The K_L Semileptonic Charge Asymmetry and CPT Tests from KTeV

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CPT Probes in the Kaon System.

- Due to the very small mass $K_L - K_S$ mass difference, the $K^0 - \bar{K^0}$ mass difference can be limited to: *(PDG-2000)*

$$\frac{|m_{K^0} - m_{\bar{K^0}}|}{m_K} < 1 \times 10^{-18} \text{ @ } 95\% CL$$

- The coherent superpostion of K^0 and $\bar{K^0}$ in the neutral kaon system can be further exploited to limit CPT violation in $K^0 \to \pi\pi$ & $K^0 \to \pi e \nu_e$ (Ke3) decay amplitudes by testing the following relations:
  - $\eta_{\pi\pi}$ phase equality, $\phi_{+-} = \phi_{00}$ *(KTeV prelim)*: $\phi_{00} - \phi_{+-} = 0.41^o \pm 0.22^o_{stat} \pm 0.48^o_{sys}$
  - $\phi_{+-} = \phi_{sw}$, where $\phi_{sw} = tan^{-1}(2\Delta m/\Gamma_S)$. *(KTeV prelim)*: $\phi_{+-} - \phi_{sw} = 0.61^o \pm 0.62^o_{stat} \pm 1.1^o_{sys}$
  - $\delta_L = 2Re(\epsilon_L)$ where δ_L is the Ke3 charge asymmetry.
  - Independence of ϕ_{+-} and δ_L from spatial (siderial) orientiation.

$K_L \to \pi e \nu$ Charge Asymmetry

- Relation to $K^0 - \overline{K}^0$ mixing :

$$K_L \sim (1+\varepsilon_L)K^0 - (1-\varepsilon_L)\overline{K}^0$$

$$(1+\varepsilon_L)K^0 \longrightarrow e^+\pi^- \qquad (1-\varepsilon_L)\overline{K}^0 \longrightarrow e^-\pi^+$$

- Assuming CPT conservation in $K^0 \to \pi e \nu$ decays and the $\Delta S = \Delta Q$ rule, these two decays tag K^0 and $\overline{K}^0$ separately :

$$\delta_L = \frac{N(e^+) - N(e^-)}{N(e^+) + N(e^-)}$$

$$\delta_L = 2\,\mathrm{Re}(\varepsilon_L)$$

K_L Interferometry

$$K_L \sim (1+\varepsilon_L)K^0 - (1-\varepsilon_L)\overline{K}^0$$

$$\downarrow \qquad \swarrow$$

$$\pi\pi$$

In the 2π system, we are sensitive to a combination of CP and CPT violating effects from both the mixing part ε_L and the decay amplitudes to $\pi\pi$.

$$K_L \sim (1+\varepsilon_L)K^0 - (1-\varepsilon_L)\overline{K}^0$$

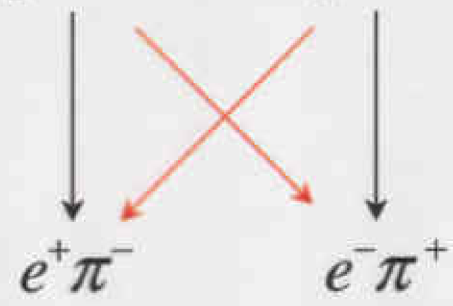
$$\downarrow \qquad\qquad \downarrow$$

$$e^+\pi^- \qquad\qquad e^-\pi^+$$

- Completely independent way to examine K_L-mixing
- Can be used to untangle effects in $\pi\pi$.

Sensitivity to CPT Violation in Comparing δ_L to η_{+-} and η_{00}

$$K_L \sim (1+\varepsilon_L)K^0 - (1-\varepsilon_L)\overline{K}^0$$



Charge asymmetry sensitive to CPT violation in $\Delta S = \Delta Q$ $\Delta S = -\Delta Q$ transitions

$$2\,\mathrm{Re}(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}) - \delta_L = 2\,\mathrm{Re}\,Y \quad +$$

CPT Violation in $\Delta S = \Delta Q$

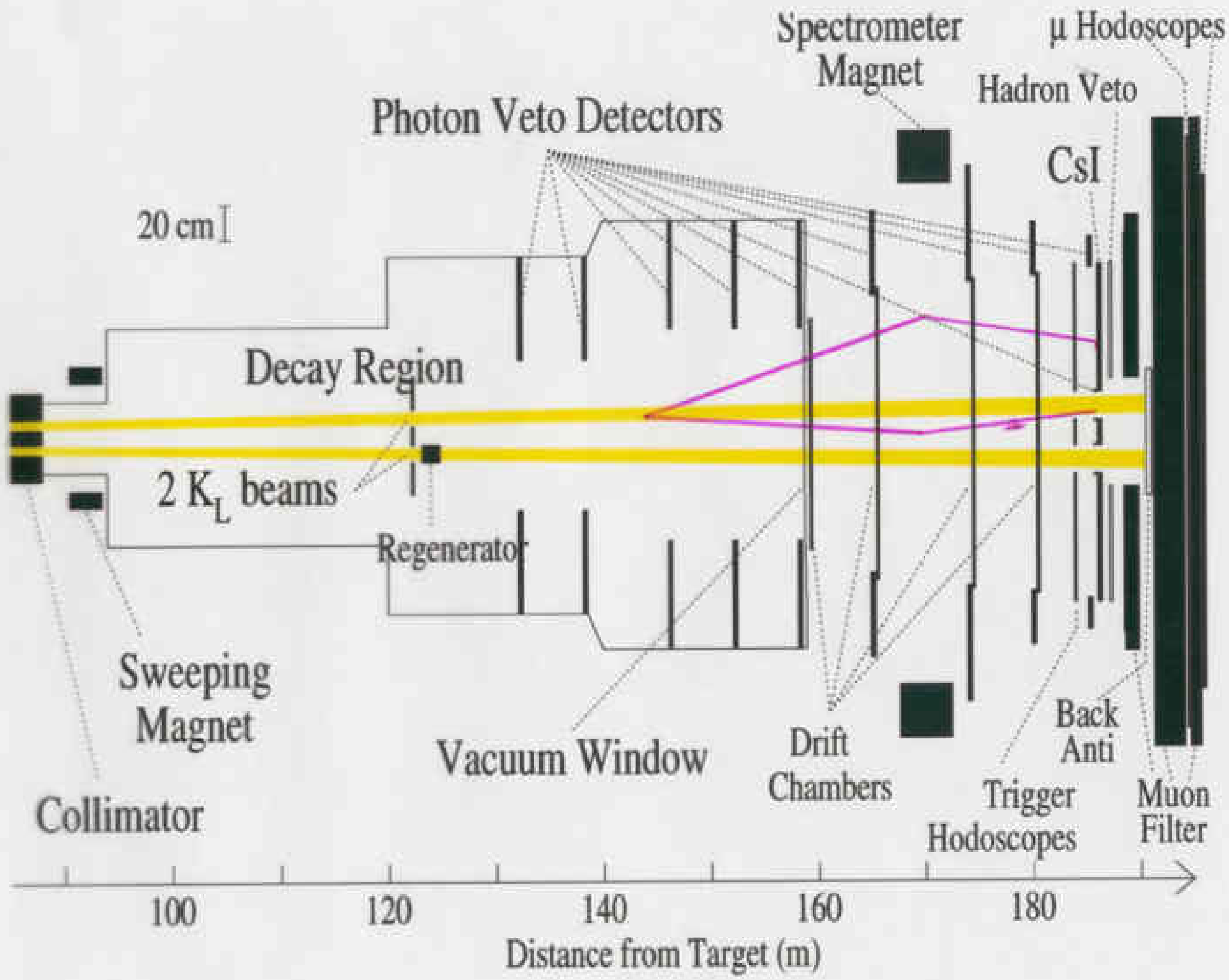
$$2\,\mathrm{Re}X_- \quad +$$

CPT Violation in $\Delta S = -\Delta Q$

$$\mathrm{Re}\left[\frac{\mathrm{Re}\,B_0 + i\,\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0 + i\,\mathrm{Im}\,B_0}\right]$$

CPT Violation in 2π decay amplitudes

KTeV Detector (E832 Configuration)



Overview of Strategy

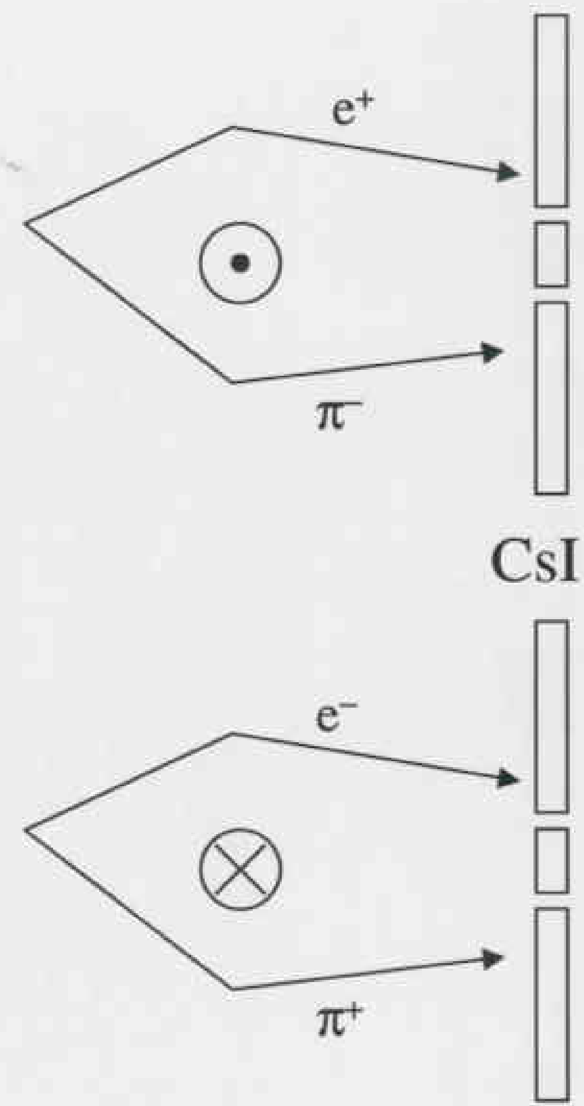
Two off-centered beams causes significant geometrical asymmetry.

- Cancel effect by combining opposite magnet polarity data

- Correct for backgrounds and matter-antimatter differences in detector

8 Configurations of Ke3 Decays

- $e^+\pi^-$ or $e^-\pi^+$
- east or west K_L beam
- + 411 or − 411 MeV analysis magnet polarity



Each configuration has a partner that has an identical geometrical acceptance:

$e^+\pi^-$ East +411 MeV ↔ $e^-\pi^+$ East −411 MeV

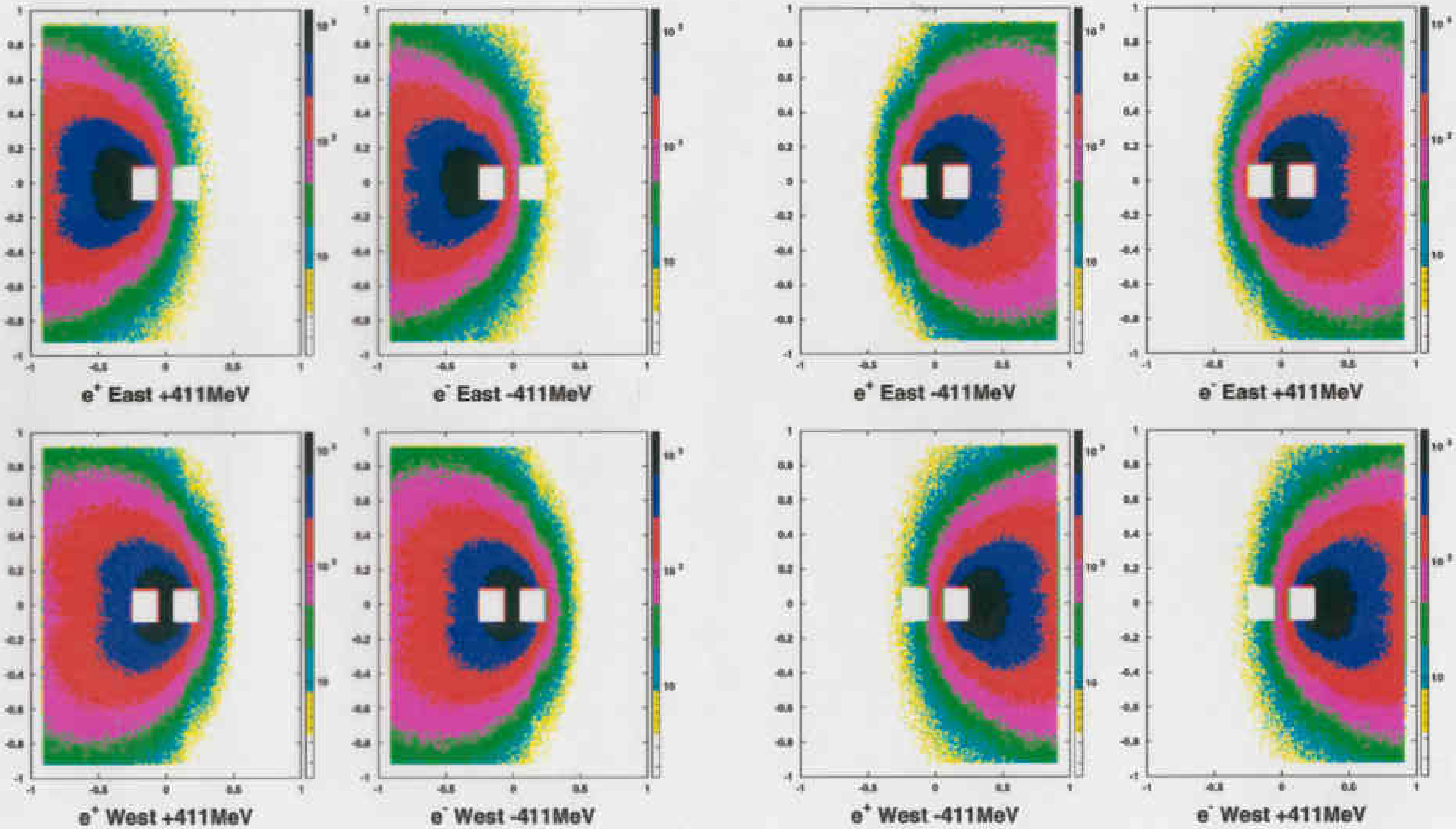
$e^+\pi^-$ West +411 MeV ↔ $e^-\pi^+$ West −411 MeV

$e^+\pi^-$ East −411 MeV ↔ $e^-\pi^+$ East +411 MeV

$e^+\pi^-$ West −411 MeV ↔ $e^-\pi^+$ West +411 MeV

However, a given configuration and its partner do not necessarily have the same beam flux

Illuminations of $e^{\pm}$ at the CsI



8 Configurations of Ke3 decays (cont)

A single ratio is formed to cancel the acceptances, the beam fluxes, and beam optics.

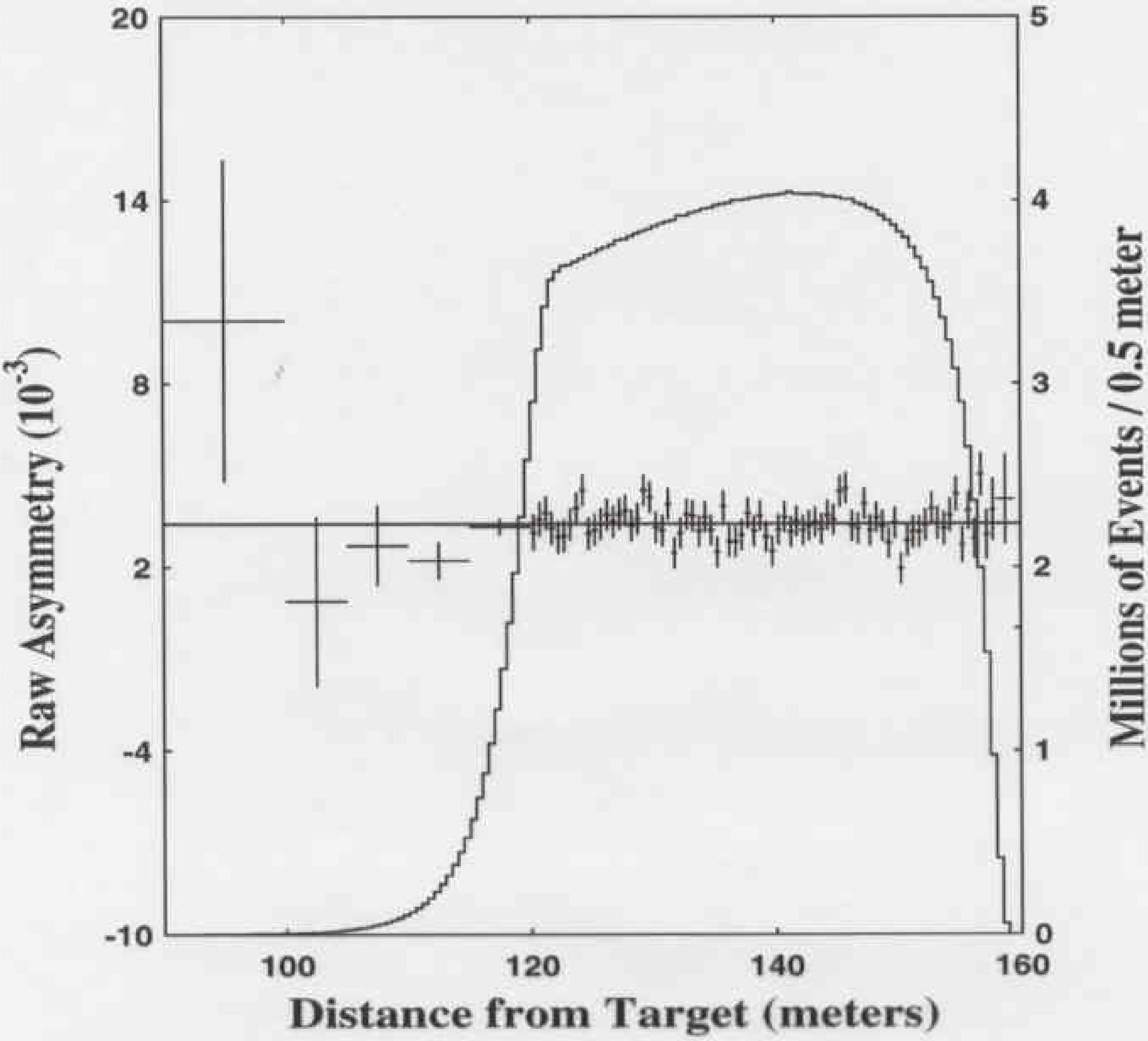
$$R^4 = \frac{Br(e^+\pi^-)\ N(K_L\ east\ +411)\ A(e^+\pi^-\ east\ +411)}{Br(e^-\pi^+)\ N(K_L\ east\ -411)\ A(e^-\pi^+\ east\ -411)} \bullet \frac{Br(e^+\pi^-)\ N(K_L\ east\ -411)\ A(e^+\pi^-\ east\ -411)}{Br(e^-\pi^+)\ N(K_L\ east\ +411)\ A(e^-\pi^+\ east\ +411)} \bullet \frac{Br(e^+\pi^-)\ N(K_L\ west\ +411)\ A(e^+\pi^-\ west\ +411)}{Br(e^-\pi^+)\ N(K_L\ west\ -411)\ A(e^-\pi^+\ west\ -411)} \bullet \frac{Br(e^+\pi^-)\ N(K_L\ west\ -411)\ A(e^+\pi^-\ west\ -411)}{Br(e^-\pi^+)\ N(K_L\ west\ +411)\ A(e^-\pi^+\ west\ +411)}$$

$$\delta_L = \frac{R-1}{R+1}$$

Fluxes Cancel

Must Check if the Acceptances Really Cancel !

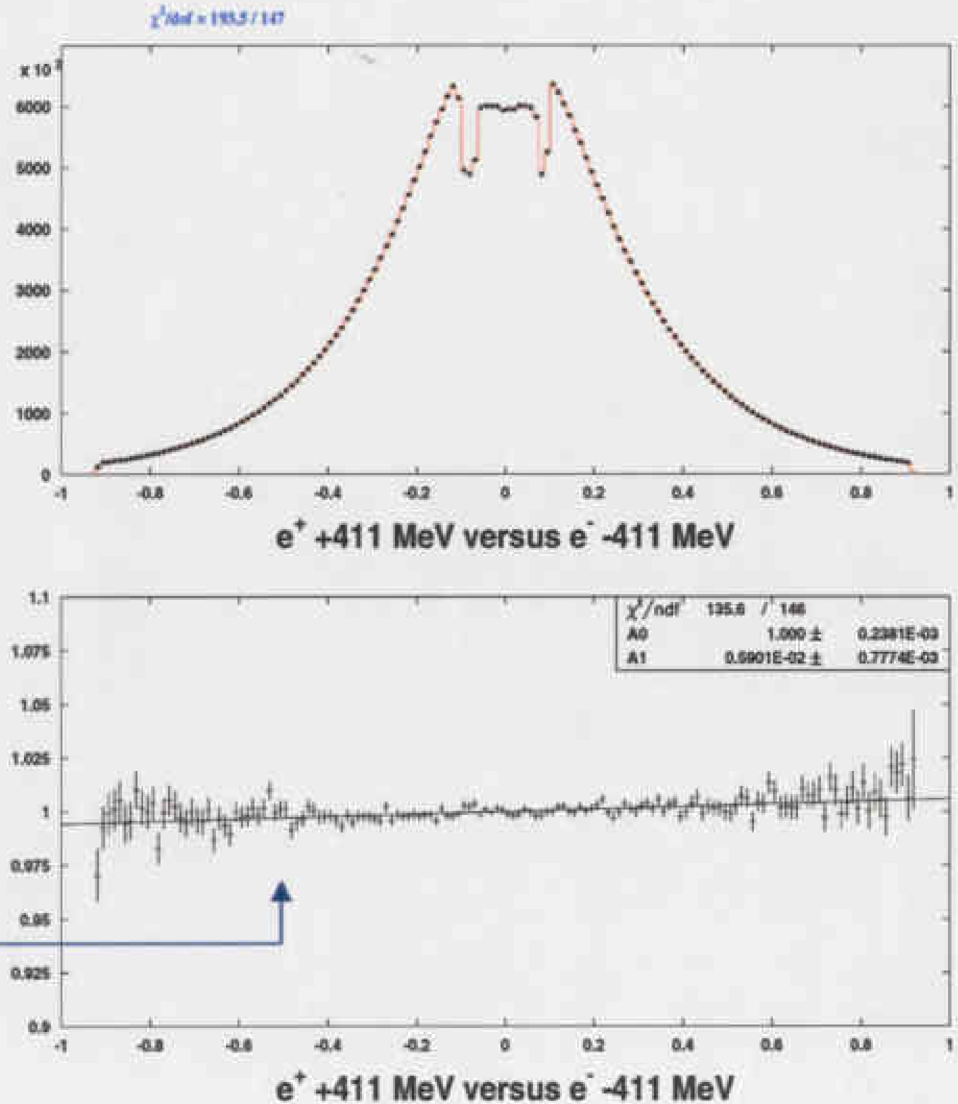
Raw Charge Asymmetry .vs. Decay Position.



Acceptance Checks of Configuration Pairs

small flaw in reversal of B_X component of magnet

Vertical Illumination of Tracks at CsI



Particle/antiparticle differences in matter

- $e^+ e^-$ differences:

  e^+ annihilation

  δ-ray production differences between Bhabha (e^+e^-) and Moller ($e^- e^-$) scattering

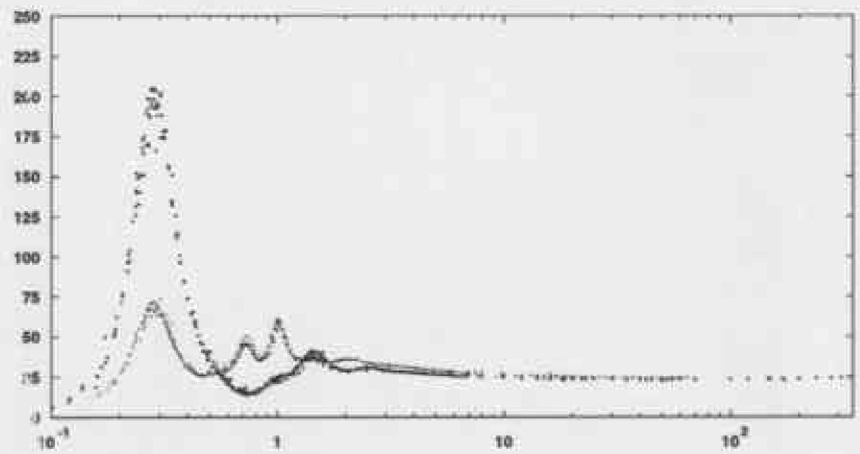
- $\pi^+ \pi^-$ differences:

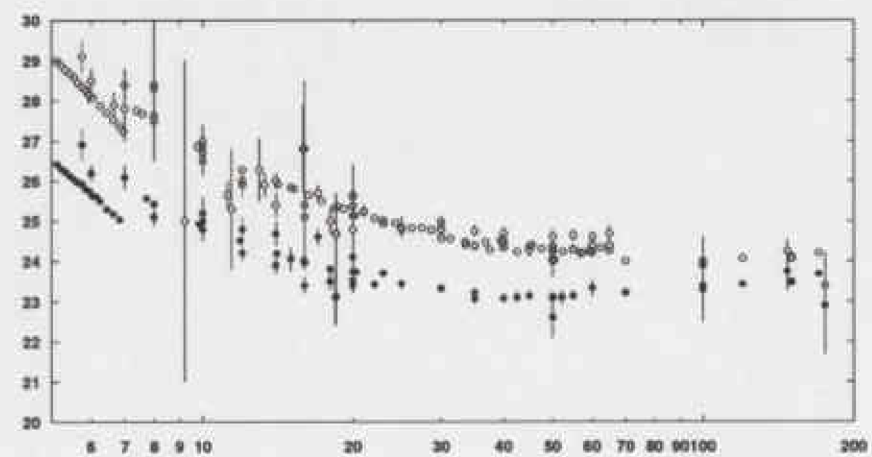
  Isospin dependence in nuclear interactions

  Detector has an unequal number of protons and neutrons

These effects bias the reconstruction of track kinematics and particle identification.

$\pi^+ p$ versus $\pi^- p$ total cross section (mb) vs p_π





† PDG 2000 Compilation

Particle/antiparticle differences in matter

$e^{\pm}$ biases: geant simulation/data

$\pi^{\pm}$ biases: measure directly with data

In comparison to previous measurements, our biases will be smaller due to:

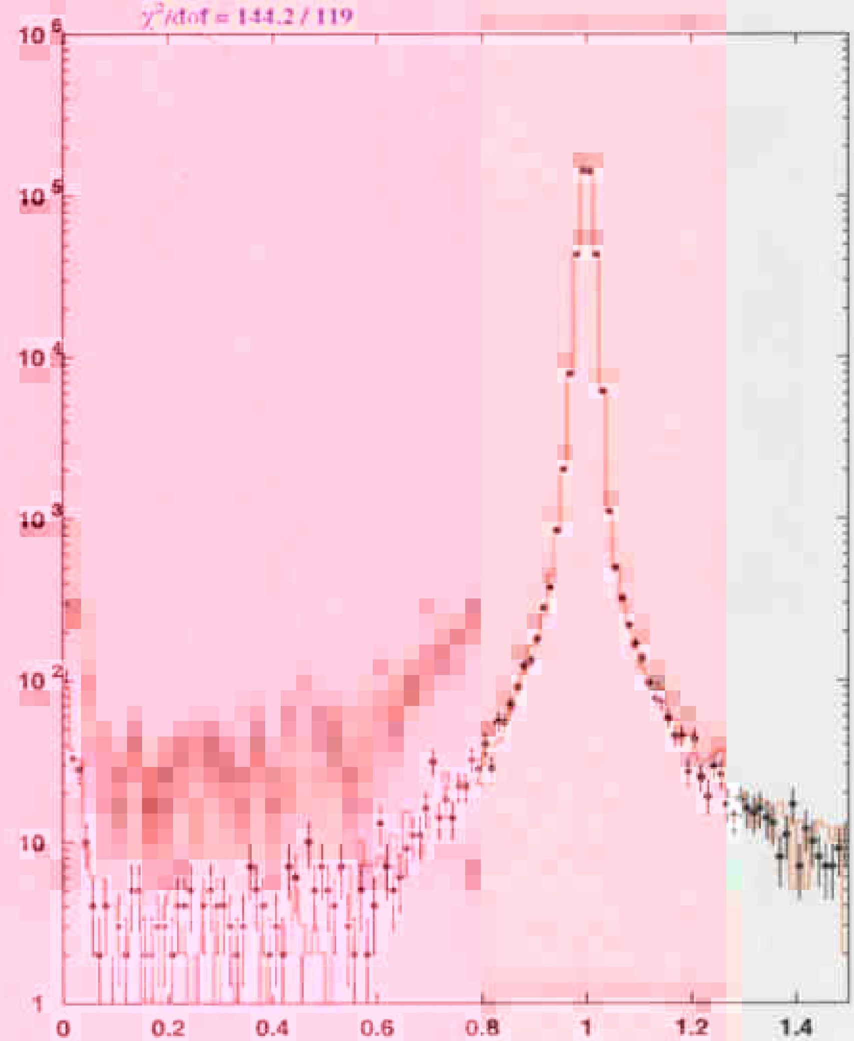
- a vacuum decay tank
- an ultra-thin magnetic spectrometer
- higher momentum spectra
- TRD in E799 data, crucial for understanding the p.i.d. biases in rest of detector

e^+ and e^- Response in the CsI (cont)

Useful cross check from KTeV-E799 data

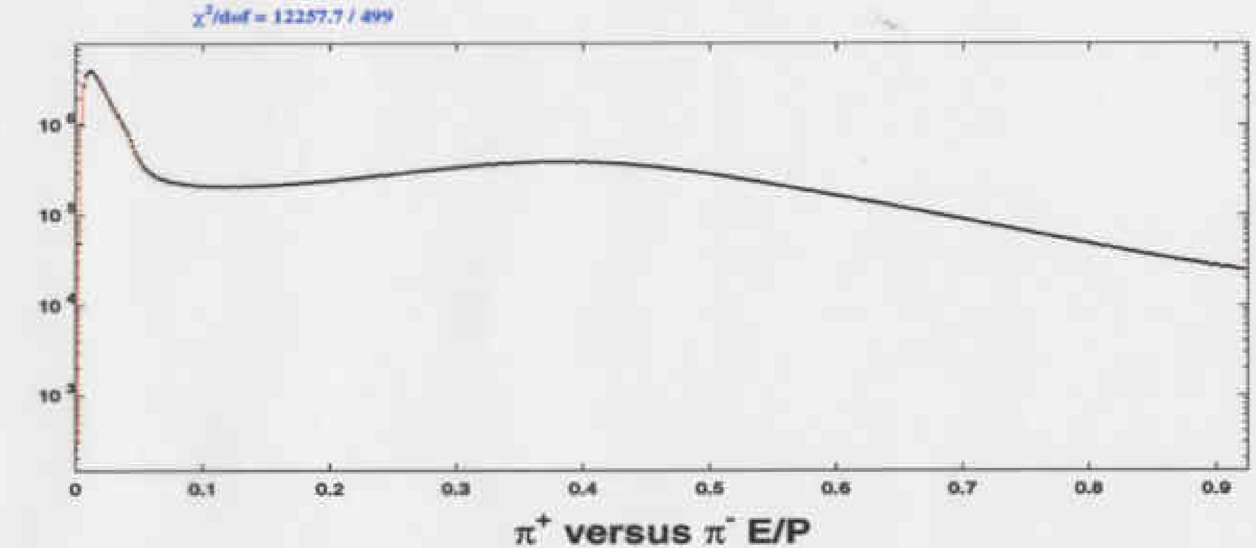
TRD used to remove pion background

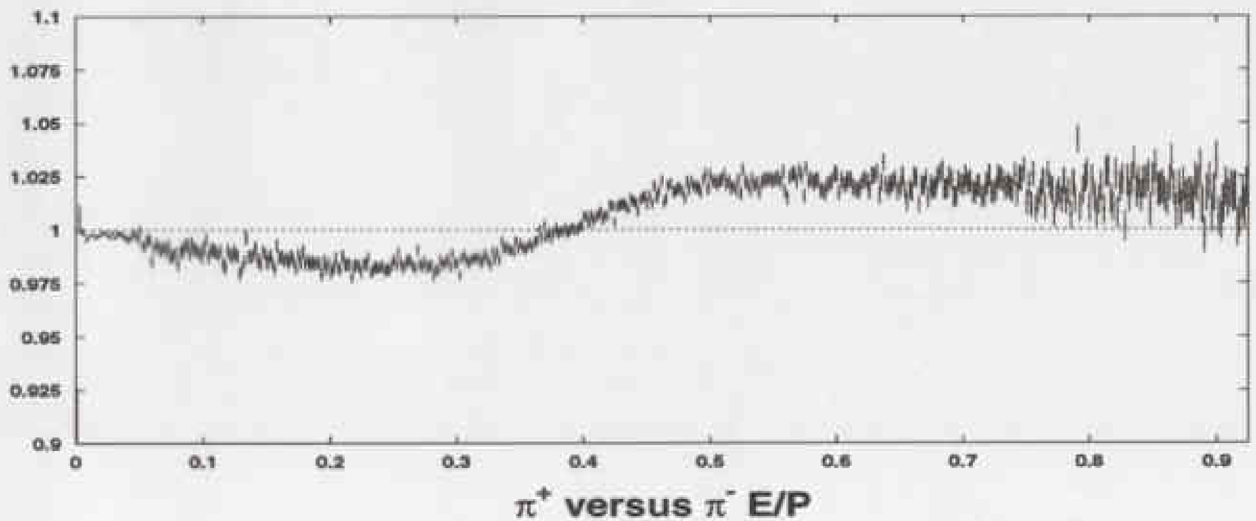
correction (E799) = 3 ± 66 ppm



π^+ and π^- Response in CsI

The requirement of E/P < 0.925 rejects more π^+ than π^-





Summary of Corrections

Effect	Correction (ppm)
$\pi^+\pi^-$ difference in CsI	-156 ± 10
$\pi^+\pi^-$ lost in trigger scintillator	54 ± 10
$\pi^+\pi^-$ lost in spectrometer	5 ± 3
$\pi^+\pi^-$ punch through	34 ± 40
e^+e^- difference in CsI	-19 ± 18
δ–ray production	-8.5 ± 4.3
e^+ annihilation in spectrometer	11 ± 1
$\pi^+\pi^-\pi^0$, $K\mu3$, Λ background	0.5 ± 0.7
Target/absorber interference	-12 ± 1
K_L scattering in final collimator	-1.2 ± 2.3
K_L scattering in regenerator	0 ± 0
B-field reversal mismatch	-3.1 ± 1.6
Sum	-95.3 ± 46.5 (ppm)

Result for $K_L \to \pi e \nu$ Charge Asymmetry

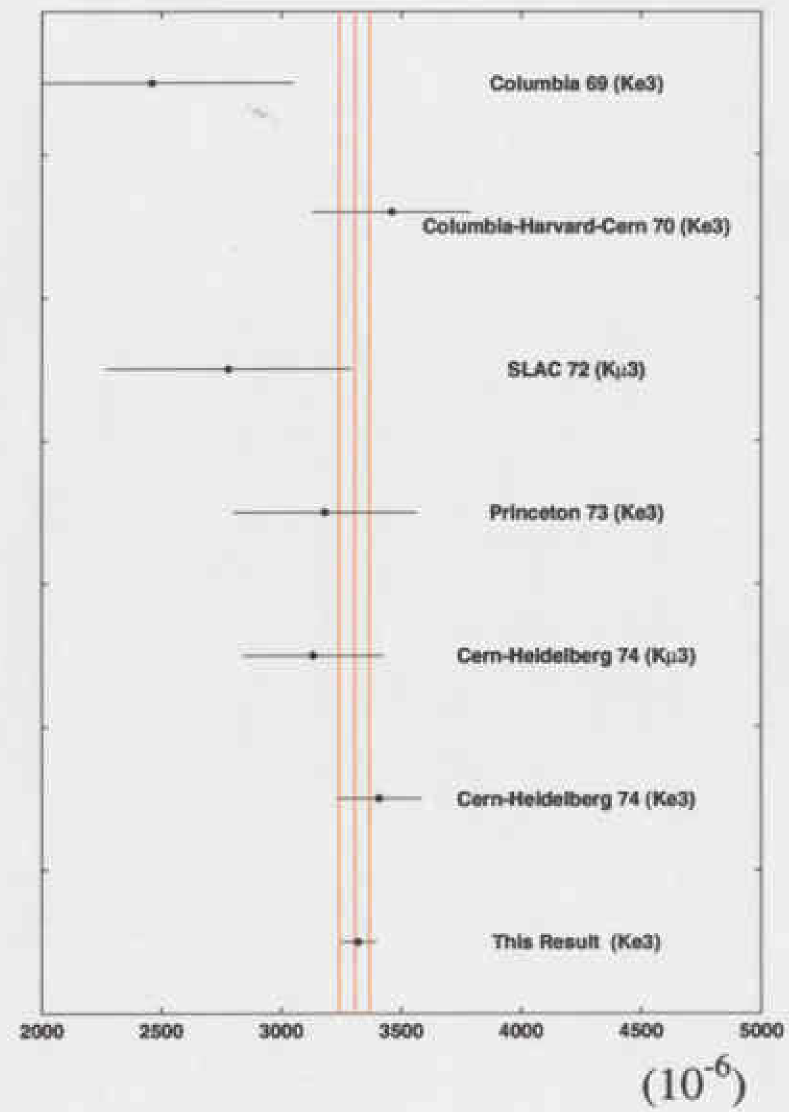
298 Million $K_L \to \pi e \nu$ collected in 1997 run of KTeV-E832

Raw δ_L = 3417 ± 58 ppm

Correction = -95 ± 47 ppm

$$\delta_L = 3322 \pm 58(\text{stat}) \pm 47(\text{sys}) \text{ ppm}$$
$$= 3322 \pm 74(\text{comb}) \text{ ppm}$$

- 2.4 x more precise than the previous best result (CERN-Heidelberg 1974)
- Excellent agreement with all previous measurements



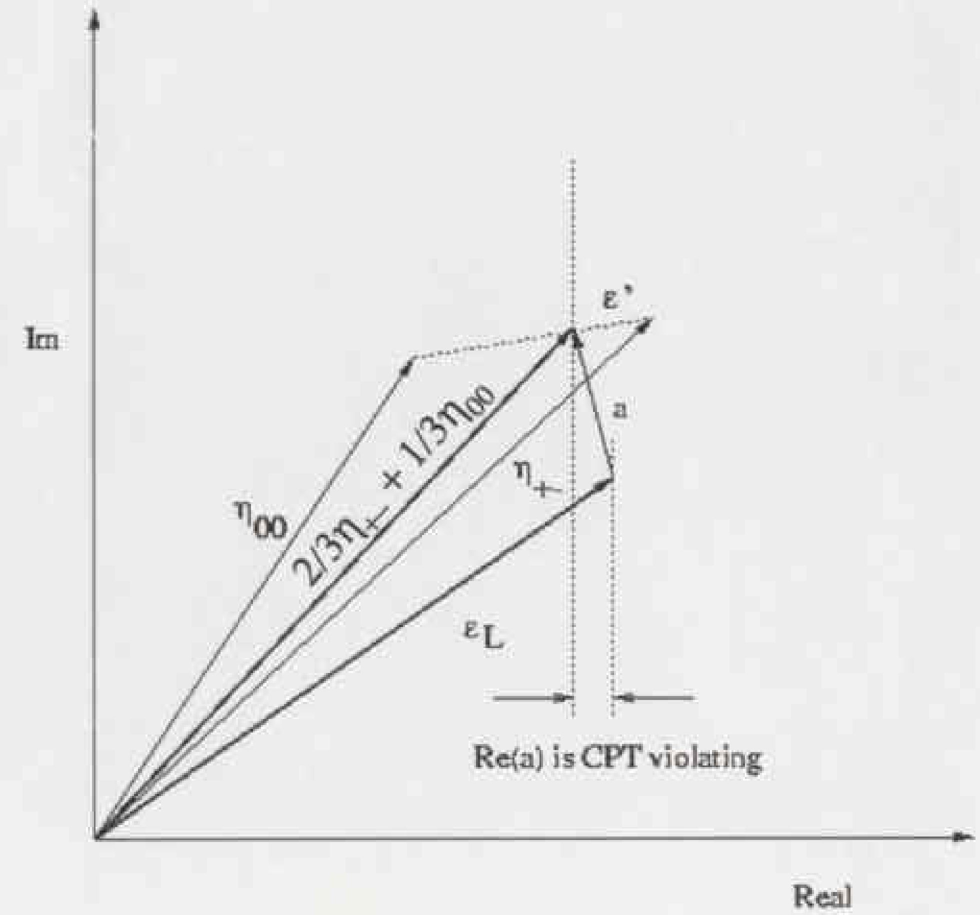
New Average: 3307 ± 63 ppm ($\chi^2 = 4.2/6$ d.o.f.)

Comparison of δ_L to $K_L \rightarrow \pi\pi$ and limit on CPT Violation

$$2\mathrm{Re}(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}) - \delta_L = 2\mathrm{Re}(Y + X_- + a)$$

$$= -6 \pm 70\,\mathrm{ppm}$$

Parameter	PDG2000 averages
$\|\eta_{+-}\|$	2276 ± 17 ppm
$\|\eta_{00}\|$	2262 ± 17 ppm
ϕ_{+-}	$43.5 \pm 0.5°$
ϕ_{00}	$43.2 \pm 1.0°$
$2\mathrm{Re}(\eta_{+-})$	3302 ± 37 ppm
$2\mathrm{Re}(\eta_{00})$	3298 ± 60 ppm
δ_L	3307 ± 63 ppm
	(PDG avg and this result)



Limits on CPT Violation

- Best CPT violation constraints are on linear combination of individual CPTV terms
- CPLEAR's production-tagged technique can unravel these combinations.

CPT Violating Parameters		Result
$\mathrm{Re}\,(Y + X_{-} + a)$		-3 ± 35 ppm (KTeV)
$\mathrm{Re}\,(Y + X_{-})$		-200 ± 300 ppm (CPLEAR)
$\mathrm{Re}\,Y$		300 ± 3100 ppm (CPLEAR)
$\mathrm{Re}\,X_{-}$		-500 ± 3000 ppm (CPLEAR)
$\mathrm{Re}\,\delta$	(CPTV in $\Delta S=2$)	240 ± 280 ppm (CPLEAR)
$\mathrm{Im}\,\delta$	(CPTV in $\Delta S=2$)	24 ± 50 ppm (CPLEAR)

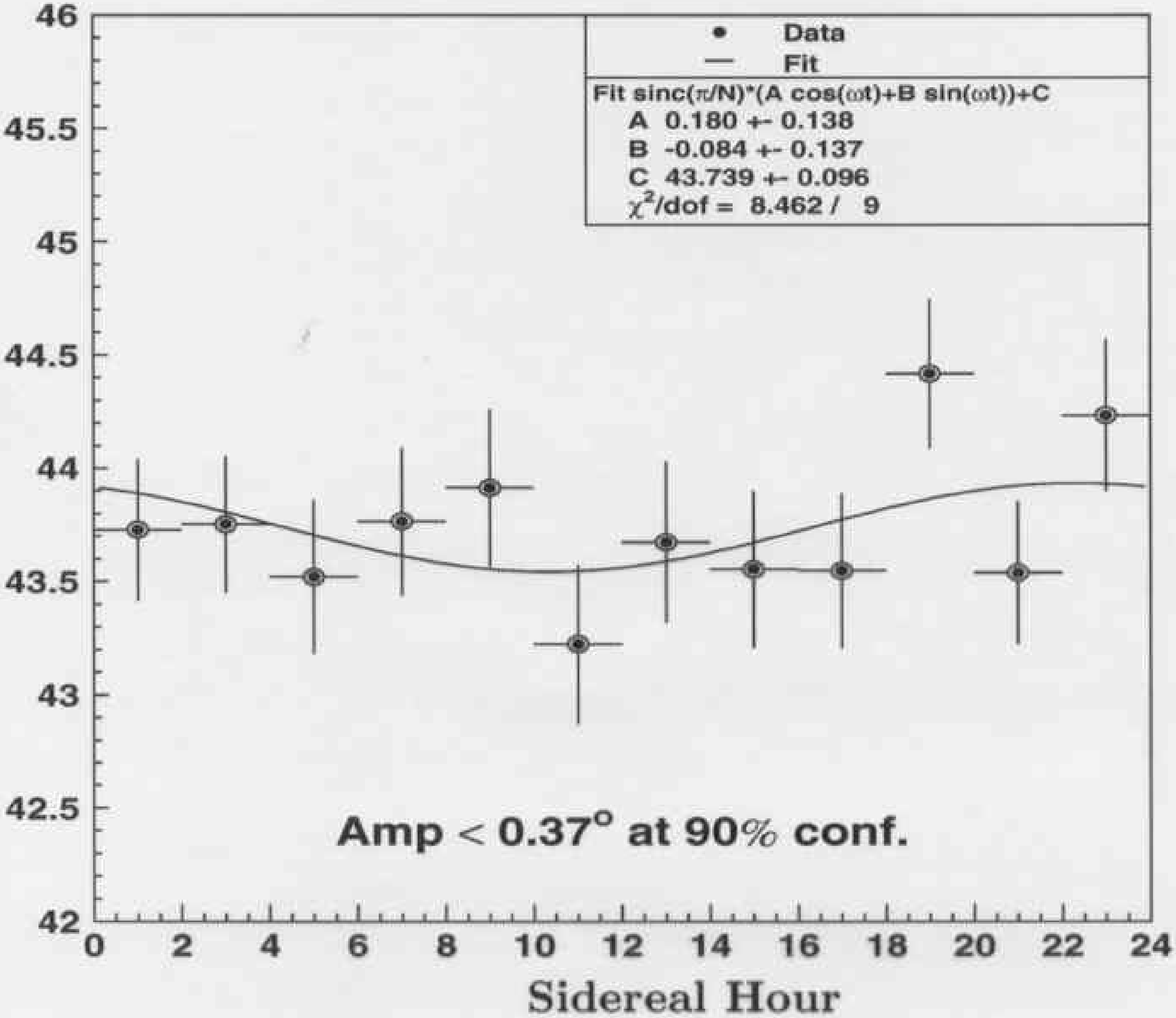
References:

CPLEAR CERN–EP/99-051 — Bell-Steinberger analysis

CPLEAR Phys. Lett. B444 (1998) 52 — Ke3 decay analysis

CPLEAR Phys. Lett. B444(1998) 43 — T-invariance in neutral kaon decays

Sidereal Time Dependence of the η_{+-} Phase.



Summary

- The KTeV measurements of ϕ_{+-}, ϕ_{00}, and δ_L have significantly tightened limits on CPT violation in $K^0 \to 2\pi$ and $K^0 \to \pi e \nu_e$ decays.

- We have searched for (and not found!) evidence of sidereal time dependence in ϕ_{+-} as proposed in a model of V. A. Kostelecky (PRL **80**, 1818 (1998)). We are currently studying the time dependence of δ_L within this model as well.

- We are now analyzing a second equivalent data set from the 1999 run, which will further improve the reach of our CPT studies by reducing *both* the statistical and systematic errors of these measurements.