The Final Measurement of ε'/ε from KTeV

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- Introduction to ε'/ε
- The KTeV Experiment
- Overview of Analysis
- Measurements of ε'/ε and other K^0 parameters
- Other KTeV results
- Summary

KTeV: Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Sao Paolo, UCLA, Virginia, Wisconsin

ε'/ε : Indirect vs. Direct CP Violation

$$K_L \sim K_{odd} + \varepsilon K_{even}$$

"Direct" in decay process — ε' → $\pi\pi$

"Indirect" from asymmetric $K^0 - \overline{K}^0$ mixing → $\pi\pi$

To distinguish between direct and indirect CP violation, compare $K_{L,S} \to \pi^+\pi^-, \pi^0\pi^0$:

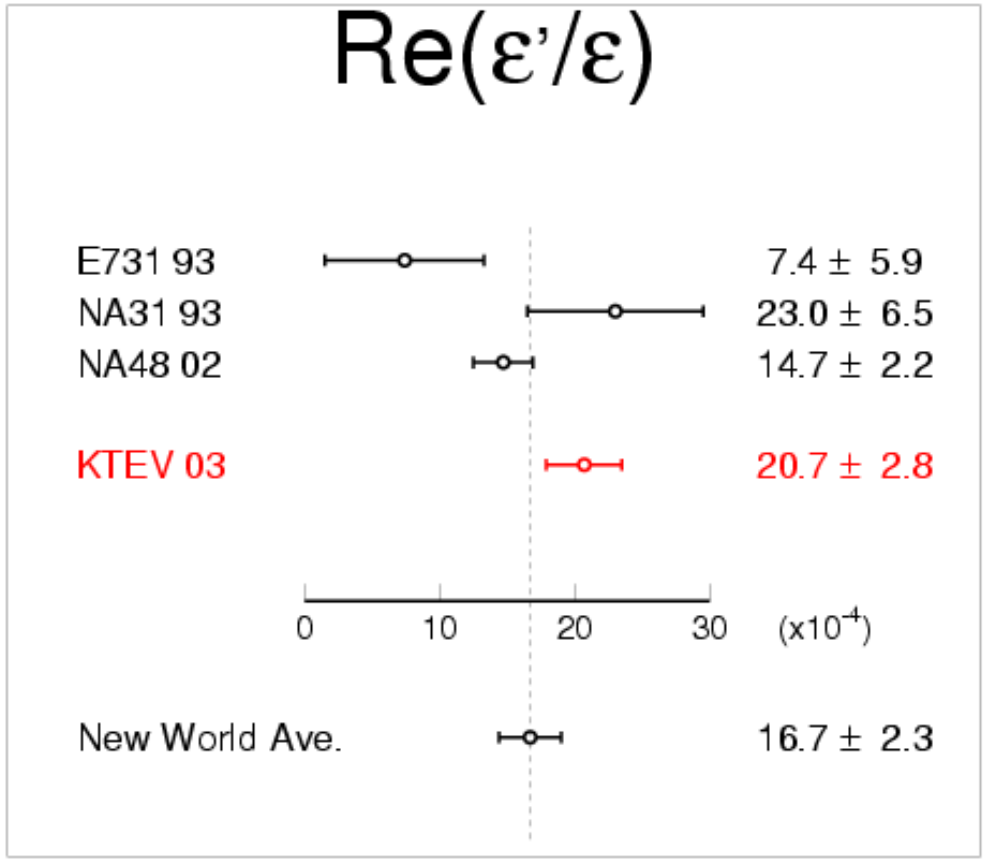
$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1\right]$$

$\varepsilon'/\varepsilon \neq 0$ ⟹ direct CP violation

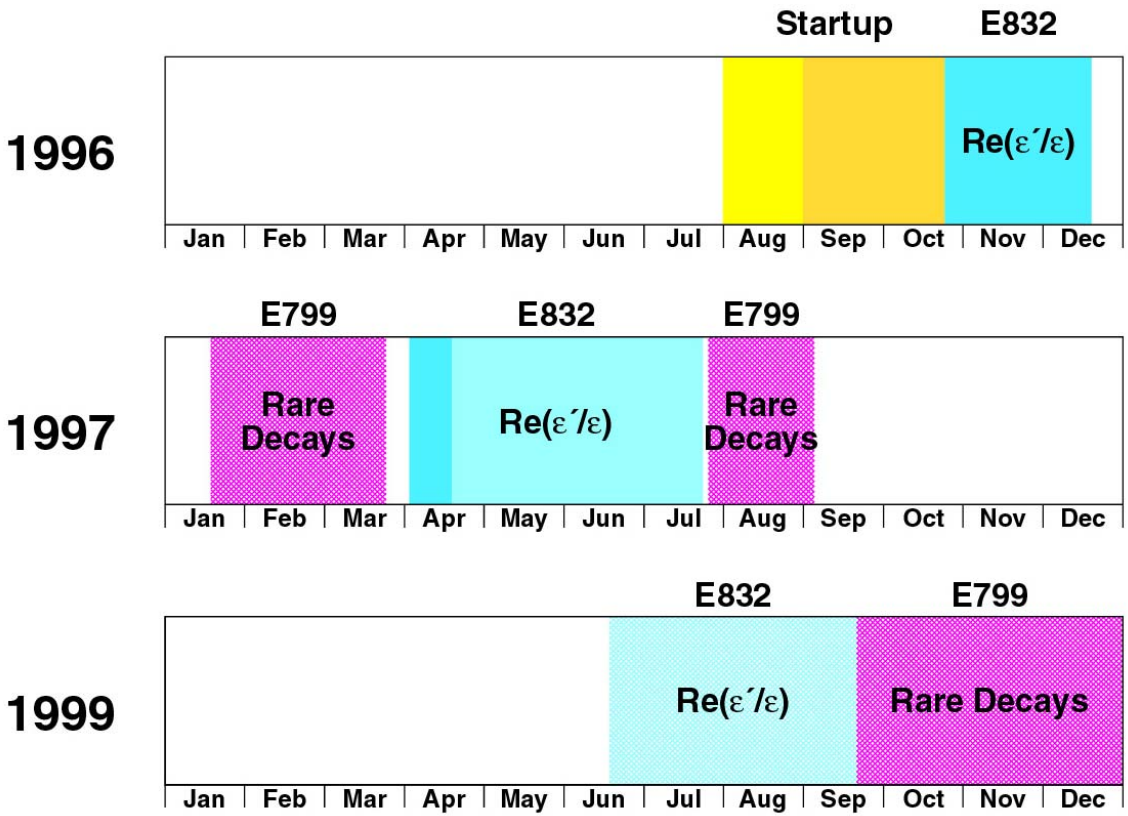
$$K^0 \to \pi^+\pi^- \neq \overline{K}^0 \to \pi^+\pi^-$$

KTeV 2003 Result

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 1.5(\mathrm{stat}) \pm 2.4(\mathrm{syst})) \times 10^{-4}$$
$$= (20.7 \pm 2.8) \times 10^{-4}$$



KTeV Data Samples



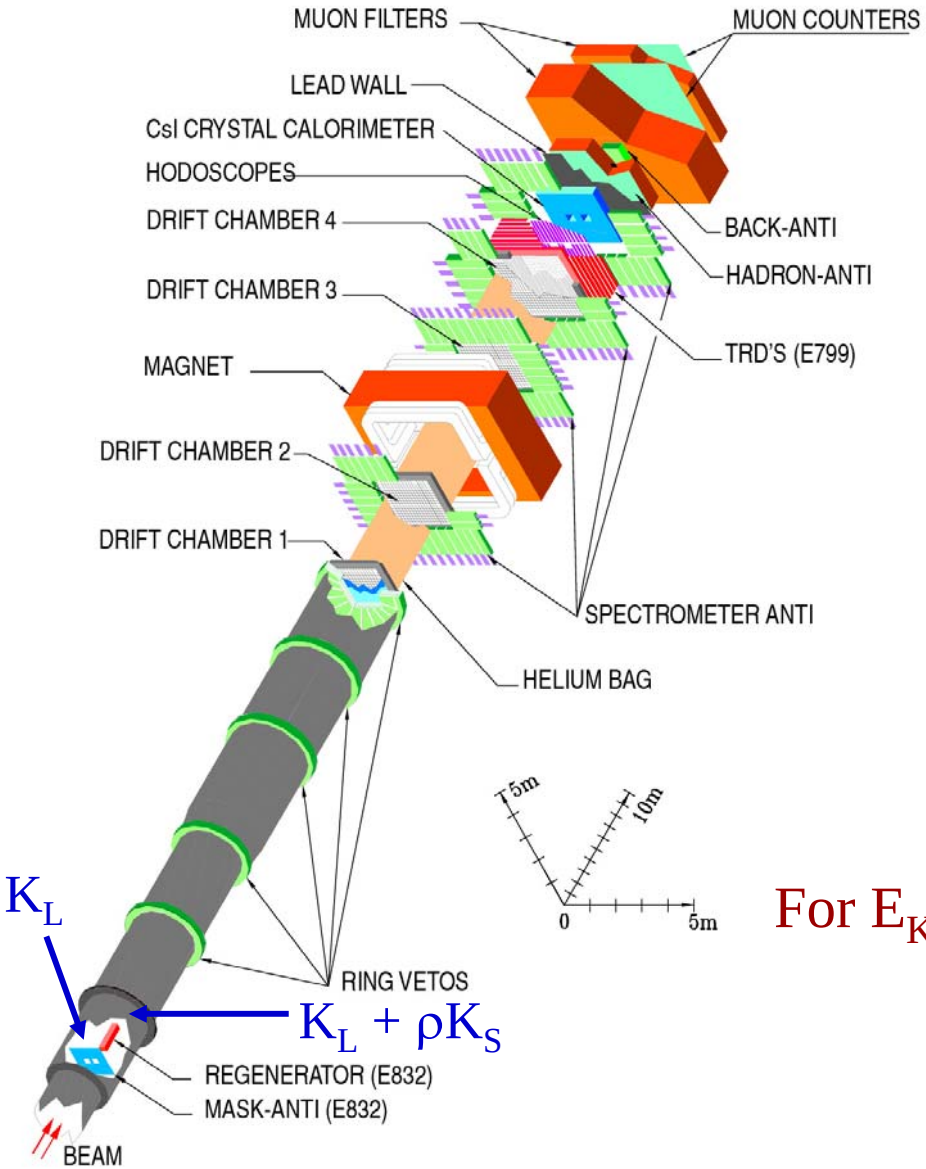
- 2003 result based on ~3 million $K_L \rightarrow \pi^0\pi^0$ decays from 1996 and 1997
  - $\sigma_{stat} = 1.6 \times 10^{-4}$
- 1999 dataset contains ~3 million $K_L \rightarrow \pi^0\pi^0$ decays
  - $\sigma_{stat} = 1.6 \times 10^{-4}$
- Full data sample: $\sigma_{stat} = 1.1 \times 10^{-4}$

Re(ε′/ε) Systematics (2003)

Source of uncertainty	$Re(\epsilon'/\epsilon)$ Uncertainty ($\times 10^{-4}$) from: $K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.58	0.18
CsI energy, position recon	–	1.47
Track reconstruction	0.32	–
Selection efficiency	0.47	0.37
Apertures	0.30	0.48
Background	0.20	1.07
z-dependence of acceptance	0.79	0.39
MC statistics	0.41	0.40
Fitting	0.30	
TOTAL	2.39	

2008 analysis of full data sample includes many improvements in charged and neutral event reconstruction and simulation.

The KTeV Detector



- Charged particle momentum resolution < 1% for p>8 GeV/c; Momentum scale known to 0.01% from $K \to \pi^+\pi^-$.

- CsI energy resolution < 1% for E_γ > 3 GeV; energy scale known to 0.05% from $K \to \pi e \nu$.

For $E_K \sim 70$ GeV, K_S: $\gamma\beta c\tau \sim 3.5$m
K_L: $\gamma\beta c\tau \sim 2.2$ km

$K_S \rightarrow \pi^+\pi^-$

KTEV Event Display

Run Number: 9097
Spill Number: 210
Event Number: 40284859
Trigger Mask: 1
All Slices

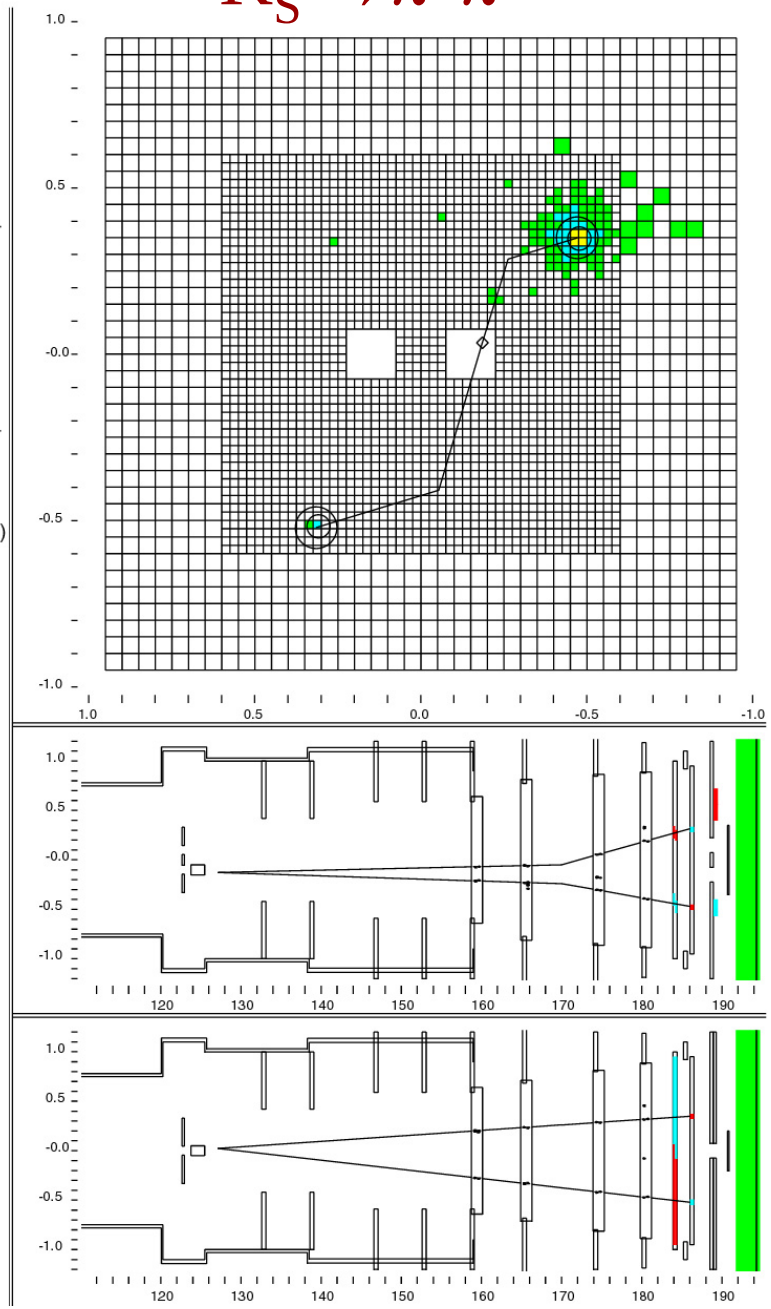
Track and Cluster Info
HCC cluster count: 2

ID	Xcsi	Ycsi	P or E
T 1:	-0.4710	0.3490	-34.98
C 2:	-0.4769	0.3477	17.30
T 2:	0.3155	-0.5218	+19.68
C 1:	0.3088	-0.5177	0.44

Vertex: 2 tracks

X	Y	Z
-0.1265	0.0232	127.122

Mass=0.4994 (assuming pions)
Chisq=0.00 Pt2v=0.000010



- Cluster
- Track
- 10.00 GeV
- 1.00 GeV
- 0.10 GeV
- 0.01 GeV

$K_L \rightarrow \pi^0 \pi^0$

KTEV Event Display

/usr/kpasa/data06/data/postcard_2pi0.dat

Run Number: 6918
Spill Number: 3
Event Number: 337734
Trigger Mask: 8
All Slices

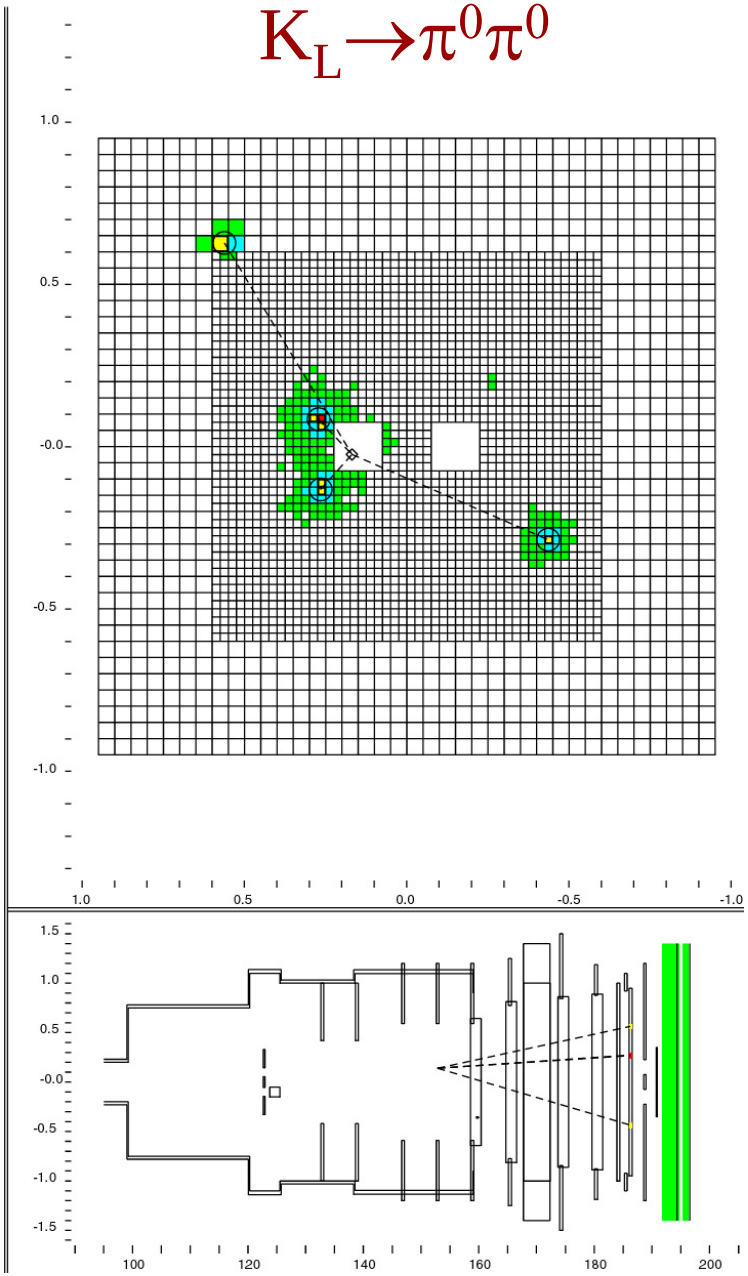
Track and Cluster Info
HCC cluster count: 4

ID	Xcsi	Ycsi	P or E
C 1:	0.5621	0.6272	1.41
C 2:	0.2722	0.0836	26.95
C 3:	0.2656	-0.1320	16.01
C 4:	-0.4359	-0.2878	8.03

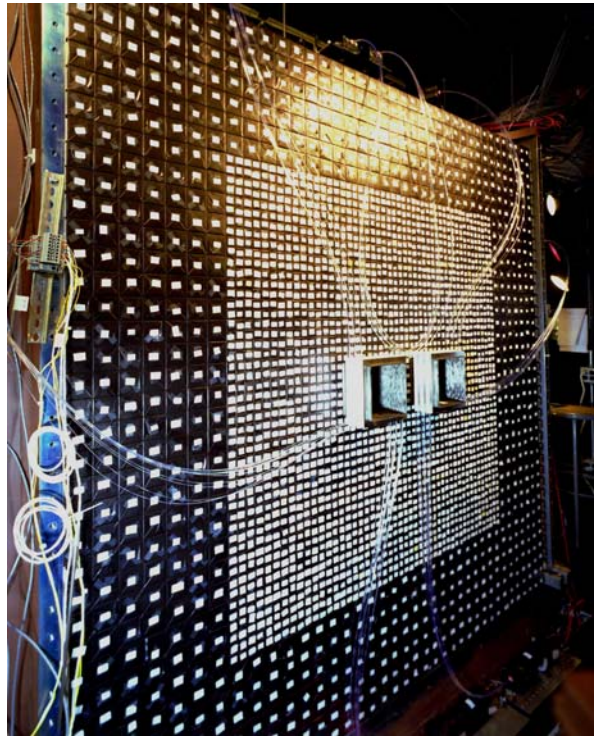
Vertex: 4 clusters

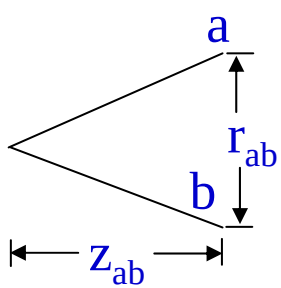
X	Y	Z
0.1390	-0.0202	152.811

Mass=0.4969
Pairing chisq=1.52



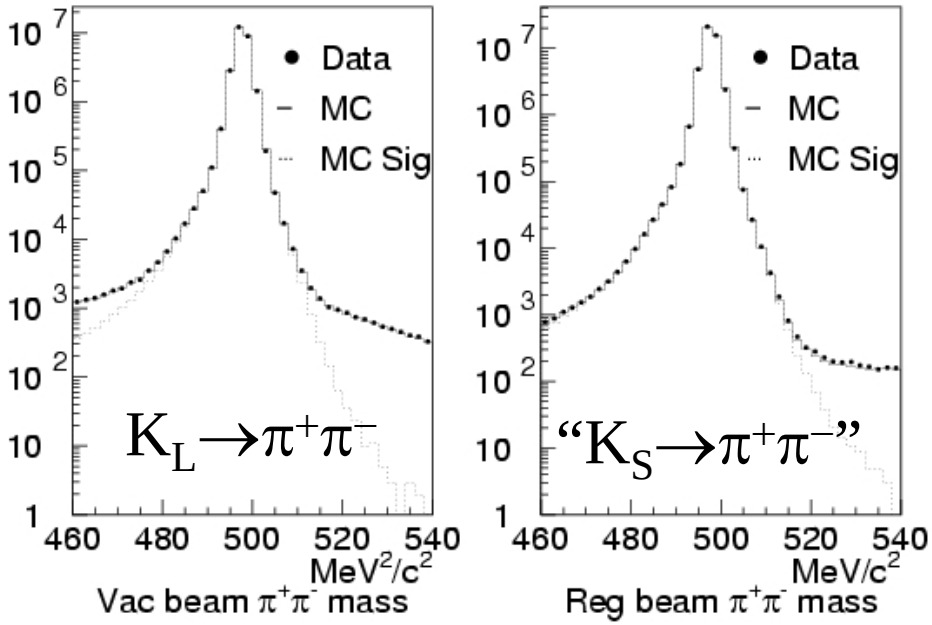
- 10.00 GeV
- 1.00 GeV
- 0.10 GeV
- 0.01 GeV



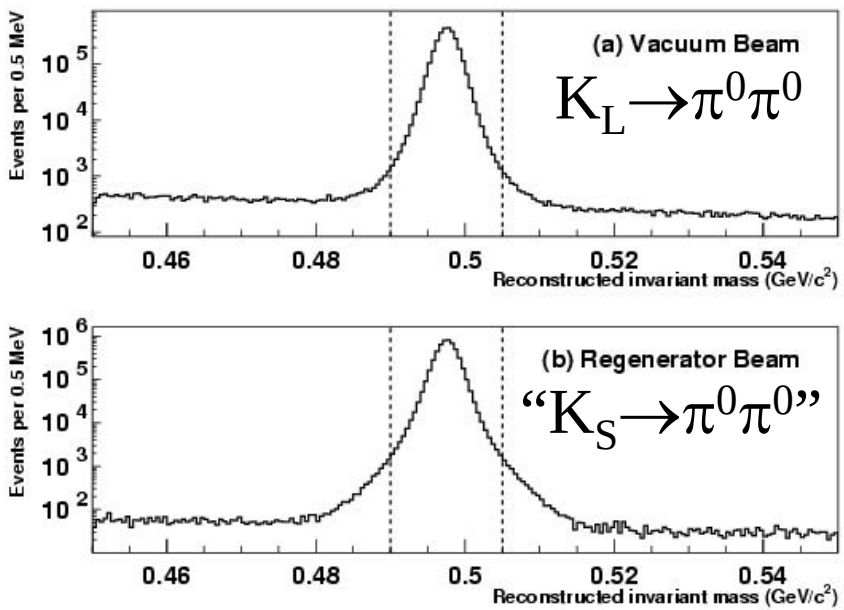


$$z_{ab}^2 \approx \frac{E_a E_b r_{ab}^2}{m_{\pi^0}^2}$$

Invariant Mass Plots



Mass resolution is ~1.5 MeV/c^2 for both decay modes.



Backgrounds and event yields

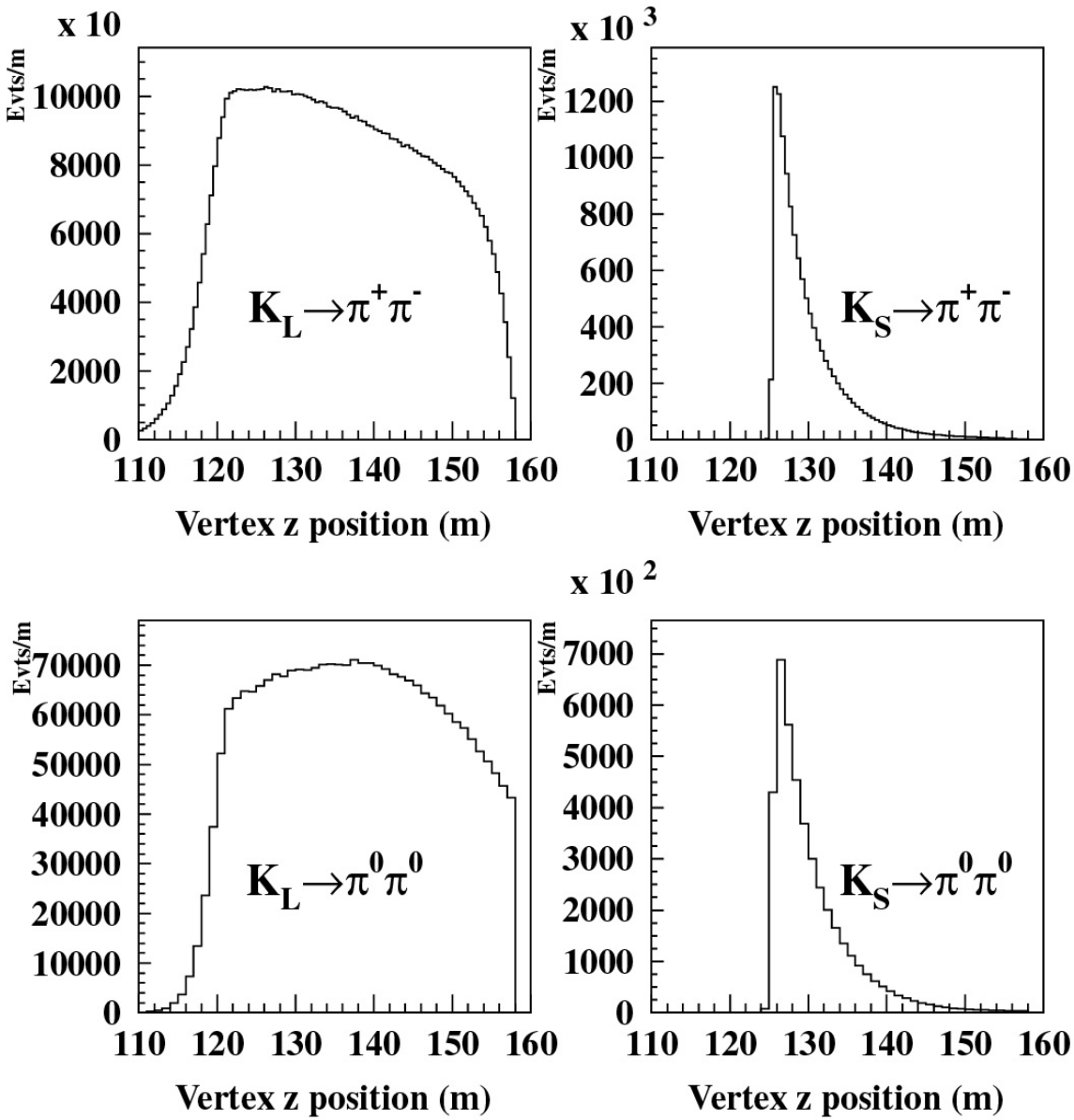
Main classes of background:

- Misidentified kaon decays
  - For $K \to \pi^+\pi^-$: $K_L \to \pi e \nu$, $K_L \to \pi \mu \nu$
  - For $K \to \pi^0\pi^0$: $K_L \to \pi^0\pi^0\pi^0$
- Scattered $K \to \pi\pi$ events
  - From regenerator and final collimator
- Backgrounds are simulated with MC, normalized to data sidebands, and subtracted
- Background level is ~0.1% for charged mode and ~1% for neutral mode.

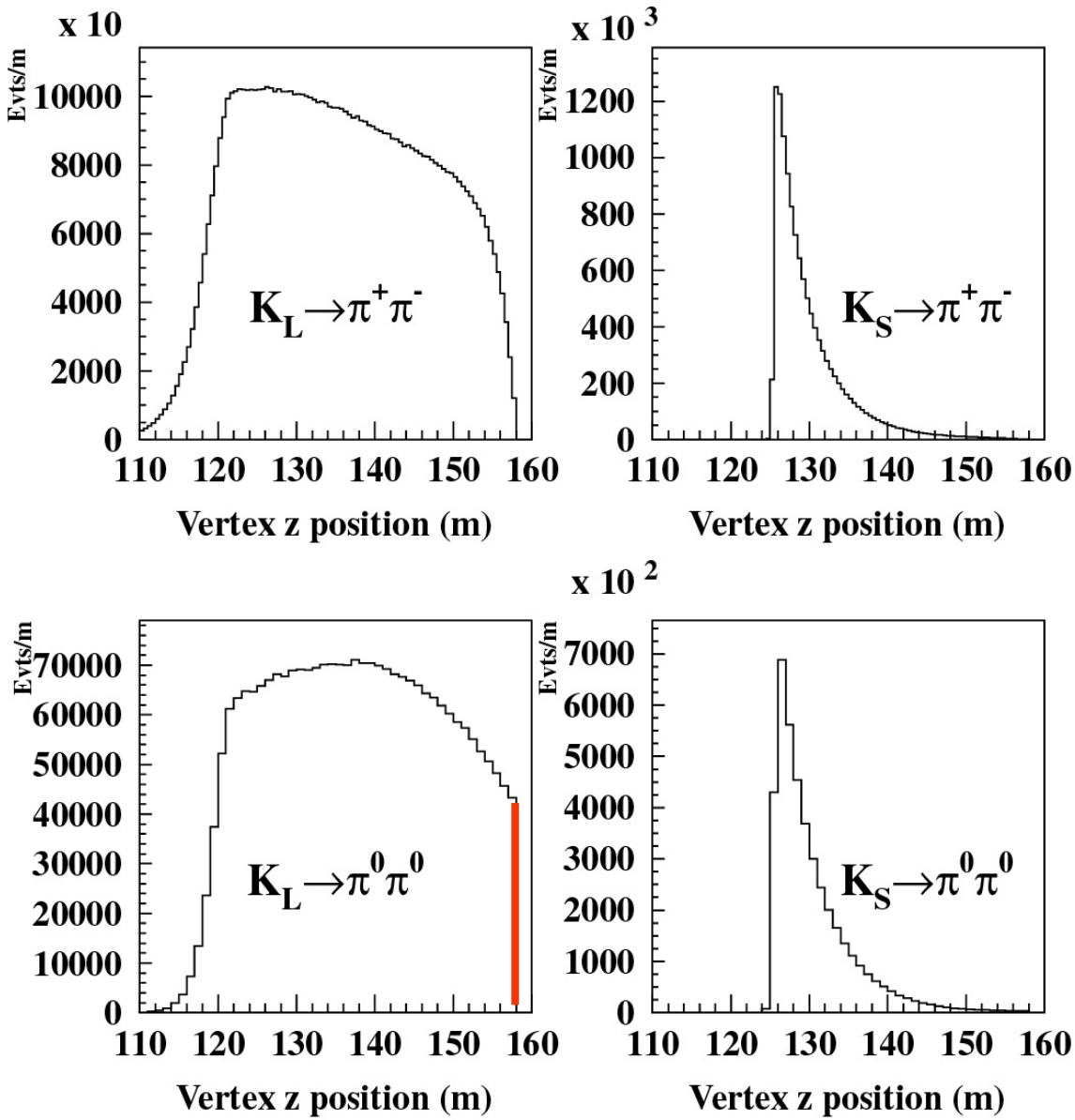
After background subtraction:

	K_L Vacuum Beam	"K_S" Reg. Beam
$K \to \pi^+\pi^-$	25,107,242	43,674,208
$K \to \pi^0\pi^0$	5,968,198	10,180,175

Reconstructed Vertex z Distributions



Reconstructed Vertex z Distributions



0.1% shift in E scale: ~3 cm shift in vertex; ~1×10^{-4} shift in ε'/ε

Acceptance Correction

- A detailed Monte Carlo simulation based on measured detector geometry and response is used to calculate acceptance as a function of p,z, and beam (reg or vac).
- Includes effects of accidental activity.

Many improvements compared to 2003 analysis:

More complete treatment of particle interactions with matter:

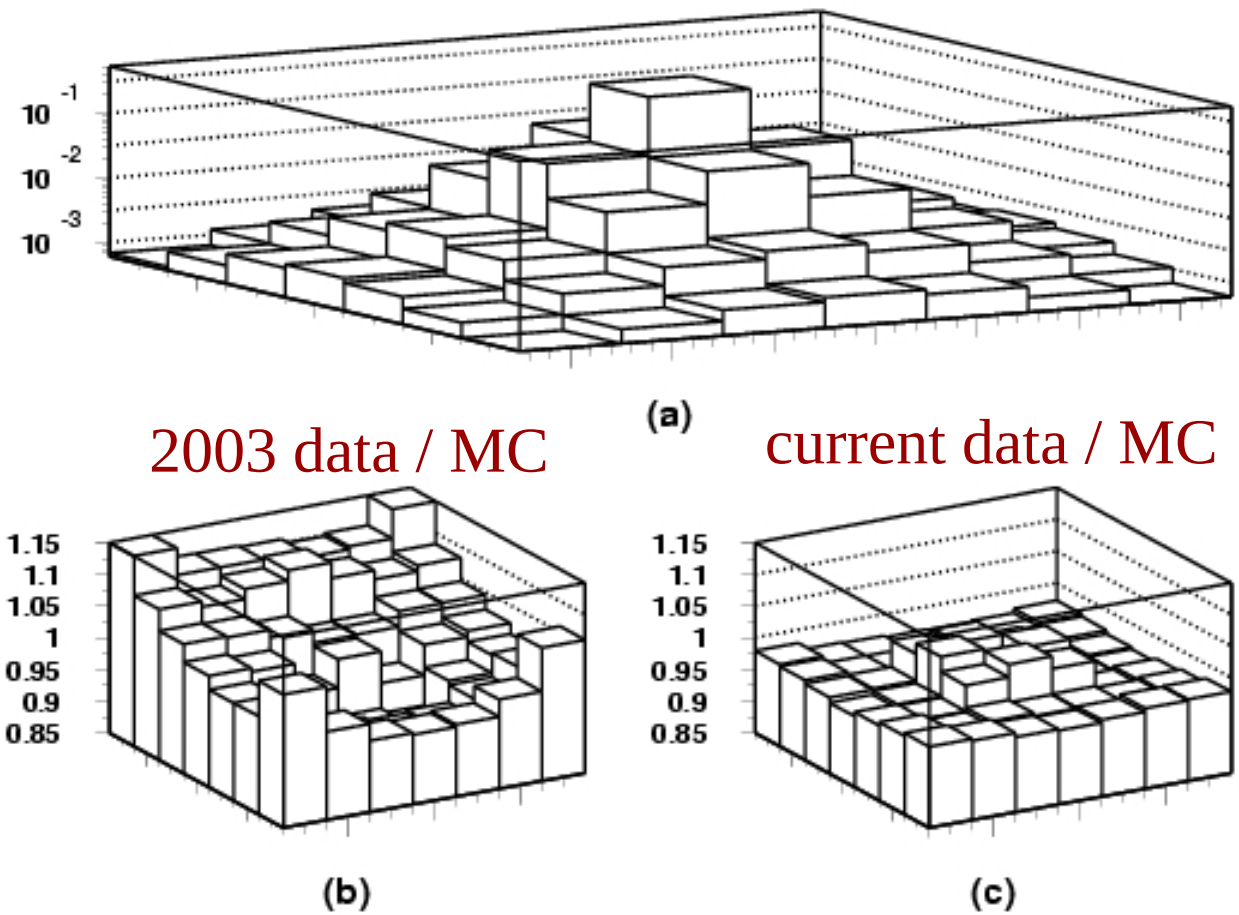
- Ionization energy loss
- Improved Bremsstrahlung
- Improved delta rays
- Hadronic interactions in drift chambers

Improved electromagnetic shower simulation:

- Shower library binned in incident particle angle
- Simulate effects of dead material (wrapping and shims) in CsI calorimeter

Monte Carlo Improvements: Simulation of photon angles

Fraction of energy in 49 crystals for electron shower

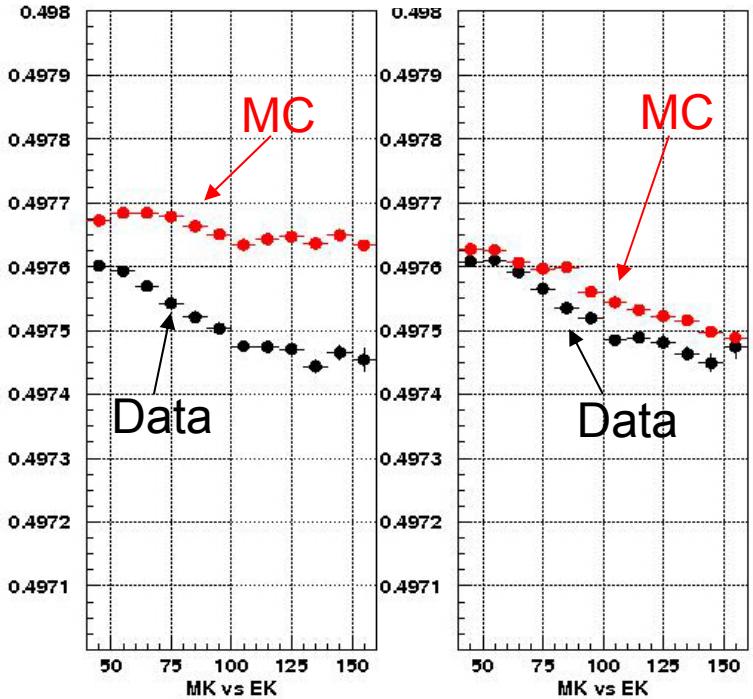


20-30 mrad incident angles used

Improved Modeling of Energy Nonlinearities

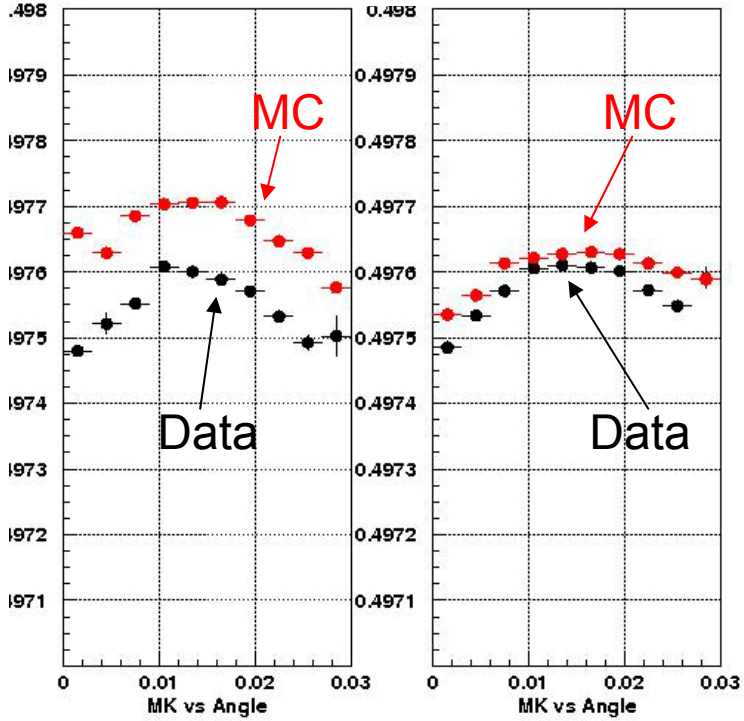
Mass vs. Energy

2003 Current



Mass vs. Photon Angle

2003 Current



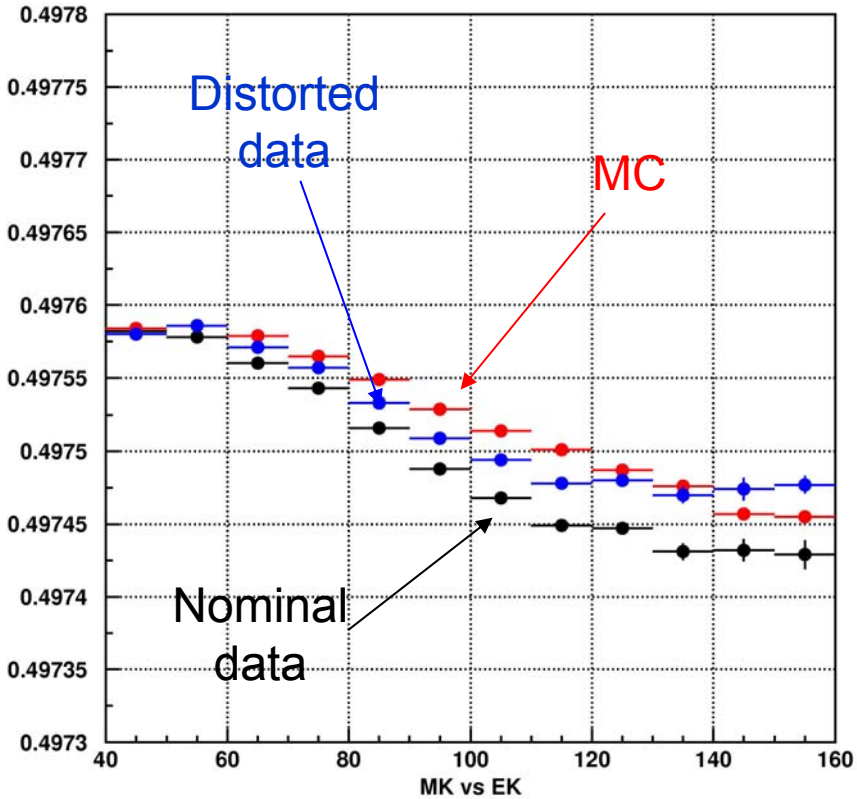
Systematic Uncertainties in Re(ε′/ ε)

Source	Error on $Re(\epsilon'/\epsilon)$ $(\times 10^{-4})$ $K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.23	0.20
CsI cluster reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Backgrounds	0.20	1.07
MC statistics	0.20	0.25
Total	0.81	1.55
Fitting	0.31	
Total	1.78	

Reduced from 1.47

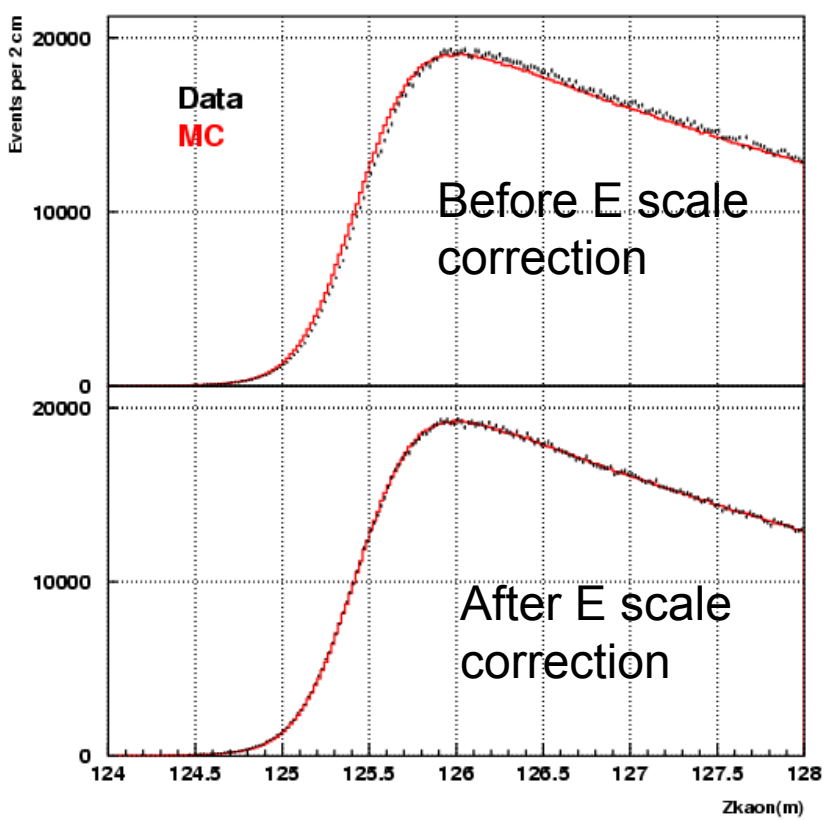
Uncertainty from Energy Non-linearity

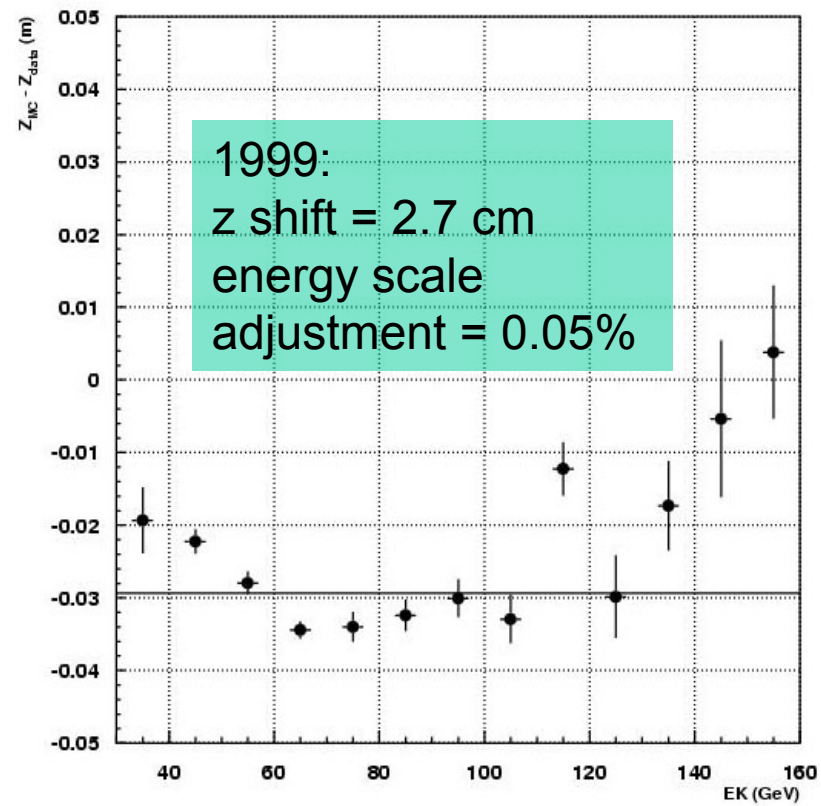
- Use M_K vs E_K plot to determine distortion that provides best data-MC match
- 0.1%/100 GeV nonlinearity applied to data for 1997 and 1999
- 0.3%/100 GeV nonlinearity for 1996
- Change in Re(e′/e)
  - 1996: -0.1×10^{-4}
  - 1997: -0.1×10^{-4}
  - 1999: $+0.2 \times 10^{-4}$
- Systematic error: $\pm 0.15 \times 10^{-4}$



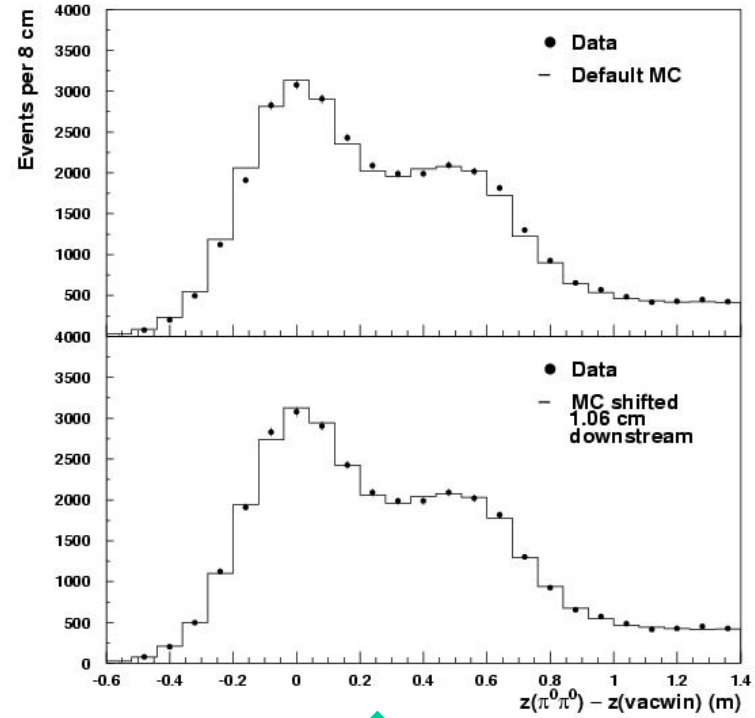
Calorimeter Energy Scale

- Calorimeter calibrated with 1.5 billion momentum-analyzed electrons from $K \rightarrow \pi e \nu$
- Final energy scale adjustment based on $K \rightarrow \pi^0 \pi^0$ at regenerator edge

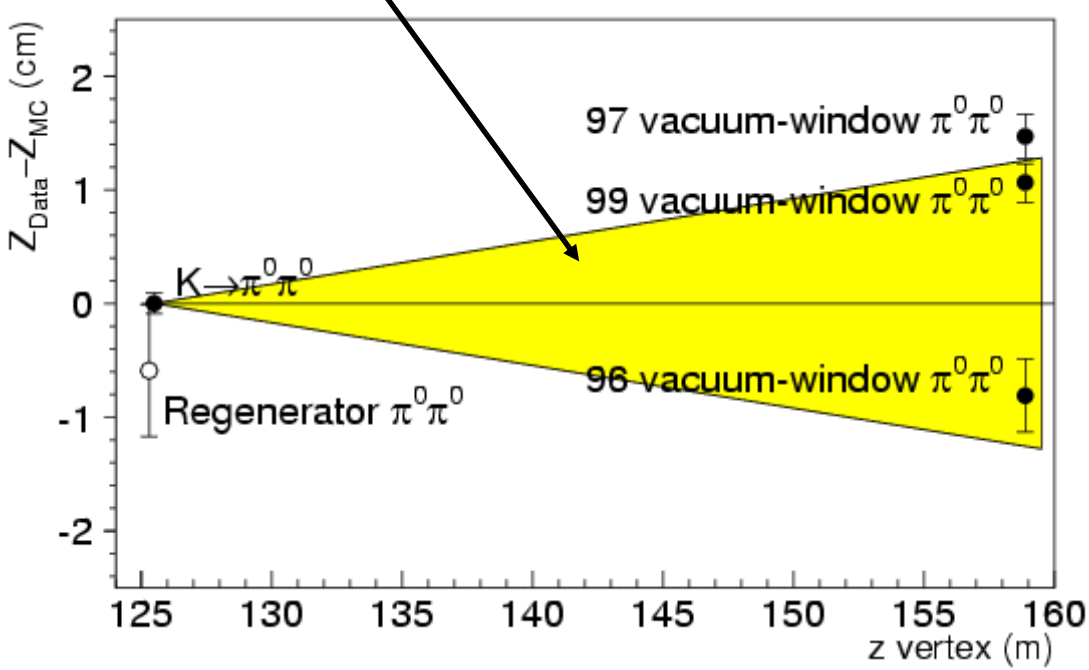




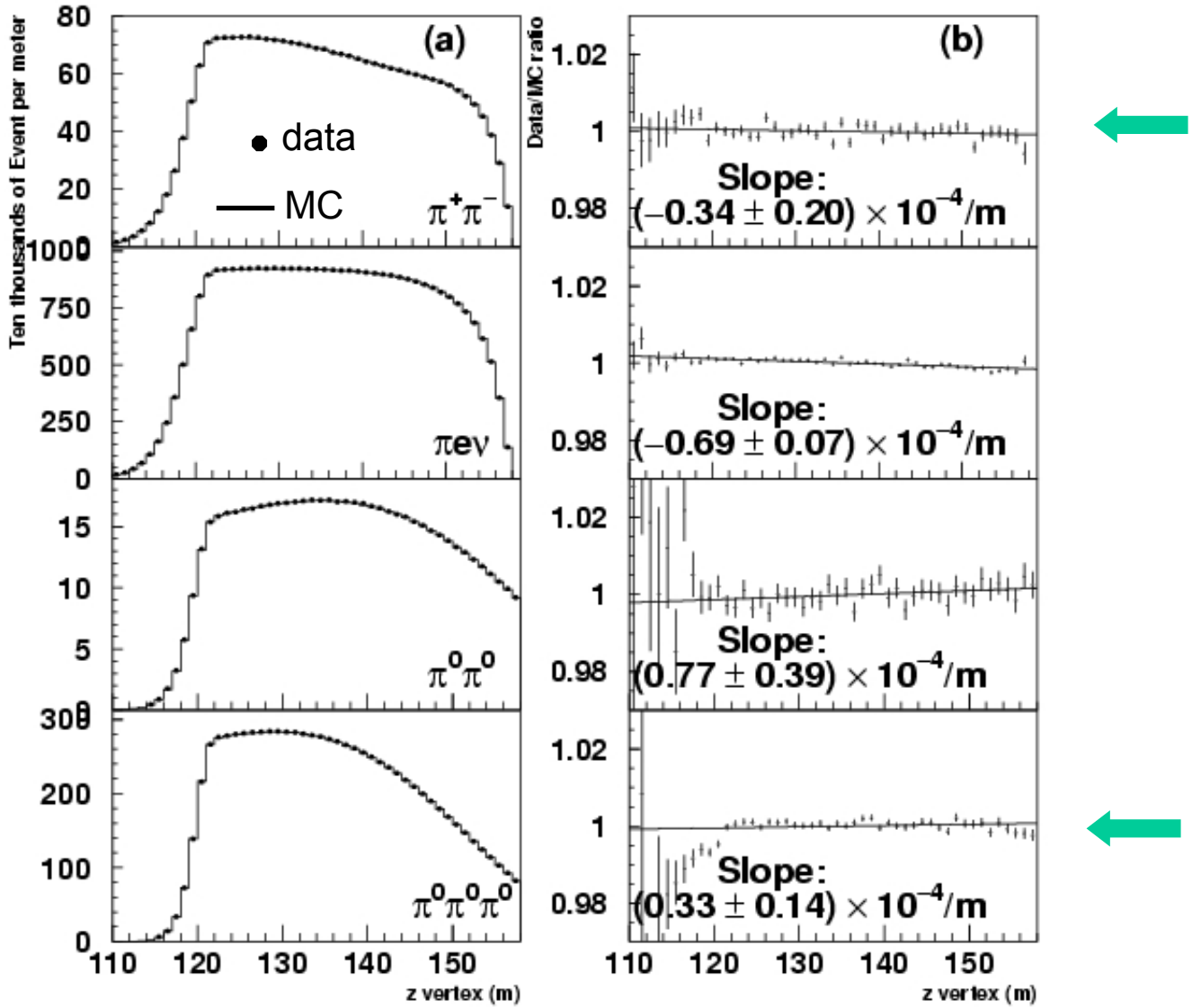
Energy scale fixed at regenerator edge → check scale at vacuum window.



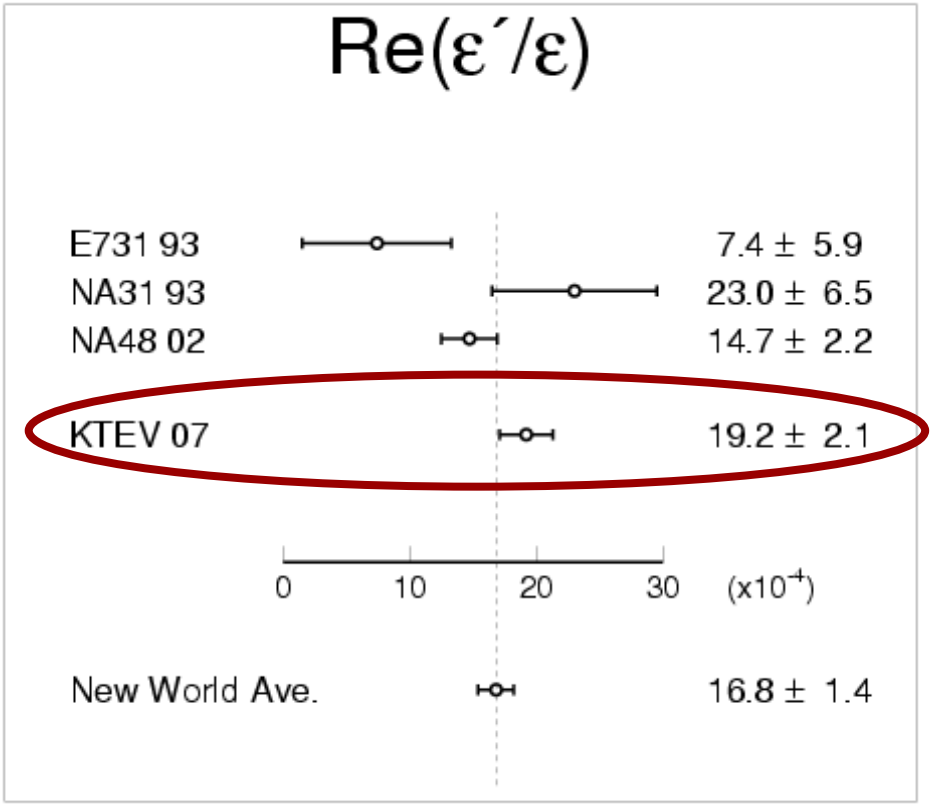
Uncertainty in Re(ε′/ε): ±0.65 × 10^{-4}



Data – MC comparisons of z vertex distributions



KTeV Result: $\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})] \times 10^{-4}$
$= (19.2 \pm 2.1) \times 10^{-4}$

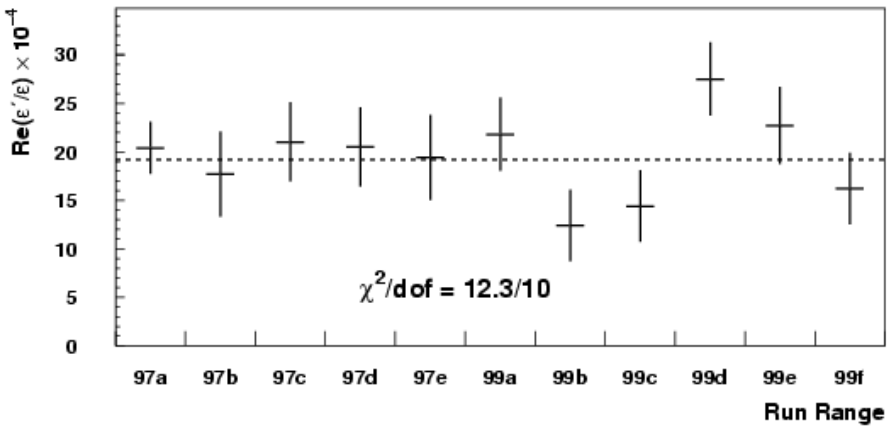


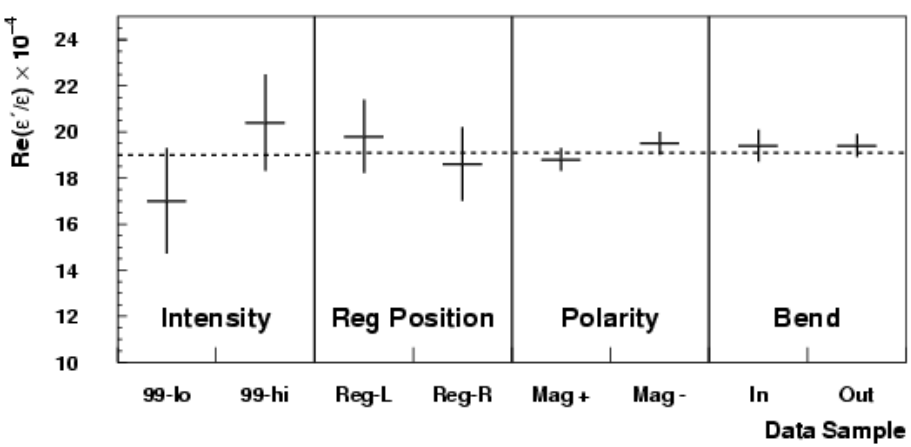
World average:
$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$
(confidence level = 13%)

(KTeV 2003: $\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\mathrm{stat}) \pm 2.4\ (\mathrm{syst})] \times 10^{-4}$)

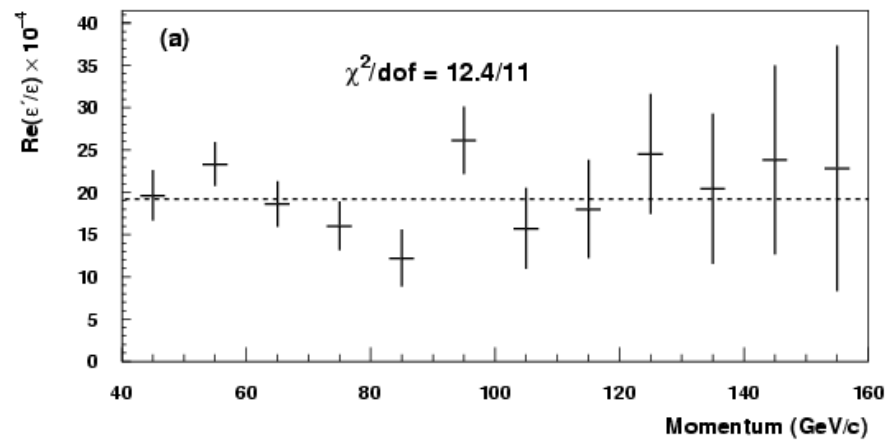
Re(ε′/ε) Cross checks

Run Ranges

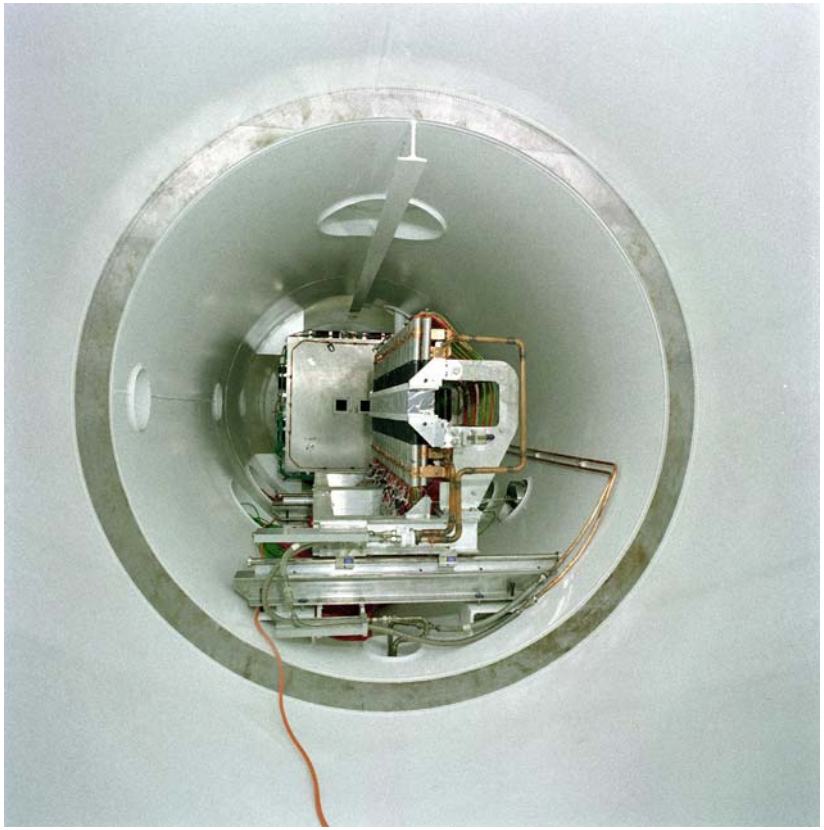


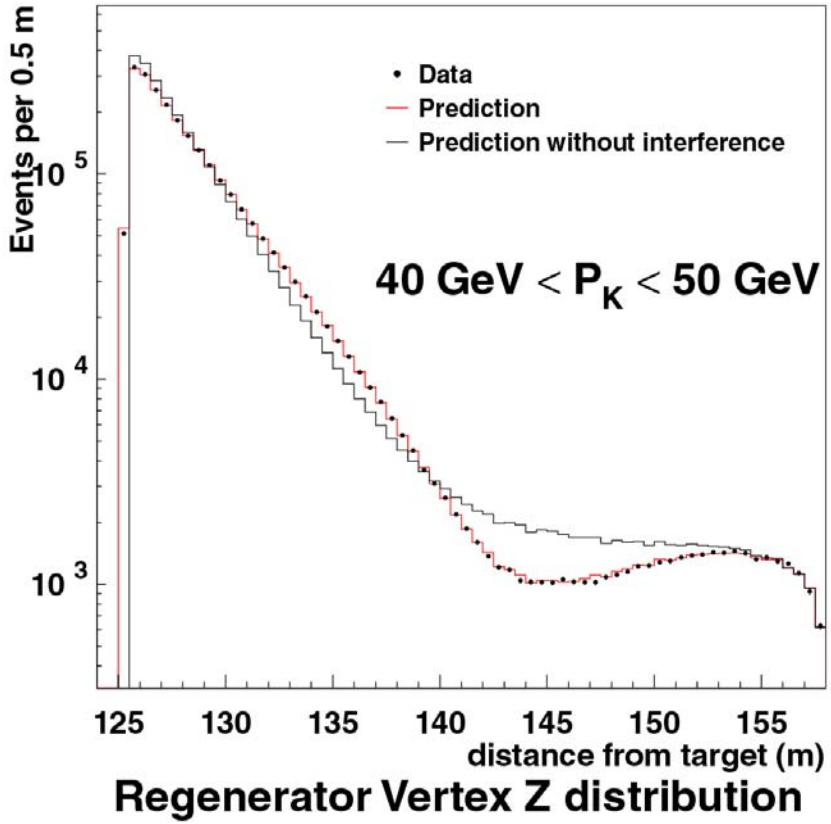


Momentum Bins



K_L - K_S Interference Downstream of Regenerator





$$R_{\pi\pi} \propto |\eta|^2 e^{-\Gamma_L t} + |\rho|^2 e^{-\Gamma_S t} + 2|\eta||\rho| e^{-(\Gamma_S+\Gamma_L)t/2} \cos(\Delta m t + \Phi_\rho - \Phi_\eta)$$

Fit Strategy for z-binned Fits

- In contrast with Re(ε′/ε) fit, in which a single ~50 m z bin is considered, we now fit the regenerator beam data in 2 m z bins.
- Float $\Delta m = m_L - m_S$, τ_S, ϕ_ε, Re(ε′/ε), Im(ε′/ε) with no CPT assumption.
- CPT constraint ($\phi_\varepsilon = \phi_{SW}$ and Im(ε′/ε)=0) then applied *a posteriori* to find best values τ_s, Δm.

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

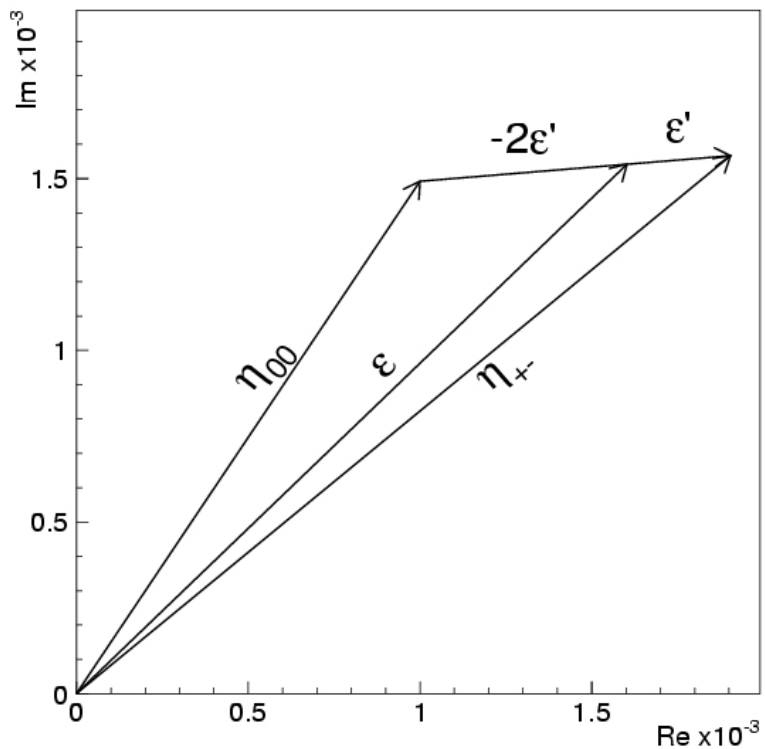
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\phi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right)$$

$$\phi_{+-} \approx \phi_\varepsilon + \mathrm{Im}(\varepsilon'/\varepsilon)$$

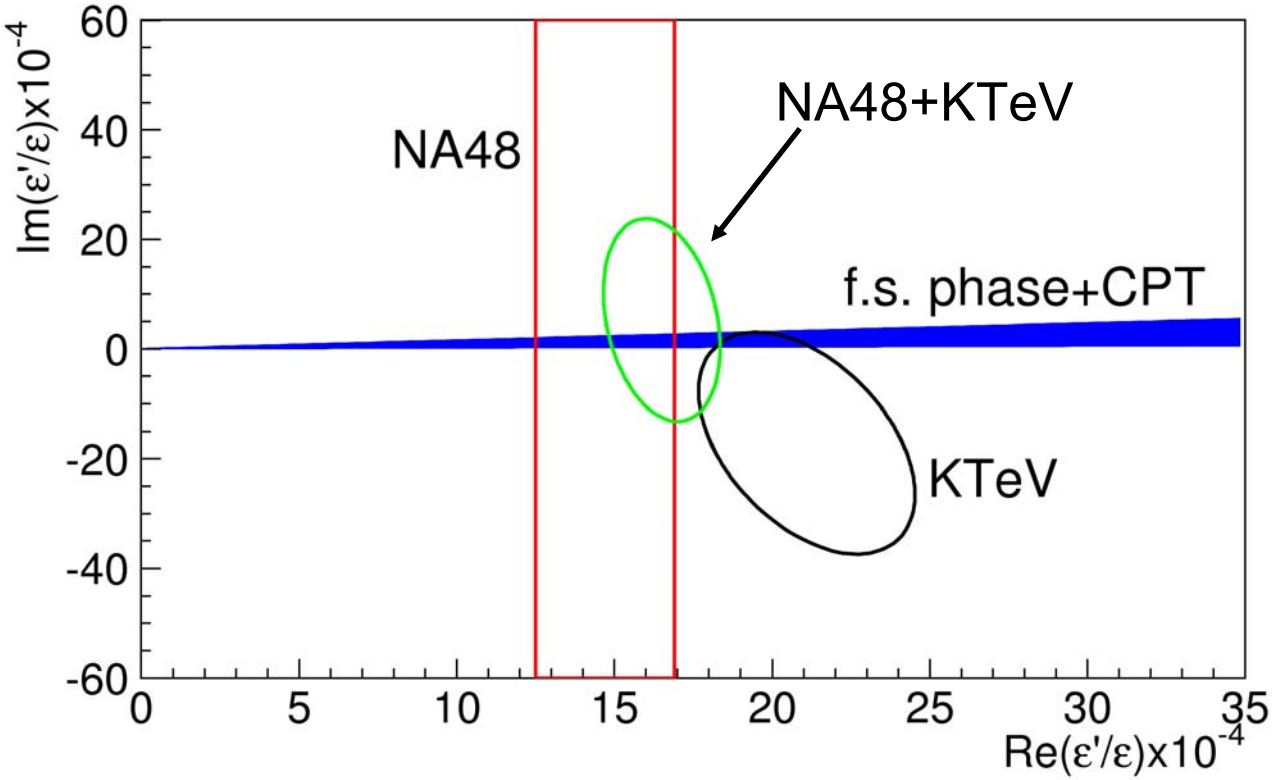
$$\phi_{00} \approx \phi_\varepsilon - 2\,\mathrm{Im}(\varepsilon'/\varepsilon)$$

$$\Delta\phi \equiv \phi_{00} - \phi_{+-} \approx -3\,\mathrm{Im}(\varepsilon'/\varepsilon)$$



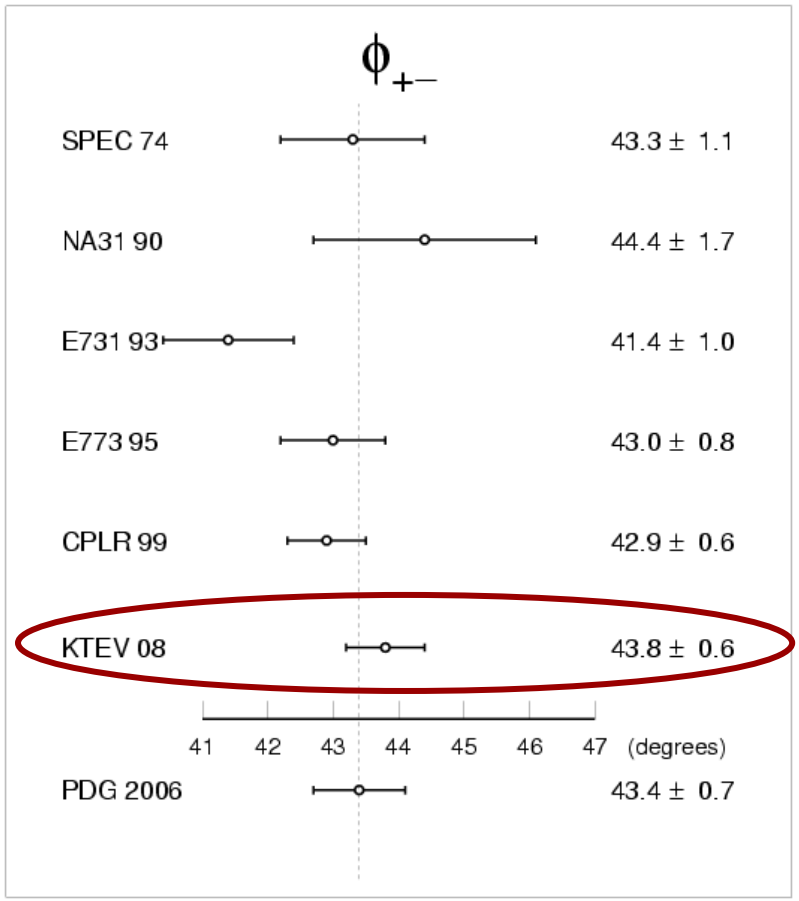
z-binned Fit Results

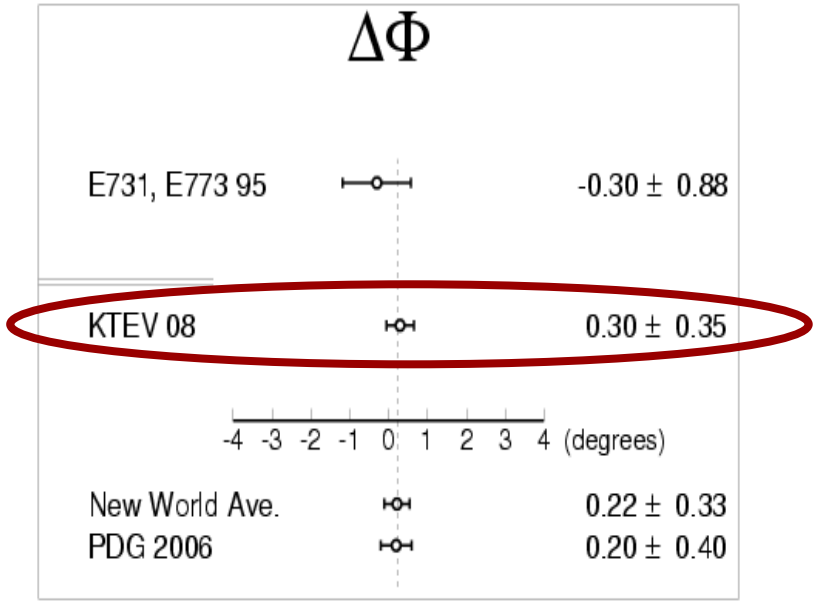
$$\phi_\varepsilon = (43.86 \pm 0.63)^\circ$$
$$\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)^\circ$$
$$\Delta\phi = (0.30 \pm 0.35)^\circ$$



All results consistent with CPT symmetry

ϕ_{+-} and $\Delta\phi$

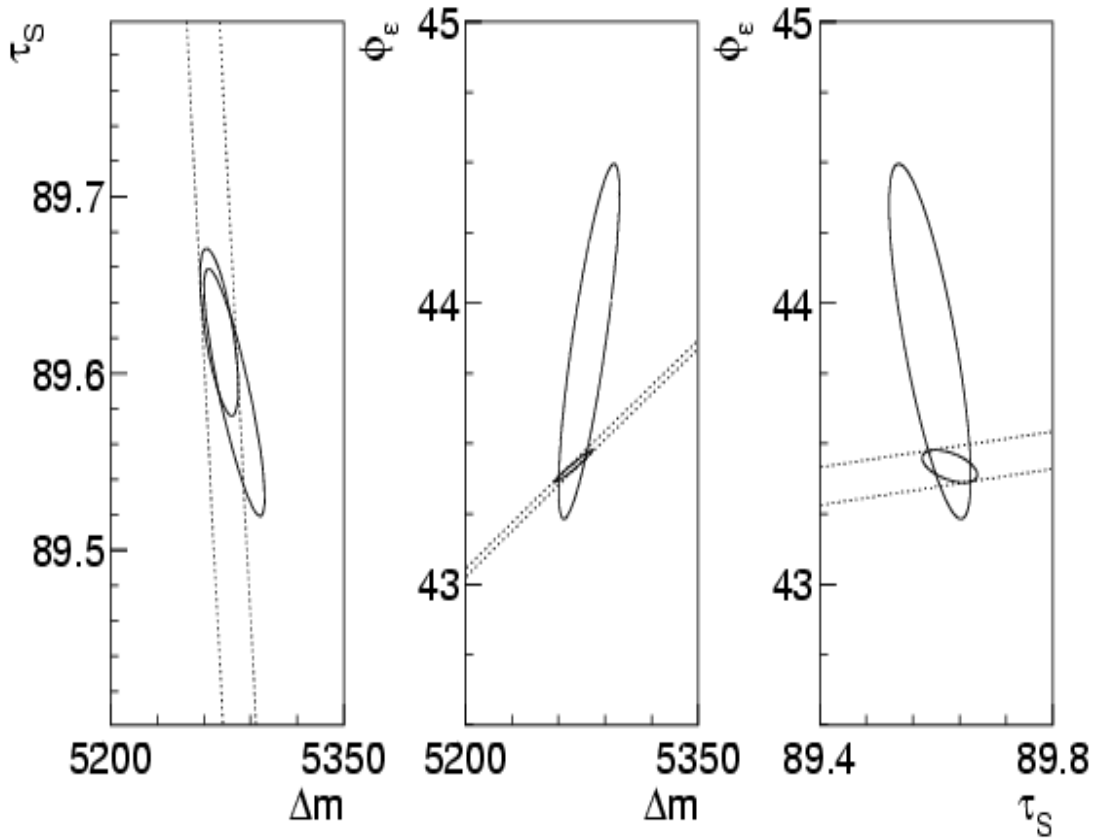




KTeV 2003: $\phi_{+-} = (44.1 \pm 1.4)°$

KTeV 2003: $\Delta\phi = (0.39 \pm 0.50)°$

z-binned Fit Results (cont)



No CPT constraint:

$\Delta m = (5279.7 \pm 19.5) \times 10^6\ \hbar s^{-1}$

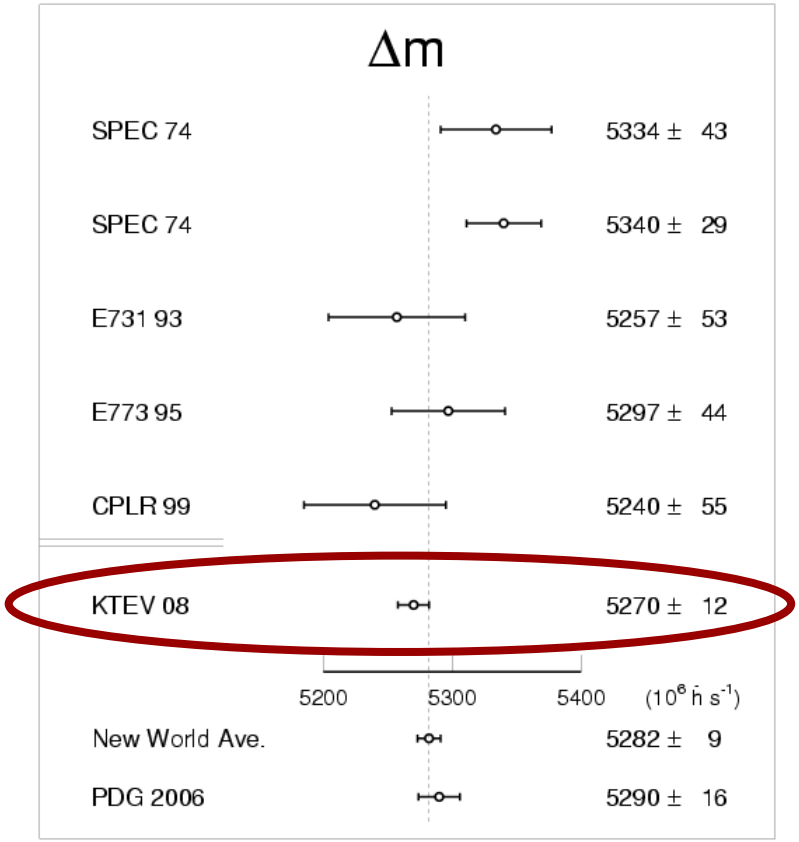
$\tau_S = (89.589 \pm 0.070) \times 10^{-12}$ s

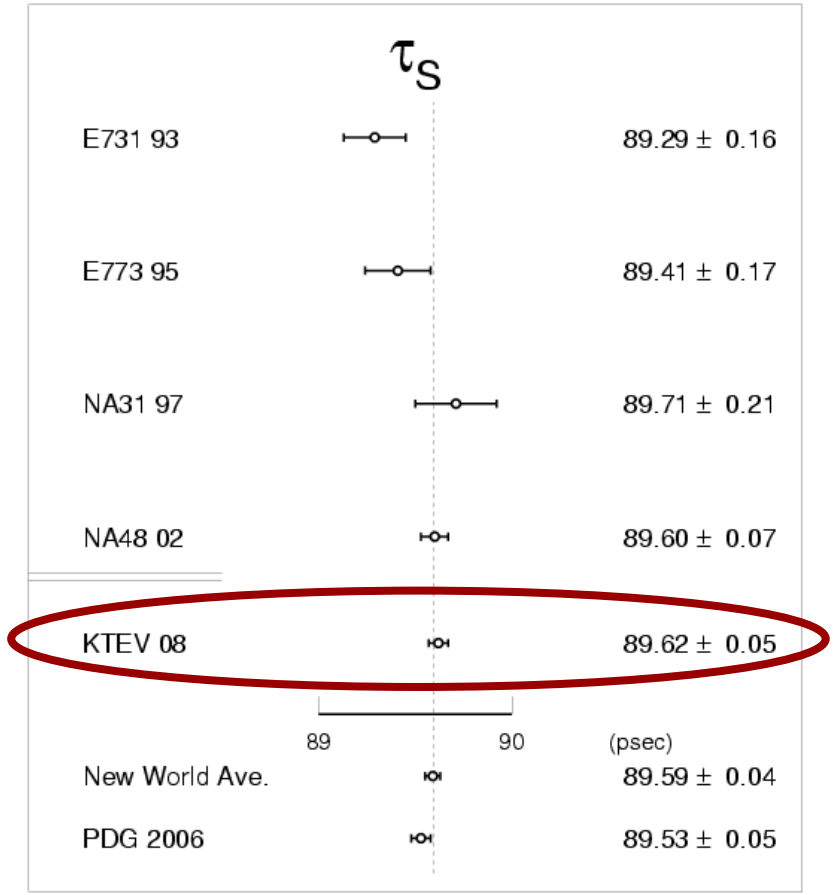
CPT constraint applied:

$\Delta m = (5269.9 \pm 12.3) \times 10^6\ \hbar s^{-1}$

$\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s

Δm and τ_S





KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6\ \hbar s^{-1}$

KTeV 2003: $\tau_S = (89.65 \pm 0.07) \times 10^{-12}$ s

Other Recent KTeV Results

Searches for lepton flavor violation:

$B(K_L \to \pi^0 \mu e) < 7.6 \times 10^{-11}$ (90% CL)

$B(K_L \to \pi^0 \mu e) < 1.7 \times 10^{-10}$ (90% CL)

$B(\pi^0 \to \mu e) < 3.6 \times 10^{-10}$ (90% CL)

arXiv:0711.3472
accepted by PRL

π^0 Physics using $K_L \to \pi^0\pi^0\pi^0$ decays

$B(\pi^0 \to e^+e^-e^+e^-) = (3.26 \pm 0.18) \times 10^{-5}$
(+ new determination of π^0 parity)

arXiv:0802.2064
submitted to PRL

$$B(\pi^0 \to e^+e^-\gamma) / B(\pi^0 \to \gamma\gamma)$$
$$= (1.1539 \pm 0.0045 \pm 0.0152)\%$$

Prel., paper in preparation

Summary

KTeV Preliminary:

- $\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
- $\Delta m = (5269.9 \pm 12.3) \times 10^{6}\ \hbar s^{-1}$
- $\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s

Assuming CPT

- $\phi_e = (43.86 \pm 0.63)°$
- $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$
- $\Delta\phi = (0.30 \pm 0.35)°$

No CPT assumption

- Direct CP violation measured precisely:

$$\frac{Rate(K^0 \to \pi^+\pi^-) - Rate(\bar{K}^0 \to \pi^+\pi^-)}{Rate(K^0 \to \pi^+\pi^-) + Rate(\bar{K}^0 \to \pi^+\pi^-)} = (5.5 \pm 0.5) \times 10^{-5}$$

- Future lattice calculations may make these precise measurements equally precise tests of the Standard Model.

- All measurements consistent with CPT symmetry.