^0$ $CP$-Violation Parameters."

### $\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$ $\Gamma_{12}/\Gamma_9$

Violates $CP$ conservation.

| VALUE (units $10^{-2}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.447±0.011 OUR FIT** | Error includes scale factor of 1.1. | | | | |
| **0.39 ±0.06 OUR AVERAGE** | | | | | |
| 0.37 ±0.08 | 29 | BARMIN | 70 | HLBC | $\eta_{00}$=2.02 ± 0.23 |
| 0.32 ±0.15 | 30 | BUDAGOV | 70 | HLBC | $\eta_{00}$=1.9 ± 0.5 |
| 0.46 ±0.11 | 57 | BANNER | 69 | OSPK | $\eta_{00}$=2.2 ± 0.3 |

## Semileptonic modes with photons

### $\Gamma(\pi^\pm e^\mp \nu_e \gamma)/\Gamma(\pi^\pm e^\mp \nu_e)$ $\Gamma_{13}/\Gamma_1$

| VALUE (units $10^{-2}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.910±0.014 OUR AVERAGE** | | | | | |
| $0.908 \pm 0.008^{+0.013}_{-0.012}$ | 15k | ALAVI-HARATI | 01J | KTEV | $E^*_\gamma \geq 30$ MeV, $\theta^*_{e\gamma} \geq 20^\circ$ |
| $0.934 \pm 0.036^{+0.055}_{-0.039}$ | 1384 | LEBER | 96 | NA31 | $E^*_\gamma \geq 30$ MeV, $\theta^*_{e\gamma} \geq 20^\circ$ |

## $\Gamma(\pi^\pm \mu^\mp \nu_\mu \gamma)/\Gamma(\pi^\pm \mu^\mp \nu_\mu)$ $\Gamma_{14}/\Gamma_4$

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$2.08 \pm 0.17 ^{+0.16}_{-0.21}$** | 4261 | BENDER | 98 | NA48 | $E^*_\gamma \geq 30$ MeV |

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

## $\Gamma(\pi^0 \pi^0 \gamma)/\Gamma_{total}$ $\Gamma_{15}/\Gamma$

| 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 |

## $\Gamma(\pi^+ \pi^- \gamma)/\Gamma_{total}$ $\Gamma_{16}/\Gamma$

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

| VALUE (units $10^{-5}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **4.38±0.13 OUR FIT** Error includes scale factor of 1.8. | | | | | |
| **4.61±0.14 OUR AVERAGE** | | | | | |
| 4.66±0.15 | 3136 | [22] RAMBERG | 93 | E731 | $E_\gamma$ >20 MeV |
| 4.41±0.32 | 1062 | [23] CARROLL | 80B | SPEC | $E_\gamma$ >20 MeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 1.52±0.16 | 516 | [24] CARROLL | 80B | SPEC | $E_\gamma$ >20 MeV |
| 2.89±0.28 | 546 | [25] CARROLL | 80B | SPEC | |

[22] RAMBERG 93 finds that fraction of Direct Emission (DE) decays with $E_\gamma$ >20 MeV is 0.685 ± 0.041.
[23] Both components. Uses $K^0_L \to \pi^+ \pi^- \pi^0$/(all $K^0_L$) decays = 0.1239.
[24] Internal Bremsstrahlung component only.
[25] Direct $\gamma$ emission component only.

## $\Gamma(\pi^+ \pi^- \gamma)/\Gamma(\pi^+ \pi^-)$ $\Gamma_{16}/\Gamma_{11}$

| VALUE (units $10^{-2}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **2.10 ±0.06 OUR FIT** Error includes scale factor of 2.1. | | | | | |
| **2.08 ±0.02 ±0.02** | 8669 | [26] ALAVI-HARATI | 01B | KTEV | $E^*_\gamma$ >20 MeV |

[26] ALAVI-HARATI 01B includes both Direct Emission (DE) and Inner Bremstrahlung (IB) processes. THey also report DE/(DE+IB)= 0.683 ± 0.011. The paper reports results for $\rho$ propagator, linear, and quadratic form factors.

## $\Gamma(\pi^0 2\gamma)/\Gamma_{total}$ $\Gamma_{17}/\Gamma$

| VALUE (units $10^{-6}$) | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **1.68±0.10 OUR AVERAGE** | | | | | | |
| 1.68±0.07±0.08 | | 884 | ALAVI-HARATI | 99B | KTEV | |
| 1.7 ±0.2 ±0.2 | | 63 | [27] BARR | 92 | SPEC | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 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 | [28] BARR | 90C | NA31 | $m_{\gamma\gamma}$ > 280 MeV |

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

## $\Gamma(\pi^0 \gamma e^+ e^-)/\Gamma_{total}$ $\Gamma_{18}/\Gamma$

| 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 $\ell\bar{\ell}$ pairs

## $\Gamma(2\gamma)/\Gamma_{total}$ $\Gamma_{19}/\Gamma$

| VALUE (units $10^{-4}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **5.96±0.15 OUR FIT** | | | | | |

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

| | | | | | |
|---|---|---|---|---|---|
| 4.54±0.84 | | [29] BANNER | 72B | OSPK | |
| 4.5 ±1.0 | 23 | ENSTROM | 71 | OSPK | $K_L^0$ 1.5–9 GeV/$c$ |
| 5.0 ±1.0 | | [30] REPELLIN | 71 | OSPK | |
| 5.5 ±1.1 | 90 | KUNZ | 68 | OSPK | Norm.to 3 $\pi$(C+N) |

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

[30] 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)$^2$.

## $\Gamma(2\gamma)/\Gamma(3\pi^0)$ $\Gamma_{19}/\Gamma_9$

| VALUE (units $10^{-3}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **2.82±0.08 OUR FIT** Error includes scale factor of 1.1. | | | | | |

• • • 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 |

## $\Gamma(2\gamma)/\Gamma(\pi^0\pi^0)$ $\Gamma_{19}/\Gamma_{12}$

| VALUE | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **0.632±0.009 OUR FIT** | | | | |
| **0.632±0.004±0.008** | 110k | BURKHARDT | 87 | NA31 |

## $\Gamma(3\gamma)/\Gamma_{total}$ $\Gamma_{20}/\Gamma$

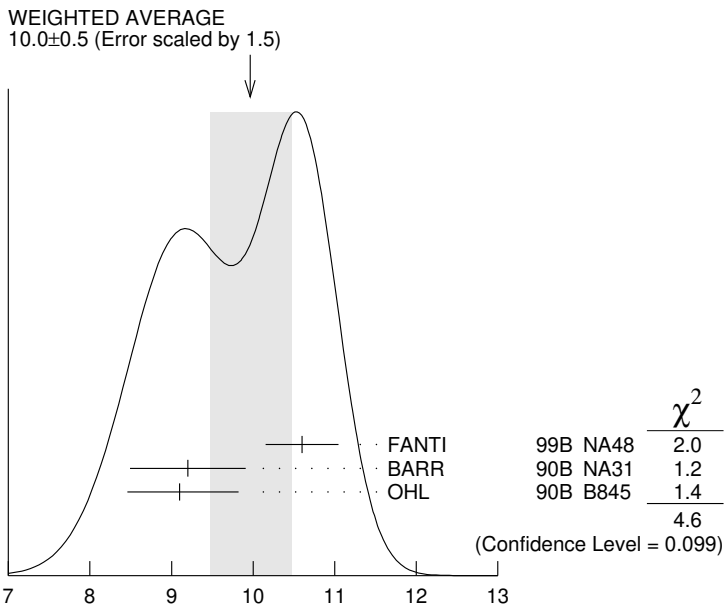
| VALUE | CL% | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **<2.4 × $10^{-7}$** | 90 | [31] BARR | 95C | NA31 |

[31] Assumes a phase-space decay distribution.

## $\Gamma(e^+ e^- \gamma)/\Gamma_{total}$ $\Gamma_{21}/\Gamma$

| 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 | [32] 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 |

[32] 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 $K_L^0 \to \pi^0 \pi^0$ branching ratios, evaluated using our 1999 Web edition values.




$\Gamma\left(e^+ e^- \gamma\right)/\Gamma_{\text{total}}$ (units $10^{-6}$)

## $\Gamma\left(\mu^+ \mu^- \gamma\right)/\Gamma_{\text{total}}$ $\Gamma_{22}/\Gamma$

| *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 |

## $\Gamma\left(e^+ e^- \gamma\gamma\right)/\Gamma_{\text{total}}$ $\Gamma_{23}/\Gamma$

| *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 |

## $\Gamma\left(\mu^+ \mu^- \gamma\gamma\right)/\Gamma_{\text{total}}$ $\Gamma_{24}/\Gamma$

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

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

### $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ $\Gamma_{25}/\Gamma_{11}$

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 | [33] 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 | [34] AKAGI | 91B | SPEC | In AKAGI 95 |
| 3.45 ±0.18 ±0.13 | 368 | [35] 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 |

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

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

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

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

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 | [36] ARISAKA | 93B | B791 |

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

### $\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_{27}/\Gamma$

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

| VALUE (units $10^{-7}$) | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **3.5±0.6 OUR AVERAGE** | | | | | | |
| 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 |

### $\Gamma(\mu^+\mu^-e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_{28}/\Gamma$

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

| VALUE (units $10^{-9}$) | CL% | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|---|
| **2.6 ±0.4 OUR AVERAGE** | | | | | |
| 2.62±0.40±0.17 | | 43 | ALAVI-HARATI | 01H | KTEV |
| $2.9\ ^{+6.7}_{-2.4}$ | | 1 | GU | 96 | E799 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <4900 | 90 | | BALATS | 83 | SPEC |

## $\Gamma(e^+ e^- e^+ e^-)/\Gamma_{total}$ $\Gamma_{29}/\Gamma$

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

| VALUE (units $10^{-8}$) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **3.75±0.27 OUR AVERAGE** | | | | | |
| 3.72±0.18±0.23 | 441 | ALAVI-HARATI | 01D | KTEV | |
| 6 ±2 ±1 | 18 | [37] AKAGI | 95 | SPEC | $m_{ee}$ >470 MeV |
| 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. • • • | | | | | |
| 7 ±3 ±2 | 6 | [37] AKAGI | 95 | SPEC | $m_{ee}$ >470 MeV |
| 10.4 ±3.7 ±1.1 | 8 | [38] BARR | 95 | NA31 | |
| 6 ±2 ±1 | 18 | AKAGI | 93 | CNTR | Sup. by AKAGI 95 |
| 4 ±3 | 2 | BARR | 91 | NA31 | Sup. by BARR 95 |

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

[38] Distribution of angles between two $e^+ e^-$ pair planes favors $CP=-1$ for $K_L^0$.

## $\Gamma(\pi^0 \mu^+ \mu^-)/\Gamma_{total}$ $\Gamma_{30}/\Gamma$

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. • • • | | | | | |
| <5.1 | 90 | 0 | HARRIS | 93 | E799 |

## $\Gamma(\pi^0 e^+ e^-)/\Gamma_{total}$ $\Gamma_{31}/\Gamma$

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

| VALUE (units $10^{-9}$) | CL% | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|---|
| **< 0.51** | 90 | 2 | ALAVI-HARATI | 01 | KTEV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 4.3 | 90 | 0 | HARRIS | 93B | E799 |
| < 7.5 | 90 | 0 | BARKER | 90 | E731 |
| < 5.5 | 90 | 0 | OHL | 90 | B845 |
| < 40 | 90 | | BARR | 88 | NA31 |
| <320 | 90 | | JASTRZEM... | 88 | SPEC |

## $\Gamma(\pi^0 \nu\overline{\nu})/\Gamma_{total}$ $\Gamma_{32}/\Gamma$

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 |

### $\Gamma(e^{\pm}\mu^{\mp})/\Gamma_{total}$ $\Gamma_{33}/\Gamma$

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 | [39] ARISAKA | 93 | B791 |

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

### $\Gamma(e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp})/\Gamma_{total}$ $\Gamma_{34}/\Gamma$

Test of lepton family number conservation.

| VALUE (units $10^{-10}$) | CL% | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|---|
| **< 1.23** | 90 | 64 | [40] ALAVI-HARATI | 01H | KTEV |

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

| | | | | | |
|---|---|---|---|---|---|
| <61 | 90 | 0 | [40] GU | 96 | E799 |

[40] Assuming uniform phase space distribution.

### $\Gamma(\pi^0\mu^{\pm}e^{\mp})/\Gamma_{total}$ $\Gamma_{35}/\Gamma$

Test of lepton family number conservation.

| VALUE | CL% | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **$<6.2\times10^{-9}$** | 90 | ARISAKA | 98 | E799 |

## ENERGY DEPENDENCE OF $K_L^0$ 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).

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

### LINEAR COEFFICIENT $g$ FOR $K_L^0 \to \pi^+\pi^-\pi^0$

| 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. • • •

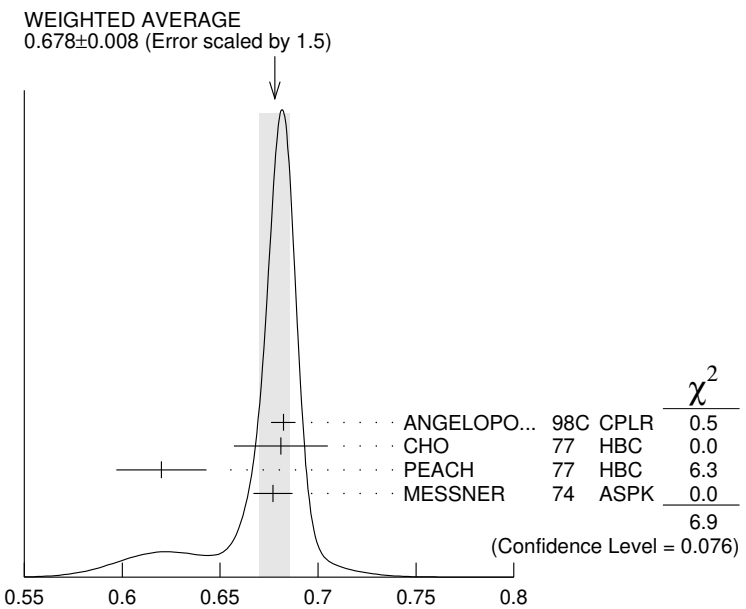
| | | | | | | |
|---|---|---|---|---|---|---|
| 0.69 ±0.07 | 192 | [41] | BALDO-... | 75 | HLBC | |
| 0.590 ±0.022 | 56k | [41] | BUCHANAN | 75 | SPEC | $a_u = -0.277 \pm 0.010$ |
| 0.619 ±0.027 | 20k | [41,42] | BISI | 74 | ASPK | $a_t = -0.282 \pm 0.011$ |
| 0.612 ±0.032 | | [41] | ALEXANDER | 73B | HBC | |
| 0.73 ±0.04 | 3200 | [41] | BRANDENB... | 73 | HBC | |
| 0.608 ±0.043 | 1486 | [41] | KRENZ | 72 | HLBC | $a_t = -0.277 \pm 0.018$ |

| | | | | | |
|---|---|---|---|---|---|
| 0.650 ±0.012 | 29k | [41] ALBROW | 70 | ASPK | $a_y = -0.858 \pm 0.015$ |
| 0.593 ±0.022 | 36k | [41,43] BUCHANAN | 70 | SPEC | $a_u = -0.278 \pm 0.010$ |
| 0.664 ±0.056 | 4400 | [41] SMITH | 70 | OSPK | $a_t = -0.306 \pm 0.024$ |
| 0.400 ±0.045 | 2446 | [41] BASILE | 68B | OSPK | $a_t = -0.188 \pm 0.020$ |
| 0.649 ±0.044 | 1350 | [41] HOPKINS | 67 | HBC | $a_t = -0.294 \pm 0.018$ |
| 0.428 ±0.055 | 1198 | [41] NEFKENS | 67 | OSPK | $a_u = -0.204 \pm 0.025$ |

[41] 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.

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

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




Linear coeff. *g* for $K_L^0 \to \pi^+\pi^-\pi^0$ matrix element squared

## QUADRATIC COEFFICIENT *h* FOR $K_L^0 \to \pi^+\pi^-\pi^0$

| 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 | [44] ALBROW | 70 | ASPK |
| 0.043±0.052 | 4400 | [44] SMITH | 70 | OSPK |

See notes in section "LINEAR COEFFICIENT *g* FOR $K_L^0 \to \pi^+\pi^-\pi^0$ |MATRIX ELEMENT|$^2$" above.

[44] 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 $K_L^0 \to \pi^+\pi^-\pi^0$

| *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 $K_L^0 \to \pi^+\pi^-\pi^0$ (*CP*-VIOLATING TERM)

Listed in *CP*-violation section below.

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

Listed in *CP*-violation section below.

## QUADRATIC COEFFICIENT $h$ FOR $K_L^0 \to \pi^0\pi^0\pi^0$

| *VALUE* (units $10^{-3}$) | *EVTS* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| **−5.0±1.4 OUR AVERAGE** Error includes scale factor of 1.7. | | | | |
| −6.1±0.9±0.5 | 14.7M | LAI | 01B | NA48 |
| −3.3±1.1±0.7 | 5M | [45] SOMALWAR | 92 | E731 |

[45] SOMALWAR 92 chose $m_{\pi^+}$ as normalization to make it compatible with the Particle Data Group $K_L^0 \to \pi^+\pi^-\pi^0$ 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.

$f_0 = f_+ + f_- t/(m_K^2 - m_\pi^2)$.

$\lambda_+$, $\lambda_-$, and $\lambda_0$ are the linear expansion coefficients of $f_+$, $f_-$, and $f_0$.

$\lambda_+$ refers to the $K^0_{\mu 3}$ value except in the $K^0_{e3}$ sections.

$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and $\lambda_+$ in $K^0_{\mu 3}$.

$d\lambda_0/d\lambda_+$ is the correlation between $\lambda_0$ and $\lambda_+$ in $K^0_{\mu 3}$.

$t$ = momentum transfer to the $\pi$ in units of $m_\pi^2$.

DP = Dalitz plot analysis.

PI = $\pi$ spectrum analysis.

MU = $\mu$ spectrum analysis.

POL= $\mu$ polarization analysis.

BR = $K^0_{\mu 3}/K^0_{e3}$ branching ratio analysis.

E = positron or electron spectrum analysis.

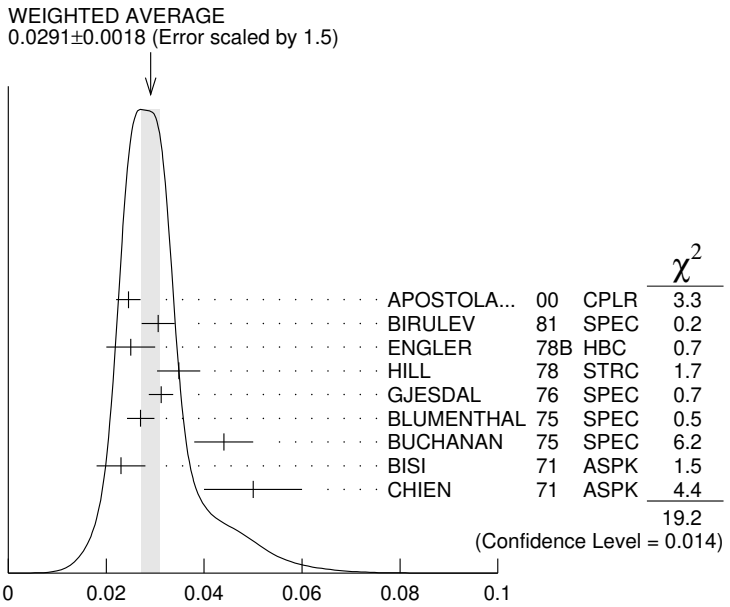
RC = radiative corrections.

## $\lambda_+$ (LINEAR ENERGY DEPENDENCE OF $f_+$ IN $K^0_{e3}$ DECAY)

For radiative correction of $K^0_{e3}$ DP, see GINSBERG 67 and BECHERRAWY 70. Results labeled OUR FIT are discussed in the review "$K^\pm_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors" in the $K^\pm$ Listings.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.0300±0.0020 OUR FIT** Error includes scale factor of 2.0. Assumes $\mu$-e universality. | | | | | |
| **0.0291±0.0018 OUR AVERAGE** Error includes scale factor of 1.5. See the ideogram below. | | | | | |
| 0.0245±0.0012±0.0022 | 366k | APOSTOLA... | 00 | CPLR | DP |
| 0.0306±0.0034 | 74k | BIRULEV | 81 | SPEC | DP |
| 0.025 ±0.005 | 12k | [46] ENGLER | 78B | HBC | DP |
| 0.0348±0.0044 | 18k | HILL | 78 | STRC | DP |
| 0.0312±0.0025 | 500k | GJESDAL | 76 | SPEC | DP |
| 0.0270±0.0028 | 25k | BLUMENTHAL | 75 | SPEC | DP |
| 0.044 ±0.006 | 24k | BUCHANAN | 75 | SPEC | DP |
| 0.023 ±0.005 | 42k | BISI | 71 | ASPK | DP |
| 0.05 ±0.01 | 16k | CHIEN | 71 | ASPK | DP, no RC |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.029 ±0.005 | 19k | [46] CHO | 80 | HBC | DP |
| 0.040 ±0.012 | 2171 | WANG | 74 | OSPK | DP |
| 0.045 ±0.014 | 5600 | ALBROW | 73 | ASPK | DP |
| 0.019 ±0.013 | 1871 | BRANDENB... | 73 | HBC | PI transv. |
| 0.022 ±0.014 | 1910 | NEUHOFER | 72 | ASPK | PI |
| 0.02 ±0.013 | 1000 | ARONSON | 68 | OSPK | PI |
| +0.023 ±0.012 | 4800 | BASILE | 68 | OSPK | DP, no RC |

[46] ENGLER 78B uses an unique $K_{e3}$ subset of CHO 80 events and is less subject to systematic effects.




$\lambda_+$ (Linear energy dependence of $f_+$, $K_{e3}$ decay)

## $\xi_A = f_-/f_+$ (determined from $K^0_{\mu 3}$ spectra)

Results labeled OUR FIT are discussed in the review "$K^\pm_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors" in the $K^\pm$ Listings. $\xi_A$ is $\xi(0)$ determined by Method $A$ of that review. The parameter $\xi(0)$ is redundant with $\lambda_0$ below and is not put into the Meson Summary Table.

| VALUE | $d\xi(0)/d\lambda_+$ | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **$-0.01\pm0.06$ OUR FIT** Error includes scale factor of 2.0. Correlation is $d\xi(0)/d\lambda_+ = -13.2$. Assumes $\mu$-$e$ universality. | | | | | | |
| **$-0.08\pm0.09$ OUR FIT** Error includes scale factor of 2.3. Correlation is $d\xi(0)/d\lambda_+ = -13.7$. | | | | | | |
| $-0.10\pm0.09$ | $-12$ | 150k | [47] BIRULEV | 81 | SPEC | DP |
| $+0.26\pm0.16$ | $-13$ | 14k | [48] CHO | 80 | HBC | DP |
| $+0.13\pm0.23$ | $-20$ | 16k | [48] HILL | 79 | STRC | DP |
| $-0.25\pm0.22$ | $-5.9$ | 32k | [49] BUCHANAN | 75 | SPEC | DP |
| $-0.11\pm0.07$ | $-17$ | 1.6M | [50] DONALDSON | 74B | SPEC | DP |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $-1.00\pm0.45$ | $-20$ | 1385 | [51] PEACH | 73 | HLBC | DP |
| $-1.5\ \pm0.7$ | $-28$ | 9086 | [52] ALBROW | 72 | ASPK | DP |
| $+0.50\pm0.61$ | unknown | 16k | [53] DALLY | 72 | ASPK | DP |
| $-3.9\ \pm0.4$ | | 3140 | [54] BASILE | 70 | OSPK | DP, indep of $\lambda_+$ |
| $-0.68^{+0.12}_{-0.20}$ | $-26$ | 16k | [53] CHIEN | 70 | ASPK | DP |
| $+1.2\ \pm0.8$ | $-18$ | 1341 | [55] CARPENTER | 66 | OSPK | DP |

[47] BIRULEV 81 error, $d\xi(0)/d\lambda_+$ calculated by us from $\lambda_0$, $\lambda_+$. $d\lambda_0/d\lambda_+ = 0$ used.

[48] HILL 79 and CHO 80 calculated by us from $\lambda_0$, $\lambda_+$, and $d\lambda_0/d\lambda_+$.

[49] BUCHANAN 75 is calculated by us from $\lambda_0$, $\lambda_+$ and $d\lambda_0/d\lambda_+$ because their appendix A value $-0.20 \pm 22$ assumes $\xi(t)$ constant, i.e. $\lambda_- = \lambda_+$.

[50] DONALDSON 74B gives $\xi = -0.11 \pm 0.02$ not including systematics. Above error and $d\xi(0)/d\lambda_+$ were calculated by us from $\lambda_0$ and $\lambda_+$ errors (which include systematics) and $d\lambda_0/d\lambda_+$.

[51] PEACH 73 gives $\xi(0) = -0.95 \pm 0.45$ for $\lambda_+ = \lambda_- = 0.025$ . The above value is for $\lambda_- = 0$. K.Peach, private communication (1974).

[52] ALBROW 72 fit has $\lambda_-$ free, gets $\lambda_- = -0.030 \pm 0.060$ or $\Lambda = +0.15^{+0.17}_{-0.11}$.

[53] CHIEN 70 errors are statistical only. $d\xi(0)/d\lambda_+$ from figure 4. DALLY 72 is a reanalysis of CHIEN 70. The DALLY 72 result is not compatible with assumption $\lambda_- = 0$ so not included in our fit. The nonzero $\lambda_-$ value and the relatively large $\lambda_+$ value found by DALLY 72 come mainly from a single low $t$ bin (figures 1,2). The ($f_+$,$\xi$) correlation was ignored. We estimate from figure 2 that fixing $\lambda_- = 0$ would give $\xi(0) = -1.4 \pm 0.3$ and would add 10 to $\chi^2$. $d\xi(0)/d\lambda_+$ is not given.

[54] BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

[55] CARPENTER 66 $\xi(0)$ is for $\lambda_+ = 0$. $d\xi(0)/d\lambda_+$ is from figure 9.

## $\xi_B = f_-/f_+$ (determined from $K^0_{\mu 3}/K^0_{e3}$)

The $K^0_{\mu 3}/K^0_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and $\lambda_+$ if $\mu$-$e$ universality is assumed. We quote the author's $\xi(0)$ and associated $\lambda_+$ but do not average because the $\lambda_+$ values differ. The result labeled OUR FIT below does not use these $\xi_b$ values. Instead it uses the authors $K^0_{\mu 3}/K^0_{e3}$ branching ratios to obtain the fitted $K^0_{\mu 3}/K^0_{e3}$ ratio which is then converted to the KL3FIT value below, as discussed in the review "$K^\pm_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors" in the $K^\pm$ Listings. $\xi_B$ is $\xi(0)$ determined by Method $B$ of that review. The parameter $\xi(0)$ is redundant with $\lambda_0$ below and is not put into the Meson Summary Table.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$-0.01 \pm 0.06$ OUR FIT** | Error includes scale factor of 2.0. Correlation is $d\xi/d\lambda_+ = -13.2$. Assumes $\mu$-$e$ universality. | | | | |
| $0.12 \pm 0.07$ | | [56] KL3FIT | 02 | RVUE | $\lambda_+ = 0.030$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $0.5 \pm 0.4$ | 6700 | BRANDENB... | 73 | HBC | BR, $\lambda_+ = 0.019 \pm 0.013$ |
| $-0.08 \pm 0.25$ | 1309 | [57] EVANS | 73 | HLBC | BR, $\lambda_+ = 0.02$ |
| $-0.5 \pm 0.5$ | 3548 | BASILE | 70 | OSPK | BR, $\lambda_+ = 0.02$ |
| $+0.45 \pm 0.28$ | 569 | BEILLIERE | 69 | HLBC | BR, $\lambda_+ = 0$ |
| $-0.22 \pm 0.30$ | 1309 | [57] EVANS | 69 | HLBC | |
| $+0.2\ ^{+0.8}_{-1.2}$ | | KULYUKINA | 68 | CC | BR, $\lambda_+ = 0$ |
| $+1.1 \pm 1.1$ | 389 | ADAIR | 64 | HBC | BR, $\lambda_+ = 0$ |
| $+0.66^{+0.9}_{-1.3}$ | | LUERS | 64 | HBC | BR, $\lambda_+ = 0$ |

[56] KL3FIT value is from fitted $K^0_{\mu 3}/K^0_{e3}$ branching ratio. $d\xi(0)/d\lambda_+ = -10.2$.

[57] EVANS 73 replaces EVANS 69.

## $\xi_C = f_-/f_+$ (determined from $\mu$ polarization in $K^0_{\mu 3}$)

The $\mu$ polarization is a measure of $\xi(t)$. No assumptions on $\lambda_{+-}$ are necessary, but $t$ (weighted by sensitivity to $\xi(t)$) should be specified. In $\lambda_+$, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+ = 0$. $d\xi/d\lambda = \xi t$. For radiative correction to $\mu$ polarization in $K^0_{\mu 3}$, see GINSBERG 73. Results labeled OUR FIT are discussed in the review "$K^\pm_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors" in the $K^\pm$ Listings. $\xi_C$ is $\xi(0)$ determined by Method $C$ of that review. The parameter $\xi(0)$ is redundant with $\lambda_0$ below and is not put into the Meson Summary Table.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$-0.01 \pm 0.06$ OUR FIT** | | | | | Error includes scale factor of 2.0. Correlation is $d\xi(0)/d\lambda_+ = -13.2$. Assumes $\mu$-$e$ universality. |
| **$-0.08 \pm 0.09$ OUR FIT** | | | | | Error includes scale factor of 2.3. Correlation is $d\xi(0)/d\lambda_+ = -13.7$. |
| $+0.178 \pm 0.105$ | 207k | [58] CLARK | 77 | SPEC | POL, $d\xi(0)/d\lambda_+ = +0.68$ |
| $-0.385 \pm 0.105$ | 2.2M | [59] SANDWEISS | 73 | CNTR | POL, $d\xi(0)/d\lambda_+ = -6$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $-1.81\ ^{+0.50}_{-0.26}$ | | [60] LONGO | 69 | CNTR | POL, $t$=3.3 |
| $-1.6 \pm 0.5$ | 638 | [61] ABRAMS | 68B | OSPK | Polarization |
| $-1.2 \pm 0.5$ | 2608 | [61] AUERBACH | 66B | OSPK | Polarization |

[58] CLARK 77 $t = +3.80$, $d\xi(0)/d\lambda_+ = \xi(t)t = 0.178 \times 3.80 = +0.68$.

[59] SANDWEISS 73 is for $\lambda_+ = 0$ and $t = 0$.

[60] LONGO 69 $t = 3.3$ calculated from $d\xi(0)/d\lambda_+ = -6.0$ (table 1) divided by $\xi = -1.81$.

[61] $t$ value not given.

## Im($\xi$) in $K^0_{\mu 3}$ DECAY (from transverse $\mu$ pol.)

Test of $T$ reversal invariance.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$-0.007 \pm 0.026$ OUR AVERAGE** | | | | | |
| $0.009 \pm 0.030$ | 12M | MORSE | 80 | CNTR | Polarization |
| $0.35 \pm 0.30$ | 207k | [62] CLARK | 77 | SPEC | POL, $t$=0 |
| $-0.085 \pm 0.064$ | 2.2M | [63] SANDWEISS | 73 | CNTR | POL, $t$=0 |
| $-0.02 \pm 0.08$ | | LONGO | 69 | CNTR | POL, $t$=3.3 |
| $-0.2 \pm 0.6$ | | ABRAMS | 68B | OSPK | Polarization |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $0.012 \pm 0.026$ | | SCHMIDT | 79 | CNTR | Repl. by MORSE 80 |

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

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

## $\lambda_+$ (LINEAR ENERGY DEPENDENCE OF $f_+$ IN $K^0_{\mu 3}$ DECAY)

See also the corresponding entries and notes in section "$\xi_A = f_-/f_+$" above and section "$\lambda_0$ (LINEAR ENERGY DEPENDENCE OF $f_0$ IN $K^0_{\mu 3}$ DECAY)" below. For radiative correction of $K^0_{\mu 3}$ Dalitz plot see GINSBERG 70 and BECHERRAWY 70. Results labeled OUR FIT are discussed in the review "$K^\pm_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors" in the $K^\pm$ Listings.

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.0300±0.0020 OUR FIT** | | Error includes scale factor of 2.0. Assumes $\mu$-e universality. | | | |
| **0.033 ±0.005 OUR FIT** | | Error includes scale factor of 2.3. | | | |
| 0.0427±0.0044 | 150k | BIRULEV | 81 | SPEC | DP |
| 0.028 ±0.010 | 14k | CHO | 80 | HBC | DP |
| 0.028 ±0.011 | 16k | HILL | 79 | STRC | DP |
| 0.046 ±0.030 | 32k | BUCHANAN | 75 | SPEC | DP |
| 0.030 ±0.003 | 1.6M | DONALDSON | 74B | SPEC | DP |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.0337±0.0033 | 129k | DZHORD... | 77 | SPEC | Repl. by BIRULEV 81 |
| 0.046 ±0.008 | 82k | ALBRECHT | 74 | WIRE | Repl. by BIRULEV 81 |
| 0.085 ±0.015 | 9086 | ALBROW | 72 | ASPK | DP |
| 0.11 ±0.04 | 16k | DALLY | 72 | ASPK | DP |
| 0.07 ±0.02 | 16k | CHIEN | 70 | ASPK | Repl. by DALLY 72 |

## $\lambda_0$ (LINEAR ENERGY DEPENDENCE OF $f_0$ IN $K^0_{\mu 3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of $\lambda_0$ using the associated $\lambda^\mu_+$ and $d\xi(0)/d\lambda_+$. Results labeled OUR FIT are discussed in the review "$K^\pm_{\ell 3}$ and $K^0_{\ell 3}$ Form Factors" in the $K^\pm$ Listings.

| VALUE | $d\lambda_0/d\lambda_+$ | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **0.030 ±0.005 OUR FIT** | Error includes scale factor of 2.0. Correlation is $d\lambda_0/d\lambda_+ = -0.12$. Assumes $\mu$-e universality. | | | | | |
| **0.027 ±0.006 OUR FIT** | Error includes scale factor of 2.3. Correlation is $d\lambda_0/d\lambda_+ = -0.17$. | | | | | |
| 0.040 ±0.006 | 0.13 | | [64] KL3FIT | 02 | RVUE | $\lambda_+ = 0.030$ |
| 0.0341±0.0067 | unknown | 150k | [65] BIRULEV | 81 | SPEC | DP |
| +0.050 ±0.008 | −0.11 | 14k | CHO | 80 | HBC | DP |
| +0.039 ±0.010 | −0.67 | 16k | HILL | 79 | STRC | DP |
| +0.047 ±0.009 | 1.06 | 207k | [66] CLARK | 77 | SPEC | POL |
| +0.025 ±0.019 | +0.5 | 32k | [67] BUCHANAN | 75 | SPEC | DP |
| +0.019 ±0.004 | −0.47 | 1.6M | [68] DONALDSON | 74B | SPEC | DP |
| −0.018 ±0.009 | +0.49 | 2.2M | [66] SANDWEISS | 73 | CNTR | POL |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.041 ±0.008 | | 14k | [69] CHO | 80 | HBC | BR, $\lambda_+ = 0.028$ |
| +0.0485±0.0076 | | 47k | DZHORD... | 77 | SPEC | In BIRULEV 81 |
| +0.024 ±0.011 | | 82k | ALBRECHT | 74 | WIRE | In BIRULEV 81 |
| +0.06 ±0.03 | | 6700 | [70] BRANDENB... | 73 | HBC | BR, $\lambda_+ = 0.019 \pm 0.013$ |
| −0.060 ±0.038 | −0.71 | 1385 | [71] PEACH | 73 | HLBC | DP |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $-0.043$ | $\pm 0.052$ | $-1.39$ | 9086 | [72] ALBROW | 72 | ASPK | DP |
| $-0.067$ | $\pm 0.227$ | unknown | 16k | [73] DALLY | 72 | ASPK | DP |
| $-0.333$ | $\pm 0.034$ | $+1.$ | 3140 | [74] BASILE | 70 | OSPK | DP |
| $-0.140$ | $^{+0.043}_{-0.022}$ | $+0.49$ | | [66] LONGO | 69 | CNTR | POL |
| $+0.08$ | $\pm 0.07$ | $-0.54$ | 1371 | [66] CARPENTER | 66 | OSPK | DP |

[64] KL3FIT 02 value is from our fitted value of the $K^{\pm}_{\mu 3}/K^{\pm}_{e3}$ branching ratio. Assumes $\mu - e$ universality.

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

[66] $\lambda_0$ value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[67] BUCHANAN 75 value is from their appendix A and uses only $K_{\mu 3}$ data. $d\lambda_0/d\lambda_+$ was obtained by private communication, C.Buchanan, 1976.

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

[69] CHO 80 BR result not independent of their Dalitz plot result.

[70] Fit for $\lambda_0$ does not include this value but instead includes the $K_{\mu 3}/K_{e3}$ result from this experiment.

[71] PEACH 73 assumes $\lambda_+ = 0.025$. Calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[72] ALBROW 72 $\lambda_0$ is calculated by us from $\xi_A$, $\lambda_+$ and $d\xi(0)/d\lambda_+$. They give $\lambda_0 = -0.043 \pm 0.039$ for $\lambda_- = 0$. We use our larger calculated error.

[73] DALLY 72 gives $f_0 = 1.20 \pm 0.35$, $\lambda_0 = -0.080 \pm 0.272$, $\lambda_0{}' = -0.006 \pm 0.045$, but with a different definition of $\lambda_0$. Our quoted $\lambda_0$ is his $\lambda_0/f_0$. We cannot calculate true $\lambda_0$ error without his ($\lambda_0$,$f_0$) correlations. See also note on DALLY 72 in section $\xi_A$.

[74] BASILE 70 $\lambda_0$ is for $\lambda_+ = 0$. Calculated by us from $\xi_A$ with $d\xi(0)/d\lambda_+ = 0$. BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

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

Ratio of scalar to $f_+$ couplings.

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **<0.04** | 68 | 25k | BLUMENTHAL 75 | | SPEC | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| <0.095 | 95 | 18k | HILL | 78 | STRC | |
| <0.07 | 68 | 48k | BIRULEV | 76 | SPEC | See also BIRULEV 81 |
| <0.19 | 95 | 5600 | ALBROW | 73 | ASPK | |
| <0.15 | 68 | | KULYUKINA | 67 | CC | |

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

Ratio of tensor to $f_+$ couplings.

| VALUE | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **<0.23** | 68 | 25k | BLUMENTHAL 75 | | SPEC | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| <0.40 | 95 | 18k | HILL | 78 | STRC | |
| <0.34 | 68 | 48k | BIRULEV | 76 | SPEC | See also BIRULEV 81 |
| <1.0 | 95 | 5600 | ALBROW | 73 | ASPK | |
| <1.0 | 68 | | KULYUKINA | 67 | CC | |

### $|f_T/f_+|$ FOR $K^0_{\mu 3}$ DECAY

Ratio of tensor to $f_+$ couplings.

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| **0.12±0.12** | BIRULEV | 81 | SPEC |

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

$\alpha_{K^*}$ 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** | | | | |
| $-0.36 \pm 0.06 \pm 0.02$ | 6864 | FANTI | 99B | NA48 |
| $-0.28 \pm 0.13$ | | BARR | 90B | NA31 |
| $-0.280^{+0.099}_{-0.090}$ | | OHL | 90B | B845 |

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

$\alpha_{K^*}$ 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 |

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

$\alpha^{\rm eff}_{K^*}$ 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 |

### DECAY FORM FACTORS FOR $K^0_L \to \pi^\pm \pi^0 e^\mp \nu_e$

Given in MAKOFF 93.

### $a_V$, VECTOR MESON EXCHANGE CONTRIBUTION

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **−0.72±0.07 OUR AVERAGE** | | | | |
| $-0.67 \pm 0.21 \pm 0.12$ | ALAVI-HARATI | 01E | KTEV | $K^0_L \to \pi^0 e^+ e^- \gamma$ |
| $-0.72 \pm 0.05 \pm 0.06$ | ALAVI-HARATI | 99B | KTEV | $K^0_L \to \pi^0 2\gamma$ |

## FITS FOR $K^0_L$ $CP$-VIOLATION PARAMETERS

Revised May 2002 by T.G. Trippe (LBNL).

In recent years, $K^0_L$ $CP$-violation experiments have improved our knowledge of $CP$-violation parameters and their

consistency with the expectations of $CPT$ invariance and unitarity. For definitions of $K^0_L$ $CP$-violation parameters and a brief discussion of the theory, see the article "$CP$ Violation" by L. Wolfenstein in the *Reviews, Tables, and Plots* section of this *Review*.

This note describes our two types of fits for the $CP$-violation parameters in $K^0_L \to \pi^+\pi^-$ and $\pi^0\pi^0$ decay, one for the phases $\phi_{+-}$ and $\phi_{00}$ jointly with $\Delta m$ and $\tau_S$, and the other for the amplitudes $|\eta_{+-}|$ and $|\eta_{00}|$ jointly with the $K^0_L \to \pi\pi$ branching fractions. In this edition, phase fits are done without and with the assumption of CPT invariance, the latter giving a significant improvement in the precision of $\Delta m$ and $\tau_S$.

***Fit to $\phi_{+-}$, $\phi_{00}$, $\Delta\phi$, $\Delta m$, and $\tau_S$ data***: This is a joint fit to the data on $\phi_{+-}$, $\phi_{00}$, the phase difference $\Delta\phi = \phi_{00} - \phi_{+-}$, the $K^0_L - K^0_S$ mass difference $\Delta m$, and the $K^0_S$ mean life $\tau_S$, including the effects of correlations. Measurements of $\phi_{+-}$ and $\phi_{00}$ are highly correlated with $\Delta m$ and $\tau_S$. Some measurements of $\tau_S$ are correlated with $\Delta m$. The correlations are given in the footnotes of the $\phi_{+-}$ and $\phi_{00}$ sections of the $K^0_L$ Particle Listings and the $\tau_S$ section of the $K^0_S$ Particle listings. In editions of the Review prior to 1996, we adjusted the experimental values of $\phi_{+-}$ and $\phi_{00}$ to account for correlations with $\Delta m$ and $\tau_S$ but did not include the effects of these correlations when evaluating $\Delta m$ and $\tau_S$. In 1996, we introduced a joint fit including these correlations. In the joint fit, the $\phi_{+-}$ measurements have a strong influence on the fitted value of $\Delta m$. This is because the CERN NA31 vacuum regeneration experiments (CAROSI 90 [1] and GEWENIGER 74B [2]), the Fermilab E773/E731 regenerator experiments (SCHWINGENHEUER 95 [3] and GIBBONS 93 [4]), and the CPLEAR $K^0 - \overline{K}^0$ asymmetry experiment (APOSTOLAKIS 99C [5]) have

very different dependences of $\phi_{+-}$ on $\Delta m$, as can be seen from their diagonal bands e, d, b, c, and a, respectively, in Fig. 1.

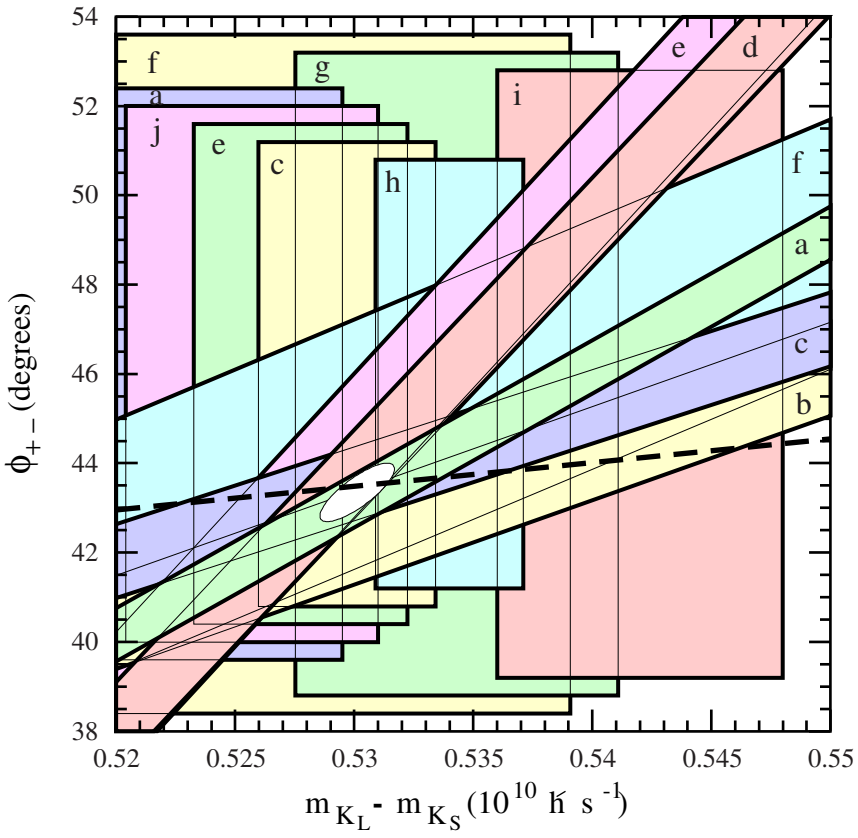



**Figure 1:** $\phi_{+-}$ vs $\Delta m$ for experiments which do not assume CPT invariance. $\Delta m$ measurements appear as vertical bands spanning $\Delta m \pm 1\sigma$, cut near the top and bottom to aid the eye. The $\phi_{+-}$ measurements appear as diagonal bands spanning $\phi_{+-} \pm \sigma_\phi$. The dashed line shows $\phi$(superweak). The ellipse shows the $1\sigma$ contour of the fit result. Data are labeled by letters and cited in Table 1.

**Table 1:** References for data in the figures and fits. The letters in the first four columns label the bands in Fig. 1 and Fig. 2. Columns 1 and 3 label the diagonal $\phi_{+-}$ bands while columns 2 and 4 label the vertical $\Delta m$ and $\tau_S$ bands. A check (✓) in a column means that the data are excluded from the figures because they assume CPT. The data are given in the $\phi_{+-}$ and $\Delta m$ sections of the $K_L$ Particle Listings, and the $\tau_S$ section of the $K_S$ Particle Listings, unless otherwise footnoted.

Location of input data

| Fig. 1 | | Fig. 2 | | | |
|---|---|---|---|---|---|
| $\phi_{+-}$ | $\Delta m$ | $\phi_{+-}$ | $\tau_S$ | PDG Document ID | Ref. |
| a | a | a | | APOSTOLAKIS 99C | [5] |
| b | | b | ✓ | GIBBONS 93 | [4] |
| c | c | c | ✓ | SCHWINGENHEUER 95 | [3] |
| d | | d | d | GEWENIGER 74B | [2] |
| e | e* | e | e* | CAROSI 90 | [1] |
| f | f† | f | f | CARITHERS 75 | [8] |
| | g | | | ANGELOPOULOS 01 | [9] |
| | h | | | GEWENIGER 74C | [7] |
| | i | | | CULLEN 70 | [6] |
| | j | | | GIBBONS 93C | [10] |
| | ✓ | | | ANGELOPOULOS 98D | [11] |
| | ✓ | | | GJESDAL 74 | [12] |
| | | | k | BERTANZA 97 | [13] |
| | | | l | GROSSMAN 87 | [14] |
| | | | m | SKJEGGESTAD 72 | [15] |

* from $\phi_{00}(\Delta m, \tau_S)$ in $\phi_{00}$ Particle Listings.

† from $\tau_S(\Delta m)$ in $\tau_S$ Particle Listings.

The region where the $\phi_{+-}$ bands from these experiments cross gives a powerful measurement of $\Delta m$ which decreases the fitted $\Delta m$ value relative to our pre-1996 average $\Delta m$ and earlier measurements such as CULLEN 70 [6] and GEWENIGER 74C [7], i and h respectively in Fig. 1. This decrease brings the $\Delta m$-dependent $\phi_{+-}$ measurements into good agreement with each other and with $\phi$(superweak), where

$$\phi(\text{superweak}) = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right) = \tan^{-1}\left(\frac{2\Delta m \tau_S \tau_L}{\hbar(\tau_L - \tau_S)}\right) \ , \quad (1)$$

which is shown as a dashed line in Fig. 1 and Fig. 2. In this edition, we have taken care in these figures to exclude experiments which assume CPT invariance. This was not the case in the 2000 edition of the *Review* and earlier editions.

Table 2 column 2, "Fit w/o CPT," gives the resulting fitted parameters, while Table 3 gives the correlation matrix for this fit. The $\chi^2 = 1$ contour for the fit result is shown as a white ellipse in Fig. 1 and Fig. 2. The fit is seen to be consistent with the $\phi$(superweak) dashed line.

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.

If CPT invariance is assumed, four experimental results, those indicated by a check (✓) in column 2 or 4 of Table 1, are added to the fit. In addition, we require that $\phi_{+-} = \phi_{00} = \phi$(superweak). The result is shown in Table 2 column 3, "Fit w/ CPT," and the correlation matrix is shown in Table 4. The resulting $\phi_{+-}$ and $\phi_{00}$ are just $\phi$(superweak) from Eq. (1), evaluated for $\Delta m$ and $\tau_S$ from this fit. The $\Delta m$ and $\tau_S$ precision are improved significantly by the CPT assumption.

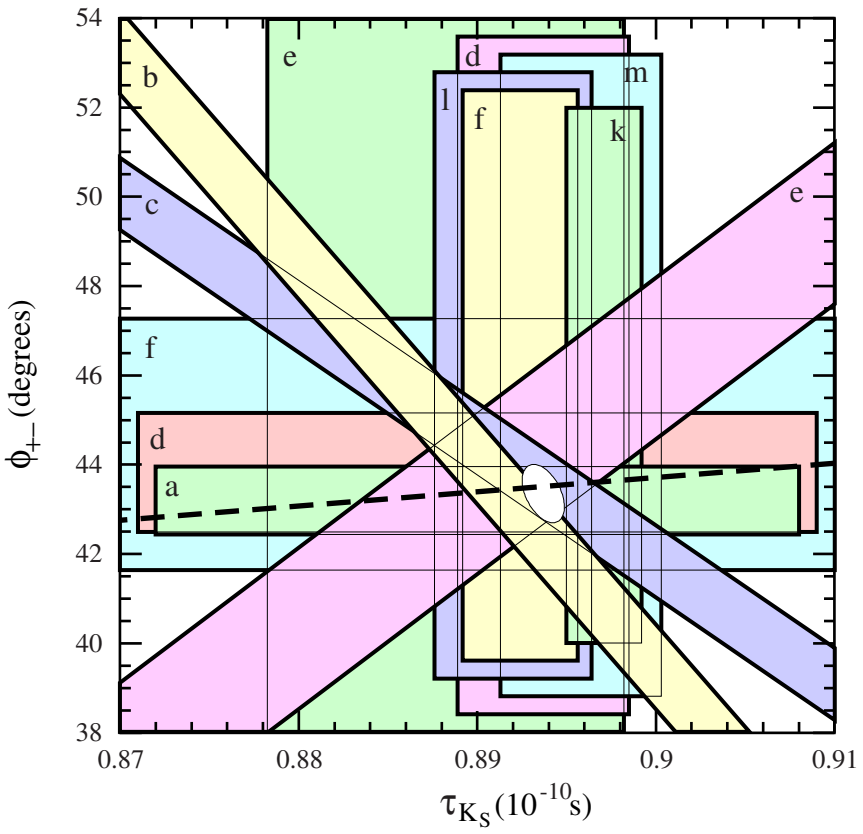



**Figure 2:** $\phi_{+-}$ vs $\tau_S$. $\tau_S$ measurements appear as vertical bands spanning $\tau_S \pm 1\sigma$, some of which are cut near the top and bottom to aid the eye. The $\phi_{+-}$ measurements appear as diagonal or horizontal bands spanning $\phi_{+-} \pm \sigma_\phi$. The dashed line shows $\phi$(superweak). The ellipse shows the fit result's $1\sigma$ contour. Data are labeled by letters and cited in Table 1.

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

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

**Table 2:** Fit results for $\phi_{+-}$, $\phi_{00}$, $\phi_{00} - \phi_{+-}$, $\Delta m$, and $\tau_S$ without and with CPT assumption.

| Quantity(units) | Fit w/o CPT | Fit w/ CPT |
|---|---|---|
| $\phi_{+-}(^\circ)$ | $43.4 \pm 0.7$ | $43.51 \pm 0.06$ |
| $\Delta m(10^{10}\hbar\ \mathrm{s}^{-1})$ | $0.5301 \pm 0.0016$ | $0.5303 \pm 0.0009$ |
| $\tau_S(10^{-10}\mathrm{s})$ | $0.8937 \pm 0.0012$ | $0.8935 \pm 0.0008$ |
| $\phi_{00}(^\circ)$ | $43.2 \pm 1.0$ | $43.51 \pm 0.06$ |
| $\Delta\phi(^\circ)$ | $-0.1 \pm 0.8$ | $- - - - - --$ |
| $\chi^2$ | 13.6 | 14.5 |
| No. Deg. Freedom | 16 | 21 |

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

| | $\phi_{+-}$ | $\Delta m$ | $\tau_S$ | $\phi_{00}$ | $\Delta\phi$ |
|---|---|---|---|---|---|
| $\phi_{+-}$ | 1.00 | 0.80 | −0.45 | 0.62 | −0.02 |
| $\Delta m$ | 0.80 | 1.00 | −0.33 | 0.54 | 0.04 |
| $\tau_S$ | −0.45 | −0.33 | 1.00 | −0.25 | 0.05 |
| $\phi_{00}$ | 0.62 | 0.54 | −0.25 | 1.00 | 0.78 |
| $\Delta\phi$ | −0.02 | 0.04 | 0.05 | 0.78 | 1.00 |

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

| | $\phi_{+-}$ | $\Delta m$ | $\tau_S$ | $\phi_{00}$ |
|---|---|---|---|---|
| $\phi_{+-}$ | 1.00 | 0.90 | 0.49 | 1.00 |
| $\Delta m$ | 0.90 | 1.00 | 0.06 | 0.90 |
| $\tau_S$ | 0.49 | 0.06 | 1.00 | 0.49 |
| $\phi_{00}$ | 1.00 | 0.90 | 0.49 | 1.00 |

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

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

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

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 $\epsilon'/\epsilon$ 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 $\epsilon'/\epsilon$ 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 02. 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 02 values) are used along with the $K_L^0$ and $K_S^0$ mean lives and the $K_S^0 \to \pi\pi$ branching fractions to compute the $K_L^0$ branching ratios $\Gamma(K_L^0 \to \pi^+\pi^-)/\Gamma(\text{total})$ and $\Gamma(K_L^0 \to \pi^0\pi^0)/\Gamma(K_L^0 \to \pi^+\pi^-)$. These branching ratio values are included as measurements in the branching ratio section with a document ID of ETAFIT 02. Thus the $K_L^0$ branching ratio fit values in this edition include the results of direct measurements of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$,

and $\epsilon'/\epsilon$. A more detailed discussion of these fits is given in the 1990 edition of this *Review* [16].

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## *CP*-VIOLATION PARAMETERS IN $K^0_L$ DECAYS

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

Such asymmetry violates *CP*. It is related to Re($\epsilon$).

#### $\delta_L$ = weighted average of $\delta_L(\mu)$ and $\delta_L(e)$

| VALUE (%) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.327±0.012 OUR AVERAGE** | | Includes data from the 2 datablocks that follow this one. | | | |
| 0.333±0.050 | 33M | WILLIAMS | 73 | ASPK | $K_{\mu 3}$ + $K_{e3}$ |

#### $\delta_L(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \overline{\nu}_\mu)]$/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 | [75] PACIOTTI | 69 | OSPK |
| 0.403±0.134 | 1M | [75] DORFAN | 67 | OSPK |

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

#### $\delta_L(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \overline{\nu}_e)]$/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. | | | | |
| **0.333±0.014 OUR AVERAGE** | | | | |
| 0.341±0.018 | 34M | GEWENIGER | 74 | ASPK |
| 0.318±0.038 | 40M | FITCH | 73 | ASPK |
| 0.346±0.033 | 10M | MARX | 70 | CNTR |
| 0.246±0.059 | 10M | [76] SAAL | 69 | CNTR |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.36 ±0.18 | 600k | ASHFORD | 72 | ASPK |
| 0.224±0.036 | 10M | [76] BENNETT | 67 | CNTR |

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

### PARAMETERS FOR $K^0_L \to 2\pi$ DECAY

$\eta_{+-} = A(K^0_L \to \pi^+ \pi^-) / A(K^0_S \to \pi^+ \pi^-)$
$\eta_{00} = A(K^0_L \to \pi^0 \pi^0) / A(K^0_S \to \pi^0 \pi^0)$

The fitted values of $|\eta_{+-}|$ and $|\eta_{00}|$ given below are the results of a fit to $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and Re($\epsilon'/\epsilon$). Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from the fitted values of the $K^0_L \to$

$\pi\pi$ 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 "Fits for $K^0_L$ *CP*-Violation Parameters" above for details.

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

| *VALUE* (units $10^{-3}$) | | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **2.274±0.017 OUR FIT** | | | | | |
| **2.23 ±0.11 OUR AVERAGE** | | | | | |
| 2.12 ±0.16 | | [77] BRFIT | 02 | | |
| 2.47 ±0.31 ±0.24 | | ANGELOPO... | 98 | CPLR | |
| 2.33 ±0.18 | | CHRISTENS... | 79 | ASPK | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 2.49 ±0.40 | | [78] ADLER | 96B | CPLR | Sup. by ANGELOPOULOS 98 |
| 2.71 ±0.37 | | [79] WOLFF | 71 | OSPK | Cu reg., 4$\gamma$'s |
| 2.95 ±0.63 | | [79] CHOLLET | 70 | OSPK | Cu reg., 4$\gamma$'s |

[77] This BRFIT value is computed from fitted values of the $K^0_L$ and $K^0_S$ lifetimes and branching fractions to $\pi\pi$. See the discussion in the note "Fits for $K^0_L$ *CP*-Violation Parameters."

[78] Error is statistical only.

[79] CHOLLET 70 gives $|\eta_{00}| = (1.23 \pm 0.24)\times$(regeneration amplitude, 2 GeV/$c$ Cu)/10000mb. WOLFF 71 gives $|\eta_{00}| = (1.13 \pm 0.12)\times$(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).

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

| *VALUE* (units $10^{-3}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **2.286±0.017 OUR FIT** | | | | | |
| **2.287±0.017 OUR AVERAGE** | | | | | |
| 2.292±0.024 | | [80] BRFIT | 02 | | |
| 2.264±0.023±0.027 | 70M | [81] APOSTOLA... | 99C | CPLR | $K^0$-$\overline{K}^0$ asymmetry |
| 2.30 ±0.035 | | GEWENIGER | 74B | ASPK | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 2.310±0.043±0.031 | | [82] ADLER | 95B | CPLR | $K^0$-$\overline{K}^0$ asymmetry |
| 2.32 ±0.14 ±0.03 | $10^5$ | ADLER | 92B | CPLR | $K^0$-$\overline{K}^0$ asymmetry |

[80] This BRFIT value is computed from fitted values of the $K^0_L$ and $K^0_S$ lifetimes and branching fractions to $\pi\pi$. See the discussion in the note "Fits for $K^0_L$ *CP*-Violation Parameters."

[81] APOSTOLAKIS 99C report $(2.264 \pm 0.023 \pm 0.026 + 9.1[\tau_s - 0.8934]) \times 10^{-3}$. We evaluate for our 1998 best value $\tau_s = (0.8934 \pm 0.0008) \times 10^{-10}$ s.

[82] 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 $\Delta m = (0.5304 \pm 0.0014) \times 10^{-10}\ \hbar\text{s}^{-1}$ and $\tau_s = (0.8927 \pm 0.0009) \times 10^{-10}$ s. Superseded by APOSTOLAKIS 99C.

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

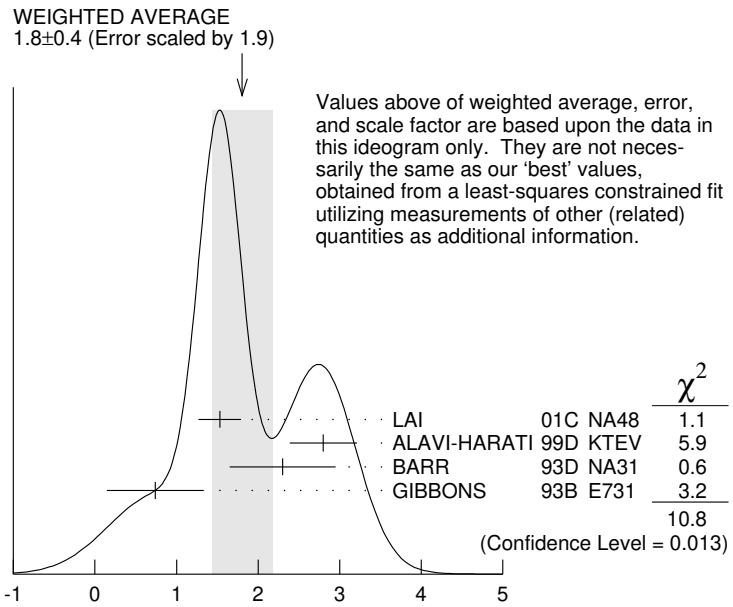
| VALUE | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **0.9946±0.0013 OUR FIT** Error includes scale factor of 2.3. | | | | |
| **0.9930±0.0020 OUR AVERAGE** | | | | |
| 0.9931±0.0020 | | [83,84] BARR | 93D | NA31 |
| 0.9904±0.0084±0.0036 | | [85] WOODS | 88 | E731 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.9939±0.0013±0.0015 | 1M | [83] BARR | 93D | NA31 |
| 0.9899±0.0020±0.0025 | | [83] BURKHARDT | 88 | NA31 |

[83] This is the square root of the ratio $R$ given by BURKHARDT 88 and BARR 93D.
[84] This is the combined results from BARR 93D and BURKHARDT 88, taking into account a common systematic uncertainty of 0.0014.
[85] We calculate $|\eta_{00}/\eta_{+-}| = 1-3(\epsilon'/\epsilon)$ from WOODS 88 $(\epsilon'/\epsilon)$ value.

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

| VALUE (units $10^{-3}$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **1.8 ±0.4 OUR FIT** Error includes scale factor of 2.3. | | | | |
| **1.8 ±0.4 OUR AVERAGE** Error includes scale factor of 1.9. See the ideogram below. | | | | |
| 1.53±0.26 | | LAI | 01C | NA48 |
| 2.80±0.30±0.28 | [86] | ALAVI-HARATI | 99D | KTEV |
| 2.3 ±0.65 | [87,88] | BARR | 93D | NA31 |
| 0.74±0.52±0.29 | | GIBBONS | 93B | E731 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1.85±0.45±0.58 | | FANTI | 99C | NA48 In LAI 01C |
| 2.0 ±0.7 | [89] | BARR | 93D | NA31 |
| −0.4 ±1.4 ±0.6 | | PATTERSON | 90 | E731 in GIBBONS 93B |
| 3.3 ±1.1 | [89] | BURKHARDT | 88 | NA31 |
| 3.2 ±2.8 ±1.2 | [87] | WOODS | 88 | E731 |

[86] As part of an improved analysis of a 4 times larger data sample, KTeV has reanalyzed the data sample reported here and finds a somewhat lower value of $\mathrm{Re}(\epsilon'/\epsilon) = (2.32 \pm 0.44) \times 10^{-3}$. The new analysis, including this updated result, is being prepared for publication. See for example, GLAZOV 01 or KESSLER 01.
[87] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements. They enter the average in this section but enter the fit via the $|\eta_{00}/\eta_{+-}|$ section only.
[88] This is the combined results from BARR 93D and BURKHARDT 88, taking into account their common systematic uncertainty.
[89] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements.




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

## $\phi_{+-}$, PHASE of $\eta_{+-}$

The dependence of the phase on $\Delta m$ and $\tau_S$ is given for each experiment in the comments below, where $\Delta m$ is the $K_L^0 - K_S^0$ mass difference in units $10^{10}\ \hbar\mathrm{s}^{-1}$ and $\tau_s$ is the $K_S$ mean life in units $10^{-10}$ s. For the "used" data, we have evaluated these mass dependences using our 2002 values not assuming *CPT*, $\Delta m = 0.5301 \pm 0.0016$, $\tau_s = 0.8937 \pm 0.0012$ to obtain the values quoted below. We also give the regeneration phase $\phi_f$ in the comments below.

OUR FIT is described in the note on "Fits for $K_L^0$ *CP*-Violation Parameters" in the $K_L^0$ Particle Listings.

| *VALUE* (°) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **43.51±0.06 OUR FIT** | Assuming *CPT* | | | | |
| **43.4 ±0.7 OUR FIT** | Not assuming *CPT* | | | | |
| 43.2 ±0.8 | 70M | [90] APOSTOLA... | 99C | CPLR | $K^0$-$\overline{K}^0$ asymmetry |
| 43.6 ±0.9 | | [91,92] SCHWINGEN... | 95 | E773 | $CH_{1.1}$ regenerator |
| 42.4 ±1.1 | | [92,93] GIBBONS | 93 | E731 | $B_4C$ regenerator |
| 44.5 ±1.8 | | [94] CAROSI | 90 | NA31 | Vacuum regen. |
| 44.5 ±2.8 | | [95] CARITHERS | 75 | SPEC | C regenerator |
| 43.8 ±1.3 | | [96] GEWENIGER | 74B | ASPK | Vacuum regen. |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 43.82±0.63 | | [97,98] ADLER | 96C | RVUE | |
| 43.6 ±1.2 | | [99] ADLER | 95B | CPLR | $K^0$-$\overline{K}^0$ asymmetry |
| 42.3 ±4.4 ±1.4 | $10^5$ | [100] ADLER | 92B | CPLR | $K^0$-$\overline{K}^0$ asymmetry |
| 47.7 ±2.0 ±0.9 | | [92,101] KARLSSON | 90 | E731 | |

[90] APOSTOLAKIS 99C report $(43.19 \pm 0.53 \pm 0.28)^\circ + 300\ [\Delta m - 0.5301]^\circ$.

[91] SCHWINGENHEUER 95 reports $\phi_{+-} = 43.53 \pm 0.76 + 173[\Delta m - 0.5282] - 275[\tau_S - 0.8926]$.

[92] These experiments measure $\phi_{+-} - \phi_f$ 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 $0.35^\circ$ [$0.5^\circ$] for uncertainties in their modeling of the regeneration amplitude. See the discussion of these systematic errors, including criticism that they could be underestimated, in the note on "$C$ violation in $K^0_L$ decay."

[93] GIBBONS 93 measures $\phi_+ - \phi_f$ and calculates the regeneration phase $\phi_f$ from the power law momentum dependence of the regeneration amplitude using analyticity. An error of $0.6^\circ$ is included for possible uncertainties in the regeneration phase. They find $\phi_{+-} = 42.21 \pm 0.9 + 189\ [\Delta m - 0.5257] - 460\ [\tau_S - 0.8922]^\circ$, as given in SCHWINGENHEUER 95, footnote 8. GIBBONS 93 reports $\phi_{+-}\ (42.2 \pm 1.4)^\circ$

[94] CAROSI 90 $\phi_{+-} = 46.9 \pm 1.4 \pm 0.7 + 579\ [\Delta m - 0.5351] + 303\ [\tau_S - 0.8922]^\circ$.

[95] CARITHERS 75 $\phi_{+-} = (45.5 \pm 2.8) + 224[\Delta m - 0.5348]^\circ$. $\phi_f = -40.9 \pm 2.6^\circ$.

[96] GEWENIGER 74B $\phi_{+-} = (49.4 \pm 1.0) + 565[\Delta m - 0.540]^\circ$.

[97] ADLER 96C fit gives $(43.82 \pm 0.41)^\circ + 339(\Delta m - 0.5307)^\circ - 252(\tau_S - 0.8922)^\circ$.

[98] 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)).

[99] ADLER 95B report $42.7^\circ \pm 0.9^\circ \pm 0.6^\circ + 316[\Delta m - 0.5274]^\circ + 30[\tau_S - 0.8926]^\circ$.

[100] ADLER 92B quote separately two systematic errors: $\pm 0.4$ from their experiment and $\pm 1.0$ degrees due to the uncertainty in the value of $\Delta m$.

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

## $\phi_{00}$, PHASE OF $\eta_{00}$

See comment in $\phi_{+-}$ header above for treatment of $\Delta m$ and $\tau_S$ dependence.

OUR FIT is described in the note on "Fits for $K^0_L$ $CP$-Violation Parameters" in the $K^0_L$ Particle Listings.

| *VALUE* (°) | | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **43.51±0.06 OUR FIT** | Assuming *CPT* | | | | |
| **43.2 ±1.0 OUR FIT** | Not assuming *CPT* | | | | |
| 41.9 ±5.9 | | [102] ANGELOPO... | 98 | CPLR | |
| 44.6 ±2.5 | | [103] CAROSI | 90 | NA31 | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 50.8 ±7.1 ±1.7 | | [104] ADLER | 96B | CPLR | Sup. by ANGELOPOULOS 98 |
| 47.4 ±1.4 ±0.9 | | [105] KARLSSON | 90 | E731 | |

[102] ANGELOPOULOS 98 $\phi_{00} = 42.0 \pm 5.6 \pm 1.9 + 240[\Delta m - 0.5307]$ with negligible $\tau_S$ dependence.

[103] CAROSI 90 $\phi_{00} = 47.1 \pm 2.1 \pm 1.0 + 579\ [\Delta m - 0.5351] + 252\ [\tau_S - 0.8922]^\circ$.

[104] ADLER 96B identified initial neutral kaon individually as being a $K^0$ or a $\overline{K}^0$. The systematic uncertainty is $\pm 1.5^\circ$ combined in quadrature with $\pm 0.8^\circ$ due to $\Delta m$.

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

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

Test of *CPT*.

OUR FIT is described in the note on "Fits for $K^0_L$ *CP*-Violation Parameters" in the $K^0_L$ Particle Listings.

| VALUE (°) | | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0** | **OUR FIT** | Assuming *CPT* | | | |
| **−0.1 ±0.8** | **OUR FIT** | Not assuming *CPT* | | | |
| **−0.3 ±0.8** | **OUR AVERAGE** | | | | |
| −0.30±0.88 | | [106] SCHWINGEN...95 | | | Combined E731, E773 |
| 0.2 ±2.6 ±1.2 | | [107] CAROSI | 90 | NA31 | |
| • • • 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 | | [108] GIBBONS | 93 | E731 | |
| −0.3 ±2.4 ±1.2 | | KARLSSON | 90 | E731 | |

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

[107] CAROSI 90 is excluded from the fit because it it is not independent of $\phi_{+-}$ and $\phi_{00}$ values.

[108] 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 $m_{K^0_L} - m_{K^0_S}$).

## 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 $\phi$ is the angle between the $e^+e^-$ and $\pi^+\pi^-$ planes in the $K^0_L$ rest frame.

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

| VALUE (%) | DOCUMENT ID | TECN |
|---|---|---|
| **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 $\phi$ distribtuion, where $\phi$ is the angle between the planes of the two $e^+e^-$ paris in the kaon rest frame:

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

### $\beta_{CP}$ from $K_L \to e^+e^-e^+e^-$

| VALUE | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| **−0.23±0.09±0.02** | 441 | ALAVI-HARATI 01D | KTEV | $M_{ee}$ >8 MeV/$c^2$ |

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

| VALUE | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|
| **−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 $K_L^0 \to \pi^+\pi^-\pi^0$ above.

See also note on Dalitz plot parameters in $K^\pm$ section and note on *CP* violation in $K_L^0$ decay above.

#### LINEAR COEFFICIENT *j* FOR $K_L^0 \to \pi^+\pi^-\pi^0$

| VALUE | EVTS | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **0.0011±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 $K_L^0 \to \pi^+\pi^-\pi^0$

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

### PARAMETERS for $K_L^0 \to \pi^+\pi^-\gamma$ DECAY

#### $|\eta_{+-\gamma}| = |A(K_L^0 \to \pi^+\pi^-\gamma, \textit{CP violating})/A(K_S^0 \to \pi^+\pi^-\gamma)|$

| 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 $K_L^0 \to \pi^+\pi^-\gamma$

| VALUE | CL% | EVTS | | DOCUMENT ID | | TECN |
|---|---|---|---|---|---|---|
| **<0.3** | 90 | 3671 | [109] | RAMBERG | 93B | E731 |

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

## $\Delta S = \Delta Q$ 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 $\mathrm{Re}\{x\}$ and $\mathrm{Im}\{x\}$ for $K_{e3}$ and $K_{\mu 3}$ 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 |
|---|---|---|---|---|---|
| **$= 0.0018 \pm 0.0041 \pm 0.0045$** | | 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 | $\pi^- p \to K^0 \Lambda$ |
| $0.04 \pm 0.03$ | 4724 | NIEBERGALL | 74 | ASPK | $K^+ p \to K^0 p \pi^+$ |
| $-0.008 \pm 0.044$ | 1757 | FACKLER | 73 | OSPK | $K_{e3}$ from $K^0$ |
| $-0.03 \pm 0.07$ | 1367 | HART | 73 | OSPK | $K_{e3}$ from $K^0 \Lambda$ |
| $-0.070 \pm 0.036$ | 1079 | MALLARY | 73 | OSPK | $K_{e3}$ from $K^0 \Lambda X$ |
| $0.03 \pm 0.06$ | 410 | [110] BURGUN | 72 | HBC | $K^+ p \to K^0 p \pi^+$ |
| $0.04^{+0.10}_{-0.13}$ | 100 | [111] GRAHAM | 72 | OSPK | $K_{\mu 3}$ from $K^0 \Lambda$ |
| $-0.05 \pm 0.09$ | 442 | [111] GRAHAM | 72 | OSPK | $\pi^- p \to K^0 \Lambda$ |
| $0.26^{+0.10}_{-0.14}$ | 126 | MANN | 72 | HBC | $K^- p \to n \overline{K}^0$ |
| $-0.13 \pm 0.11$ | 342 | [111] MANTSCH | 72 | OSPK | $K_{e3}$ from $K^0 \Lambda$ |
| $0.04^{+0.07}_{-0.08}$ | 222 | [110] BURGUN | 71 | HBC | $K^+ p \to K^0 p \pi^+$ |
| $0.25^{+0.07}_{-0.09}$ | 252 | WEBBER | 71 | HBC | $K^- p \to n \overline{K}^0$ |
| $0.12 \pm 0.09$ | 215 | [112] CHO | 70 | DBC | $K^+ d \to K^0 p p$ |
| $-0.020 \pm 0.025$ | | [113] BENNETT | 69 | CNTR | Charge asym+ Cu regen. |
| $0.09^{+0.14}_{-0.16}$ | 686 | LITTENBERG | 69 | OSPK | $K^+ n \to K^0 p$ |
| $0.03 \pm 0.03$ | | [113] 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 | $\pi^- p \to K^0 \Lambda$ |
| $0.17 \pm 0.10$ | 335 | [112] HILL | 67 | DBC | $K^+ d \to K^0 p p$ |
| $0.035^{+0.11}_{-0.13}$ | 196 | AUBERT | 65 | HLBC | $K^+$ charge exchange |
| $0.06^{+0.18}_{-0.44}$ | 152 | [114] BALDO-... | 65 | HLBC | $K^+$ charge exchange |
| $-0.08^{+0.16}_{-0.28}$ | 109 | [115] FRANZINI | 65 | HBC | $\overline{p} p$ |

[110] BURGUN 72 is a final result which includes BURGUN 71.
[111] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[112] CHO 70 is analysis of unambiguous events in new data and HILL 67.
[113] BENNETT 69 is a reanalysis of BENNETT 68.
[114] BALDO-CEOLIN 65 gives $x$ and $\theta$ converted by us to Re($x$) and Im($x$).
[115] FRANZINI 65 gives $x$ and $\theta$ for Re($x$) and Im($x$). See SCHMIDT 67.

## IMAGINARY PART OF $x$

Assumes $m_{K_L^0} - m_{K_S^0}$ 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 | [116] ANGELOPO... | 98E | CPLR | $K_{e3}$ from $K^0$ |
| $-0.10\ ^{+0.16}_{-0.19}$ | 79 | SMITH | 75B | WIRE | $\pi^- p \to K^0 \Lambda$ |
| −0.06 ±0.05 | 4724 | NIEBERGALL | 74 | ASPK | $K^+ p \to K^0 p \pi^+$ |
| −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 | [117] BURGUN | 72 | HBC | $K^+ p \to K^0 p \pi^+$ |
| $0.12\ ^{+0.17}_{-0.16}$ | 100 | [118] GRAHAM | 72 | OSPK | $K_{\mu 3}$ from $K^0 \Lambda$ |
| 0.05 ±0.13 | 442 | [118] GRAHAM | 72 | OSPK | $\pi^- p \to K^0 \Lambda$ |
| $0.21\ ^{+0.15}_{-0.12}$ | 126 | MANN | 72 | HBC | $K^- p \to n \overline{K}^0$ |
| −0.04 ±0.16 | 342 | [118] MANTSCH | 72 | OSPK | $K_{e3}$ from $K^0 \Lambda$ |
| $0.12\ ^{+0.08}_{-0.09}$ | 222 | [117] BURGUN | 71 | HBC | $K^+ p \to K^0 p \pi^+$ |
| 0.0 ±0.08 | 252 | WEBBER | 71 | HBC | $K^- p \to n \overline{K}^0$ |
| −0.08 ±0.07 | 215 | [119] CHO | 70 | DBC | $K^+ d \to K^0 p p$ |
| $-0.11\ ^{+0.10}_{-0.11}$ | 686 | LITTENBERG | 69 | OSPK | $K^+ n \to K^0 p$ |
| $+0.22\ ^{+0.37}_{-0.29}$ | 121 | JAMES | 68 | HBC | $\overline{p} p$ |
| 0.0 ±0.25 | 116 | FELDMAN | 67B | OSPK | $\pi^- p \to K^0 \Lambda$ |
| −0.20 ±0.10 | 335 | [119] HILL | 67 | DBC | $K^+ d \to K^0 p p$ |
| $-0.21\ ^{+0.11}_{-0.15}$ | 196 | AUBERT | 65 | HLBC | $K^+$ charge exchange |
| $-0.44\ ^{+0.32}_{-0.19}$ | 152 | [120] BALDO-... | 65 | HLBC | $K^+$ charge exchange |
| $+0.24\ ^{+0.40}_{-0.30}$ | 109 | [121] FRANZINI | 65 | HBC | $\overline{p} p$ |

[116] Superseded by ANGELOPOULOS 01B.
[117] BURGUN 72 is a final result which includes BURGUN 71.
[118] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[119] 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.
[120] BALDO-CEOLIN 65 gives $x$ and $\theta$ converted by us to Re($x$) and Im($x$).
[121] FRANZINI 65 gives $x$ and $\theta$ for Re($x$) and Im($x$). See SCHMIDT 67.

# $K^0_L$ REFERENCES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ALAVI-HARATI 01H PRL 87 111802 A. Alavi-Harati *et al.* (KTeV Collab.)
ALAVI-HARATI 01J PR D64 112004 A. Alavi-Harati *et al.* (KTeV Collab.)
ANGELOPO... 01 PL B503 49 A. Angelopoulos *et al.* (CPLEAR Collab.)
ANGELOPO... 01B EPJ C22 55 A. Angelopoulos *et al.* (CPLEAR Collab.)
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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.)
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 00B 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 01B 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+)

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| 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 | 97 | 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 | 97 | 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 | 95 | 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 | 92 | 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 | 88 | 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 | 82 | 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 | 82B | PL 116B 73 | E. Fischbach *et al.* | (PURD, BNL, CHIC) |
| Also | 83 | PR D28 476 | S.H. Aronson *et al.* | (BNL, CHIC, PURD) |
| Also | 83B | 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) |
| Also | 80 | SJNP 31 622 | V.K. Birulev *et al.* | (JINR) |
| | | Translated from YAF 31 1204. | | |
| 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) |

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|---|---|---|---|---|
| HILL | 79 | NP B153 39 | D.G. Hill *et al.* | (BNL, SLAC, SBER) |
| SCHMIDT | 79 | PRL 43 556 | M.P. Schmidt *et al.* | (YALE, BNL) |
| ENGLER | 78B | PR D18 623 | A. Engler *et al.* | (CMU, ANL) |
| 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 | 75 | Thesis LBL-4275 | G. Shen | (LBL) |
| DEVOE | 77 | PR D16 565 | R. Devoe *et al.* | (EFI, ANL) |
| DZHORD... | 77 | SJNP 26 478 | V.P. Dzhordzhadze *et al.* | (JINR) |
| | | Translated from YAF 26 910. | | |
| 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) |
| ALBRECHT | 74 | PL 48B 393 | K.F. Albrecht (JINR, BERL, BUDA, PRAG, SERP+) | |
| BISI | 74 | PL 50B 504 | V. Bisi, M.I. Ferrero | (TORI) |
| DONALDSON | 74 | Thesis SLAC-0184 | G. Donaldson | (SLAC) |
| Also | 76 | PR D14 2839 | G. Donaldson *et al.* | (SLAC) |
| DONALDSON | 74B | PR D9 2960 | G. Donaldson *et al.* | (SLAC, UCSC) |
| Also | 73B | PRL 31 337 | G. Donaldson *et al.* | (SLAC, UCSC) |
| GEWENIGER | 74 | PL 48B 483 | C. Geweniger *et al.* | (CERN, HEIDH) |
| Also | 74 | Thesis CERN Int. 74-4 | V. Luth | (CERN) |
| GEWENIGER | 74B | PL 48B 487 | C. Geweniger *et al.* | (CERN, HEIDH) |
| Also | 74B | 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) |
| WANG | 74 | PR D9 540 | L. Wang *et al.* | (UMD, BNL) |
| WILLIAMS | 74 | PRL 33 240 | H.H. Williams *et al.* | (BNL, YALE) |
| ALBROW | 73 | NP B58 22 | M.G. Albrow *et al.* | (MCHS, DARE) |
| 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) |
| Also | 69 | PRL 23 427 | G.R. Evans *et al.* | (EDIN, CERN) |
| FACKLER | 73 | PRL 31 847 | O. Fackler *et al.* | (MIT) |
| FITCH | 73 | PRL 31 1524 | V.L. Fitch *et al.* | (PRIN) |
| Also | 72 | Thesis COO-3072-13 | R.C. Webb | (PRIN) |
| GINSBERG | 73 | PR D8 3887 | E.S. Ginsberg, J. Smith | (MIT, STON) |
| HART | 73 | NP B66 317 | J.C. Hart *et al.* | (CAVE, RHEL) |
| MALLARY | 73 | PR D7 1953 | M.L. Mallary *et al.* | (CIT) |
| Also | 70 | PRL 25 1214 | F.J. Sciulli *et al.* | (CIT) |
| MCCARTHY | 73 | PR D7 687 | R.L. McCarthy *et al.* | (LBL) |
| Also | 72 | PL 42B 291 | R.L. McCarthy *et al.* | (LBL) |
| Also | 71 | Thesis LBL-550 | R.L. McCarthy | (LBL) |
| MESSNER | 73 | PRL 30 876 | R. Messner *et al.* | (COLO, SLAC, UCSC) |
| PEACH | 73 | PL 43B 441 | K.J. Peach *et al.* | (EDIN, CERN, AACH) |
| SANDWEISS | 73 | PRL 30 1002 | J. Sandweiss *et al.* | (YALE, ANL) |
| WILLIAMS | 73 | PRL 31 1521 | H.H. Williams *et al.* | (BNL, YALE) |
| ALBROW | 72 | NP B44 1 | M.G. Albrow *et al.* | (MCHS, DARE) |
| 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) |
| DALLY | 72 | PL 41B 647 | E.B. Dally *et al.* | (SLAC, JHU, UCLA) |
| Also | 70 | PL 33B 627 | C.Y. Chien *et al.* | (JHU, SLAC, UCLA) |
| Also | 71 | PL 35B 261 | C.Y. Chien *et al.* | (JHU, SLAC, UCLA) |
| 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) |
| NEUHOFER | 72 | PL 41B 642 | G. Neuhofer *et al.* | (CERN, ORSAY, VIEN) |

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| PICCIONI | 72 | PRL 29 1412 | R. Piccioni *et al.* | (SLAC) |
| Also | 74 | PR D9 2939 | R. Piccioni *et al.* | (SLAC, UCSC, COLO) |
| VOSBURGH | 72 | PR D6 1834 | K.G. Vosburgh *et al.* | (RUTG, MASA) |
| Also | 71 | 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) |
| BISI | 71 | PL 36B 533 | V. Bisi *et al.* | (AACH, CERN, TORI) |
| 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) |
| CHIEN | 71 | PL 35B 261 | C.Y. Chien *et al.* | (JHU, SLAC, UCLA) |
| Also | 72 | PL 41B 647 | E.B. Dally *et al.* | (SLAC, JHU, UCLA) |
| CHO | 71 | PR D3 1557 | Y. Cho *et al.* | (CMU, BNL, CASE) |
| ENSTROM | 71 | PR D4 2629 | J. Enstrom *et al.* | (SLAC, STAN) |
| Also | 70 | 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) |
| REPELLIN | 71 | PL 36B 603 | J.P. Repellin *et al.* | (ORSAY, CERN) |
| WEBBER | 71 | PR D3 64 | B.R. Webber *et al.* | (LRL) |
| Also | 68 | PRL 21 498 | B.R. Webber *et al.* | (LRL) |
| Also | 69 | Thesis UCRL 19226 | B.R. Webber | (LRL) |
| WOLFF | 71 | PL 36B 517 | B. Wolff *et al.* | (ORSAY, CERN) |
| ALBROW | 70 | PL 33B 516 | M.G. Albrow *et al.* | (MCHS, DARE) |
| ARONSON | 70 | PRL 25 1057 | S.H. Aronson *et al.* | (EFI, ILLC, SLAC) |
| BARMIN | 70 | PL 33B 377 | V.V. Barmin *et al.* | (ITEP, JINR) |
| 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 | 71 | Private Comm. | A.J. Cox | |
| BUDAGOV | 70 | PR D2 815 | I.A. Budagov *et al.* | (CERN, ORSAY, EPOL) |
| Also | 68B | PL 28B 215 | I.A. Budagov *et al.* | (CERN, ORSAY, EPOL) |
| CHIEN | 70 | PL 33B 627 | C.Y. Chien *et al.* | (JHU, SLAC, UCLA) |
| Also | 71 | Private Comm. | A.J. Cox | |
| CHO | 70 | PR D1 3031 | Y. Cho *et al.* | (CMU, BNL, CASE) |
| Also | 67 | PRL 19 668 | D.G. Hill *et al.* | (BNL, CMU) |
| CHOLLET | 70 | PL 31B 658 | J.C. Chollet *et al.* | (CERN) |
| CULLEN | 70 | PL 32B 523 | M. Cullen *et al.* | (AACH, CERN, TORI) |
| GINSBERG | 70 | PR D1 229 | E.S. Ginsberg | (HAIF) |
| MARX | 70 | PL 32B 219 | J. Marx *et al.* | (COLU, HARV, CERN) |
| Also | 70B | 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) |
| WEBBER | 70 | PR D1 1967 | B.R. Webber *et al.* | (LRL) |
| Also | 69 | Thesis UCRL 19226 | B.R. Webber | (LRL) |
| BANNER | 69 | PR 188 2033 | M. Banner *et al.* | (PRIN) |
| Also | 68 | PRL 21 1103 | M. Banner *et al.* | (PRIN) |
| Also | 68 | PRL 21 1107 | J.W. Cronin, J.K. Liu, J.E. Pilcher | (PRIN) |
| BEILLIERE | 69 | PL 30B 202 | P. Beilliere, G. Boutang, J. Limon | (EPOL) |
| BENNETT | 69 | PL 29B 317 | S. Bennett *et al.* | (COLU, BNL) |
| EVANS | 69 | PRL 23 427 | G.R. Evans *et al.* | (EDIN, CERN) |
| FAISSNER | 69 | PL 30B 204 | H. Faissner *et al.* | (AACH3, CERN, TORI) |
| LITTENBERG | 69 | PRL 22 654 | L.S. Littenberg *et al.* | (UCSD) |
| LONGO | 69 | PR 181 1808 | M.J. Longo, K.K. Young, J.A. Helland | (MICH, UCLA) |
| PACIOTTI | 69 | Thesis UCRL 19446 | M.A. Paciotti | (LRL) |
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