

A Measurement of the  $K_L$  Charge Asymmetry

A. Alavi-Harati<sup>12</sup>, T. Alexopoulos<sup>12</sup>, M. Arenton<sup>11</sup>, K. Arisaka<sup>2</sup>, S. Averitte<sup>10</sup>, R.F. Barbosa<sup>7,\*\*</sup>, A.R. Barker<sup>5</sup>, M. Barrio<sup>4</sup>, L. Bellantoni<sup>7</sup>, A. Bellavance<sup>9</sup>, J. Belz<sup>10</sup>, R. Ben-David<sup>7</sup>, D.R. Bergman<sup>10</sup>, E. Blucher<sup>4</sup>, G.J. Bock<sup>7</sup>, C. Bown<sup>4</sup>, S. Bright<sup>4</sup>, E. Cheu<sup>1</sup>, S. Childress<sup>7</sup>, R. Coleman<sup>7</sup>, M.D. Corcoran<sup>9</sup>, G. Corti<sup>11</sup>, B. Cox<sup>11</sup>, M.B. Crisler<sup>7</sup>, A.R. Erwin<sup>12</sup>, R. Ford<sup>7</sup>, A. Glazov<sup>4</sup>, A. Golossanov<sup>11</sup>, G. Graham<sup>4</sup>, J. Graham<sup>4</sup>, K. Hagan<sup>11</sup>, E. Halkiadakis<sup>10</sup>, J. Hamm<sup>1</sup>, K. Hanagaki<sup>8</sup>, S. Hidaka<sup>8</sup>, Y.B. Hsiung<sup>7</sup>, V. Jejer<sup>11</sup>, D.A. Jensen<sup>7</sup>, R. Kessler<sup>4</sup>, H.G.E. Kobrak<sup>3</sup>, J. LaDue<sup>5</sup>, A. Lath<sup>10</sup>, A. Ledovskoy<sup>11</sup>, P.L. McBride<sup>7</sup>, P. Mikelsons<sup>5</sup>, E. Monnier<sup>4,\*</sup>, T. Nakaya<sup>7</sup>, K.S. Nelson<sup>11</sup>, H. Nguyen<sup>7,†</sup>, V. O'Dell<sup>7</sup>, M. Pang<sup>7</sup>, R. Pordes<sup>7</sup>, V. Prasad<sup>4</sup>, X.R. Qi<sup>7</sup>, B. Quinn<sup>4,§</sup>, E.J. Ramberg<sup>7</sup>, R.E. Ray<sup>7</sup>, A. Roodman<sup>4</sup>, M. Sadamoto<sup>8</sup>, S. Schnetzer<sup>10</sup>, K. Senyo<sup>8</sup>, P. Shanahan<sup>7</sup>, P.S. Shawhan<sup>4</sup>, J. Shields<sup>11</sup>, W. Slater<sup>2</sup>, N. Solomey<sup>4</sup>, S.V. Somalwar<sup>10</sup>, R.L. Stone<sup>10</sup>, E.C. Swallow<sup>4,6</sup>, S.A. Taegar<sup>1</sup>, R.J. Tesarek<sup>10</sup>, G.B. Thomson<sup>10</sup>, P.A. Toale<sup>5</sup>, A. Tripathi<sup>2</sup>, R. Tschirhart<sup>7</sup>, S.E. Turner<sup>2</sup>, Y.W. Wah<sup>4</sup>, J. Wang<sup>1</sup>, H.B. White<sup>7</sup>, J. Whitmore<sup>7</sup>, B. Winstein<sup>4</sup>, R. Winston<sup>4</sup>, T. Yamanaka<sup>8</sup>, E.D. Zimmerman<sup>4</sup>

## The KTeV Collaboration

<sup>1</sup> University of Arizona, Tucson, Arizona 85721

<sup>2</sup> University of California at Los Angeles, Los Angeles, California 90095

<sup>3</sup> University of California at San Diego, La Jolla, California 92093

<sup>4</sup> The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

<sup>5</sup> University of Colorado, Boulder, Colorado 80309

<sup>6</sup> Elmhurst College, Elmhurst, Illinois 60126

<sup>7</sup> Fermi National Accelerator Laboratory, Batavia, Illinois 60510

<sup>8</sup> Osaka University, Toyonaka, Osaka 560-0043 Japan

<sup>9</sup> Rice University, Houston, Texas 77005

<sup>10</sup> Rutgers University, Piscataway, New Jersey 08854

<sup>11</sup> The Department of Physics and Institute of Nuclear and Particle Physics,

University of Virginia, Charlottesville, Virginia 22901

<sup>12</sup> University of Wisconsin, Madison, Wisconsin 53706

We present a measurement of the charge asymmetry  $\delta_L$  in the mode  $K_L \rightarrow \pi^\pm e^\mp \nu$  based on 298 million analyzed decays. We measure a value of  $\delta_L = (3322 \pm 58(stat) \pm 47(sys)) \cdot 10^{-6}$ , in good agreement with previous measurements and 2.4 times more precise than the current best published result. The result is used to place more stringent limits on CPT and  $\Delta S = \Delta Q$  violation in the neutral kaon system.

PACS numbers: 11.30.Er, 11.30.-j, 13.25.Es, 13.20.-v

The charge asymmetry in  $K_L$  semileptonic decays is deeply related to CP violation through neutral kaon mixing. The  $K_L$  wavefunction is proportional to  $(1 + \epsilon_L)K^0 - (1 - \epsilon_L)\bar{K}^0$ , where  $\epsilon_L$  parameterizes CP violation in mixing. This parameter can be determined in the decay modes  $K_L \rightarrow \pi^\pm e^\mp \nu$  (Ke3) and  $K_L \rightarrow \pi^\pm \mu^\mp \nu$  ( $K\mu 3$ ). The charge asymmetry ( $\delta_L$ ) is defined as

$$\delta_L = \frac{BR(e^+ \pi^-) - BR(e^- \pi^+)}{BR(e^+ \pi^-) + BR(e^- \pi^+)}.$$

Assuming  $\Delta S = \Delta Q$  and no CPT violation in the decay  $K^0(\bar{K}^0) \rightarrow e^+ \pi^- \nu(e^- \pi^+ \bar{\nu})$ ,  $\delta_L$  is simply  $2\text{Re } \epsilon_L$ . To first order in the parameters that violate CP and CPT,

$$\delta_L = 2\text{Re } \epsilon_L - 2\text{Re } Y - \text{Re}(x - \bar{x}).$$

The terms  $Y$  and  $\text{Re}(x - \bar{x})$  parameterize CPT violation in the  $\Delta S = \Delta Q$  and  $\Delta S = -\Delta Q$  transitions respectively[1, 2]:

$$\frac{\langle e^+ \pi^- \nu | \bar{K}^0 \rangle}{\langle e^- \pi^+ \bar{\nu} | \bar{K}^0 \rangle^*} = \frac{1 - Y}{1 + Y}$$

$$x = \frac{\langle e^+ \pi^- \nu | \bar{K}^0 \rangle}{\langle e^+ \pi^- \nu | K^0 \rangle} \quad \bar{x} = \frac{\langle e^- \pi^+ \bar{\nu} | K^0 \rangle^*}{\langle e^- \pi^+ \bar{\nu} | \bar{K}^0 \rangle^*}.$$

In the Standard Model, the  $\Delta S = \Delta Q$  violation is CPT-conserving and occurs in 2nd order weak decays. Estimates for  $|x|$  are in the range  $10^{-7}$ [3].  $\delta_L$  is modified to order  $|x|^2$  and will not be considered in this letter.

The measurement of  $\delta_L$  can be compared to expectations derived from the  $K_L \rightarrow 2\pi$  ( $K\pi 2$ ) amplitudes  $(\eta_{+-}, \eta_{00})$ [2, 4]:

$$\text{Re} \left( Y + \frac{x - \bar{x}}{2} + a \right) = \text{Re} \left( \frac{2}{3} \eta_{+-} + \frac{1}{3} \eta_{00} \right) - \frac{\delta_L}{2}. \quad (1)$$

This comparison is sensitive to CPT violation in Ke3 and  $K\pi 2$  decays, where the latter is parameterized by  $\text{Re } a$ .

The current world average on  $\delta_L$  comes mainly from a measurement by the CERN-Heidelberg collaboration in 1974. Using 34 million Ke3 decays, they found  $\delta_L = (3409 \pm 171(stat) \pm 50(sys)) \cdot 10^{-6}$ [5]. We describe in this letter a measurement of  $\delta_L$  in the Ke3 mode based on approximately 298 million Ke3 decays.

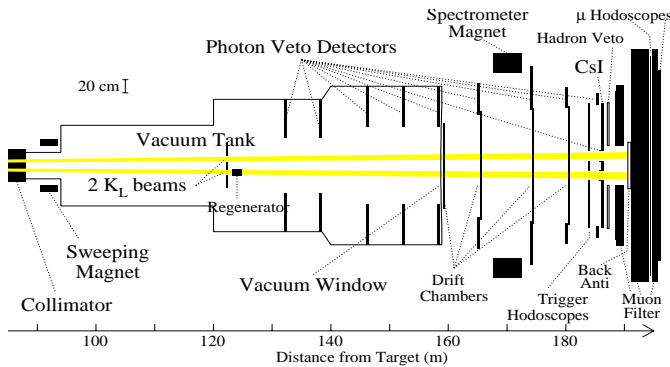


FIG. 1: The KTeV detector configured for measuring  $\text{Re}(\epsilon'/\epsilon)$ .

The KTeV beamline and detector at Fermilab is described elsewhere[6]. For this analysis, the detector is configured for the measurement of  $\text{Re}(\epsilon'/\epsilon)$ . As shown in Fig. 1, two approximately parallel neutral  $K_L$  beams enter a long vacuum tank, which defines the fiducial volume for accepted decays. One of the beams strikes an active absorber (regenerator), which serves to tag the coherent regeneration of  $K_S$ . The regenerator moves to the other beam in between Tevatron spill cycles. Following the vacuum tank, there are 4 planar drift chambers and an analysis magnet that imparts a 411 MeV/c horizontal transverse kick to the charged particles. A high precision 3100-element pure Cesium Iodide calorimeter (CsI) is used primarily to measure the energy of  $e^\pm$  and photons. Photon veto detectors surrounding the vacuum tank, drift chambers, and CsI serve to reject events with particles escaping the calorimeter.

Only Ke3 decays in the beam opposite the regenerator were used in this analysis. They were triggered by the presence of hits in the drift chambers and scintillators placed immediately upstream of the CsI, and by the lack of activity in the regenerator or photon vetoes. To keep the event rate manageable, the trigger rejected beam muons and  $K\mu 3$  events by requiring no activity in the scintillation counters (muon veto) placed behind 4 meters of Fe absorbers downstream of the CsI.

Selecting Ke3 events is relatively straightforward, as they are the most copious  $K_L$  decay mode ( $\text{BR}(\text{Ke3}) \approx 0.39$ ). We identify two-track vertices in the region between 90 and 160 meters from the target with kinematics inconsistent with  $K_L \rightarrow \pi^+\pi^-\pi^0$  ( $K\pi 3$ ) and  $\Lambda(\bar{\Lambda}) \rightarrow p\pi^-(\bar{p}\pi^+)$ . The tracks are required to extrapolate to CsI energy deposits while maintaining sufficient clearance from the inner and outer edges. A track is identified as an electron if its momentum exceeds 5 GeV/c and its CsI energy deposit divided by its momentum (E/P) exceeded 0.925. Pions are identified as having momentum exceeding 8 GeV/c and E/P less than 0.925. The tighter pion momentum requirement rejects  $K\mu 3$

background, since 8 GeV/c is the threshold for minimum-ionizing particles to penetrate through to the muon veto counters.

To minimize background from target  $K_S$  coherently interfering with the  $K_L$ , the event proper time ( $\tau$ ) had to exceed  $10.5 K_S$  lifetimes ( $\tau_S$ ). The  $K_L$  momentum ( $P_K$ ) reconstruction has ambiguities inherent to any 3-body decay with one unobserved particle. The longitudinal component of the neutrino momentum in the kaon rest frame can be either parallel or anti-parallel to the kaon flight direction in the lab frame. This introduces two possible solutions for  $P_K$ . We use the low  $P_K$  solution to calculate  $\tau$ . Based on Monte Carlo (MC) simulations, this choice is at least 70% correct for  $\tau < 22.5 \tau_S$ . A small correction, derived from MC, was made for errors in the  $P_K$  solution and the residual target  $K_S$  interference.

The measurement of  $\delta_L$  requires a careful control of systematics. The most important of these is to ensure an equal acceptance and efficiency for oppositely charged particles. We combine data sets of opposite analysis magnet polarities, which was reversed about once per day, to ensure that the detector is exposed to oppositely charged particles in the same manner. We also used data collected during rare decay running (E799), which included a transition radiation detector (TRD)[7, 8] used for the study of electron and pion identification.

There are eight possible configurations for Ke3 decays:  $e^+\pi^-$  or  $e^-\pi^+$ , east (E) or west (W)  $K_L$  beams, and positive (+) or negative (-) magnet polarities. The number of Ke3 events in each configuration ( $N_i$ ) depends on the branching ratio (BR), the acceptance and efficiency (A), and the flux  $N(K_L)$ . We define  $R$  as:

$$R^4 = \frac{\text{BR}(e^+\pi^-)A(e^+\pi^-, E, +)N(K_L, E, +)}{\text{BR}(e^-\pi^+)A(e^-\pi^+, E, -)N(K_L, E, -)} \quad (2)$$

$$\times \frac{\text{BR}(e^+\pi^-)A(e^+\pi^-, E, -)N(K_L, E, -)}{\text{BR}(e^-\pi^+)A(e^-\pi^+, E, +)N(K_L, E, +)}$$

$$\times \frac{\text{BR}(e^+\pi^-)A(e^+\pi^-, W, +)N(K_L, W, +)}{\text{BR}(e^-\pi^+)A(e^-\pi^+, W, -)N(K_L, W, -)}$$

$$\times \frac{\text{BR}(e^+\pi^-)A(e^+\pi^-, W, -)N(K_L, W, -)}{\text{BR}(e^-\pi^+)A(e^-\pi^+, W, +)N(K_L, W, +)},$$

where the four numerators and denominators represent  $N_i$ ,  $i = 1, 8$ . Since the fluxes cancel and  $A(e^\pm\pi^\mp) = A(e^\mp\pi^\pm)$  under magnetic field reversal, Eq. 2 reduces to:

$$\text{raw } \delta_L = \frac{R-1}{R+1} \quad \sigma(\text{raw } \delta_L) = \frac{1}{8} \cdot \sqrt{\sum_{i=1}^8 \frac{1}{N_i}}. \quad (3)$$

Equation 3 defines the “raw”  $\delta_L$ , and does not take into account several effects discussed below. Our data yields  $\text{raw } \delta_L = (3417 \pm 58) \cdot 10^{-6}$  (ppm). Figure 2 shows its dependence on the decay vertex distance from the target.

In principle, the same flux and acceptance/efficiency cancellation occurs in the pairing of the first and second

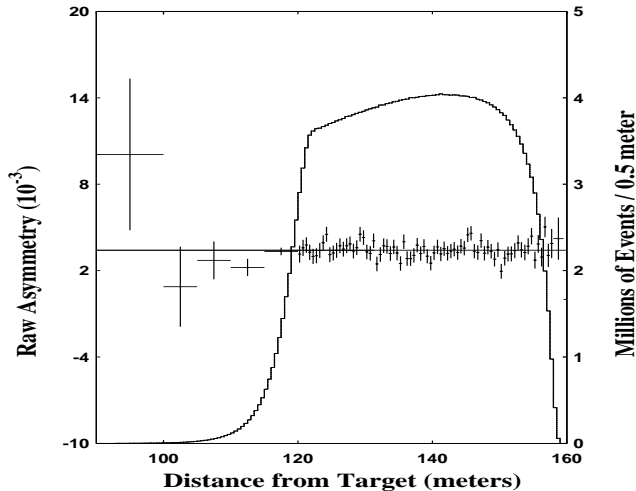


FIG. 2: Raw  $\delta_L$  and number of events versus vertex distance from target. A fit to a constant yields  $3417 \pm 58$  ppm with a  $\chi^2$  of 81.53 for 81 degrees of freedom.

(third and fourth) factors of Eq. 2, such that  $\delta_L$  can be measured within the east and west beams. Eq. 3 is the geometric mean of the two  $\delta_L$  measurements.

Figure 3 shows the raw asymmetry in various data subsets. In particular, we see the importance of combining data from opposite polarity runs. The difference between measurements made with only one magnet setting,  $\delta_L(+)$  –  $\delta_L(-)$ , is significant and on the order of  $\delta_L$  itself. This difference is due to very small offsets of the inner apertures and is well-reproduced by our MC. The MC is not used to correct this large effect since Eq. 2 naturally accounts for such geometrical asymmetries. On the other hand, the values for  $\delta_L$  agree between decays in the east and west beams. Other data divisions yield good agreement except for the sample with  $8 \text{ GeV}/c < P_\pi < 15 \text{ GeV}/c$  (discussed below).

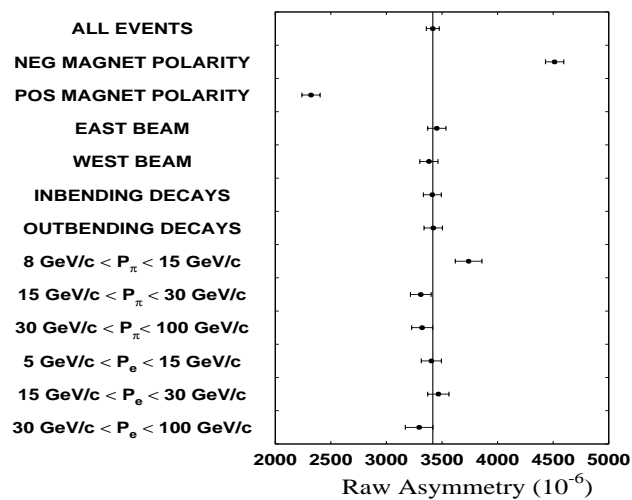


FIG. 3: Raw  $\delta_L$  for all events and various data subsets. The line indicates the raw value of 3417 ppm.

We account for the different behavior of particles and

antiparticles in matter. For each cut that introduces a bias, we measure  $f^+$  ( $f^-$ ), the inefficiency in the  $e^+\pi^-$  ( $e^-\pi^+$ ) configuration. The correction to raw  $\delta_L$  for the cut, summarized in table I, is simply  $(f^+ - f^-)/2$ .

Many biases due to  $\pi^\pm$  interaction differences were considered, and data were used to measure most of these corrections. These include the  $\pi^\pm$  energy deposition in the CsI, the loss of pions due to interactions in the trigger scintillators, and pion punchthrough past the Fe absorbers depositing energy in the muon veto. Events with E/P for pions exceeding 0.925 would be removed since the analysis requires exactly one identified electron. This effect, studied using pions in  $K\pi^3$  events, removes  $\approx 0.6\%$  of the pions, with the probability being slightly larger for  $\pi^+$  than  $\pi^-$ . The asymmetry between  $\pi^+$  and  $\pi^-$  has a strong momentum dependence and explains the trend seen for the  $8 \text{ GeV}/c < P_\pi < 15 \text{ GeV}/c$  data sample (see Fig. 3). The correction to  $\delta_L$  is  $-156 \pm 10$  ppm.

A correction was estimated for possible biases due to the trigger muon veto requirement, which removed approximately 3% of pions due to decay-in-flight and punchthrough. Good events can also be lost if accompanied by accidental muons. Only pion punchthrough would cause a bias due to the neutron excess in the Fe absorbers. The estimate used a Ke3 sample collected in E799, where the TRD gave additional electron purity. The sample is triggered by *requiring* muon counter hits, as these events are the ones that would be removed by the analysis trigger. This sample had a charge asymmetry of  $(4.4 \pm 1.3) \cdot 10^{-3}$ , consistent with no bias. Nevertheless, we use a correction of  $34 \pm 40$  ppm, where the error is given by the sample statistics.

Pion interactions in the trigger scintillator can confuse the reconstruction so that the track fails to match to a CsI cluster. This effect, studied using Ke3 events with a relaxed track-cluster matching requirement, removes  $\approx 0.42\%$  of all pions and was slightly more probable for the  $\pi^-$  than  $\pi^+$ , leading to a correction of  $54 \pm 10$  ppm.

Considering  $e^\pm$  interaction differences, one has primarily  $e^+$  annihilation and  $\delta$ -ray production. An  $e^+$  annihilation occurring near the upstream surface of the trigger scintillator would fail the trigger requirement due to the reduced energy deposition.  $\delta$ -rays more than 10 MeV and emitted from the vacuum window or tracking system can cause losses since the momentum transfer would drastically change the event kinematics. These losses cause a bias due to the small difference between the Bhabha ( $e^+e^-$ ) and Moller ( $e^-e^-$ ) scattering cross section. These corrections were derived by a Geant simulation of the detector material. They are of order  $\pm 10$  ppm, mitigated by the high momentum of the tracks and the minimal material ( $2\% X_0$ ) upstream of the CsI.

Finally, a Ke3 sample was used to study potential biases of the E/P cut on electrons. This sample was selected by a relaxed E/P cut and by the tagging of a minimum-ionizing  $\pi$  in the CsI. The E/P removed re-

moved approximately 0.233% of  $e^+$  and  $e^-$ . No bias is seen, and we assigned a correction of  $-19 \pm 18$  ppm. This result was confirmed with a similar Ke3 sample collected in E799, where the TRD gave additional electron purity.

We applied a small correction to account for pions absorbed in the vacuum window, drift chambers, and helium bags. This was estimated assuming isospin conservation in strong interactions, and so the  $\pi^+$  and  $\pi^-$  absorption differences depended on the excess protons, which was predominantly in the form of hydrogen. We accounted for a small bias due to  $\pi^-$  charge exchange near the upstream surface of the trigger scintillator (analogous to the case of  $e^+$  trigger loss). For this, we used the measurements of [9] and [10] and extrapolated them to our  $\pi^-$  momentum range.

Other small corrections, derived from MC, accounted for the inexact reversal of the analysis magnet polarity and the residual coherent  $K_S$  from the target, absorber, and  $K_L$  scatters with the final collimator and regenerator. Table I shows the summary of all systematic cor-

TABLE I: Corrections in ppm for this analysis.

$\pi^+\pi^-$ difference in CsI	$-156 \pm 10$
$\pi^\pm$ interaction in trigger scintillator	$+54 \pm 10$
$\pi$ decay and punchthrough	$+34 \pm 40$
$e^+e^-$ difference in CsI	$-19 \pm 18$
target/absorber $K_S - K_L$ interference	$-12 \pm 1$
$e^+$ annihilation in spectrometer	$+11 \pm 1$
Delta ray production	$-8.5 \pm 4.3$
$\pi$ absorption in spectrometer	$+5.0 \pm 3.2$
inexact analysis magnet polarity reversal	$-3.1 \pm 1.6$
final collimator and regenerator scatters	$-1.2 \pm 2.3$
$\pi^+\pi^-\pi^0$ background	$+0.5 \pm 0.7$
$K\mu 3$ background	$0 \pm 0$
$\Lambda_{p\pi}$ and $\Lambda_\beta$ background	$0 \pm 0$
Total correction	$-95.3 \pm 46.5$

rections. The uncertainties are uncorrelated since they are mainly statistical errors of the Ke3 and  $K\pi 3$  control samples. Combining the corrections with raw  $\delta_L$ , we find:

$$\begin{aligned}\delta_L &= 3322 \pm 58 \text{ (stat)} \pm 47 \text{ (syst)} \text{ ppm} \\ &= 3322 \pm 74 \text{ (combined)} \text{ ppm}.\end{aligned}$$

This result is in excellent agreement with previous measurements and 2.4 times more precise than the current best result (see Fig. 4). A combination of all results including ours yields:

$$\delta_L = 3307 \pm 63 \text{ ppm} \quad \chi^2 = 4.2/6 \text{ d.o.f.}$$

Substituting  $\eta_{+-}$  and  $\eta_{00}$  values from [11] and the combined  $\delta_L$  into Eq. 1, we find:

$$\begin{aligned}Re(Y + \frac{x - \bar{x}}{2} + a) &= (1650 \pm 16) - (1653 \pm 32) \\ &= -3 \pm 35 \text{ ppm}.\end{aligned}$$

The result is consistent with no CPT violation and is limited by the charge asymmetry uncertainty. It limits  $|Re(Y + (x - \bar{x})/2 + a)| < 61$  ppm at the 90% C.L.. Barring fortuitous cancellations, this is thus far the most stringent limit on  $Y$ ,  $x$ , and  $a$ .

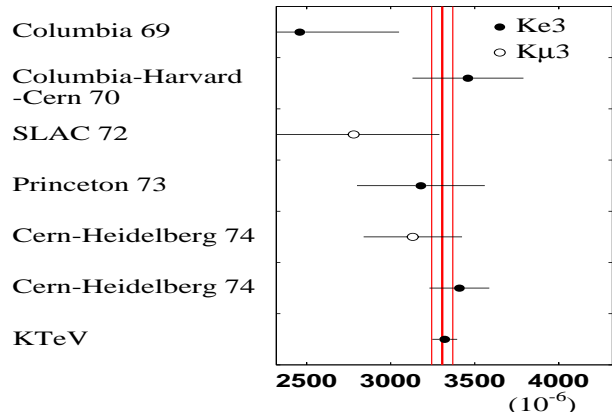


FIG. 4: Compilation of  $\delta_L$  measurements including this result. Lines indicate the average and its uncertainty.

We gratefully acknowledge the support and effort of the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported in part by the DOE, the NSF and the Ministry of Education and Science of Japan. A.R.B., E.B. and S.V.S. acknowledge support from the NYI program of the NSF; A.R.B. and E.B. from the Alfred P. Sloan Foundation; E.B. from the OJI program of the DOE; K.H., T.N. and M.S. from the Japan Society for the Promotion of Science; and R.F.B from the Fundação de Amparo à Pesquisa do Estado de São Paulo. P.S.S. acknowledges receipt of a Grainger Fellowship.

† To whom correspondence should be addressed: hogann@fnal.gov.

\* Perm. address C.P.P. Marseille/C.N.R.S., France

\*\*Perm. address Univ. of São Paulo, São Paulo, Brazil

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