

The Final Measurement of ϵ'/ϵ from KTeV

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Overview

- Introduction
- The KTeV Experiment
- Data Analysis
- Monte Carlo Simulation
- Backgrounds
- Systematic Uncertainties
- Results

CP Violation in Kaon System

$$K_L = \overset{\text{CP}-1}{K_2} + \epsilon \overset{\text{CP}+1}{K_1}$$

“Direct” in decay process ϵ' \downarrow “Indirect” from asymmetric $K^0-\bar{K}^0$ mixing
 $\pi\pi$
 CP +1

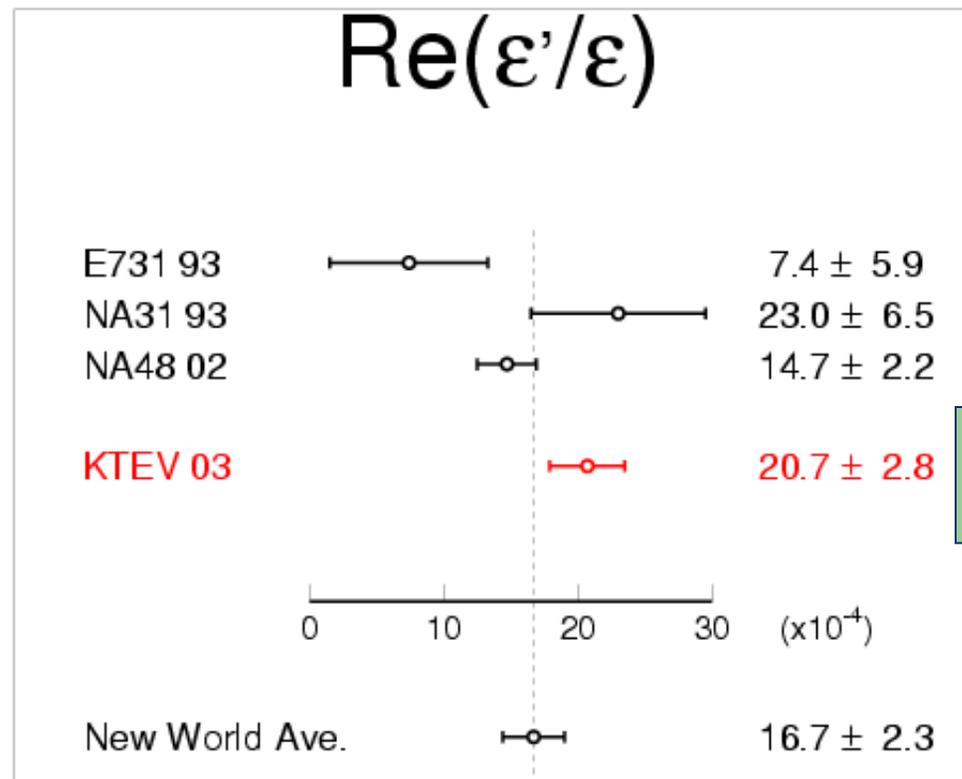
$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon'$$

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

If CPT: $\phi_\epsilon \approx \phi_{\epsilon'}$
 $\text{Re}(\epsilon'/\epsilon) \rightarrow$ direct CP violation
 $\text{Im}(\epsilon'/\epsilon) \rightarrow$ CPT violation

$$\text{Re}(\epsilon'/\epsilon) \approx \frac{1}{6} \left(\left| \frac{\eta_{+-}}{\eta_{00}} \right|^2 - 1 \right)$$

Previous Results



Data from 1996
and 1997

$$\text{Re}(\epsilon'/\epsilon) = [20.7 \pm 1.48(\text{stat}) \pm 2.39(\text{syst})] \times 10^{-4}$$

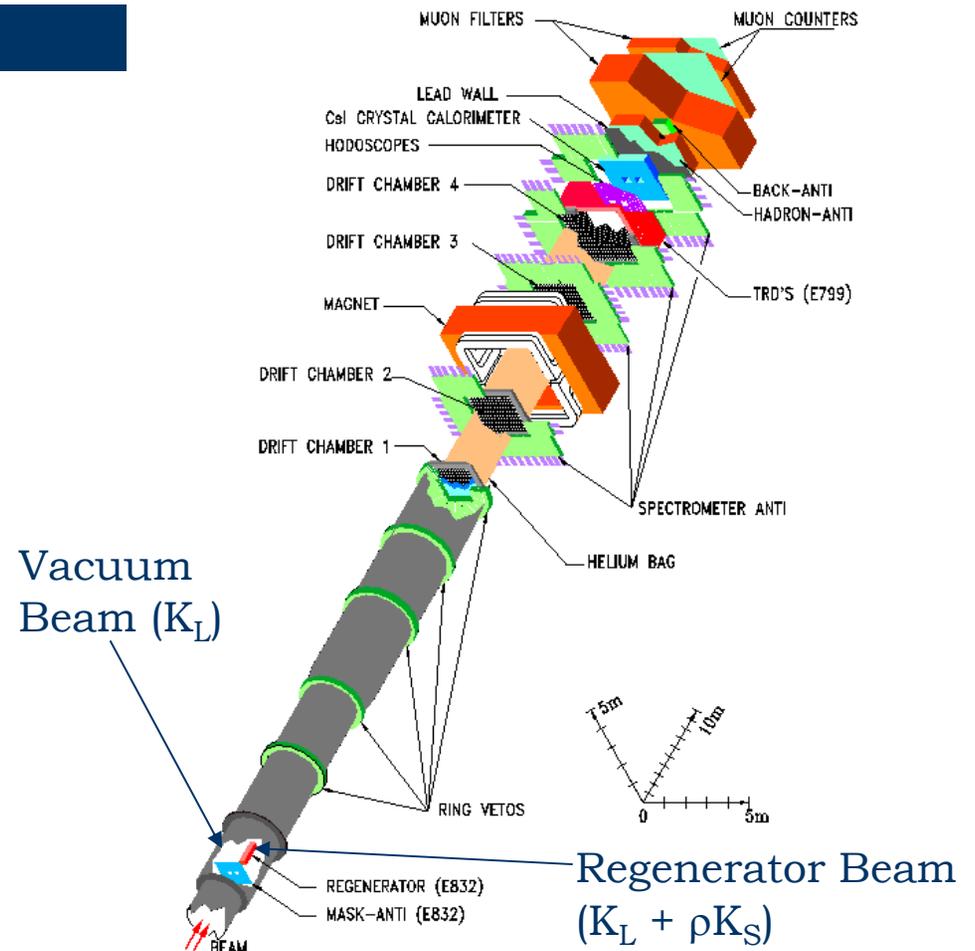
Re(ϵ'/ϵ) Uncertainties (2003)

Source of uncertainty	Re(ϵ'/ϵ) Uncertainty ($\times 10^{-4}$)	
	from:	
	$K \rightarrow \pi^+ \pi^-$	$K \rightarrow \pi^0 \pi^0$
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

Statistical
Uncertainty:
 1.5×10^{-4}

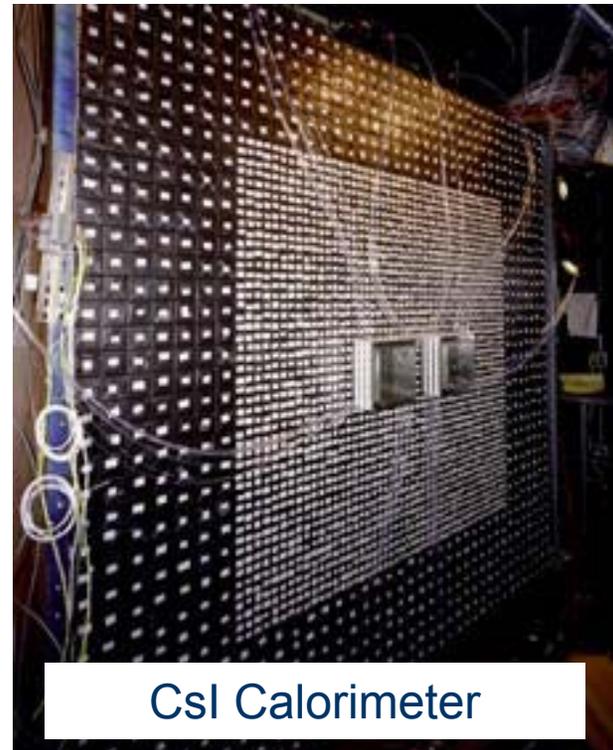
The KTeV Detector

- Movable active regenerator to provide a coherent mixture of K_L and K_S and to veto scattered kaons
- Charged spectrometer to reconstruct $K \rightarrow \pi^+\pi^-$ decays
- CsI calorimeter to reconstruct $K \rightarrow \pi^0\pi^0$ decays



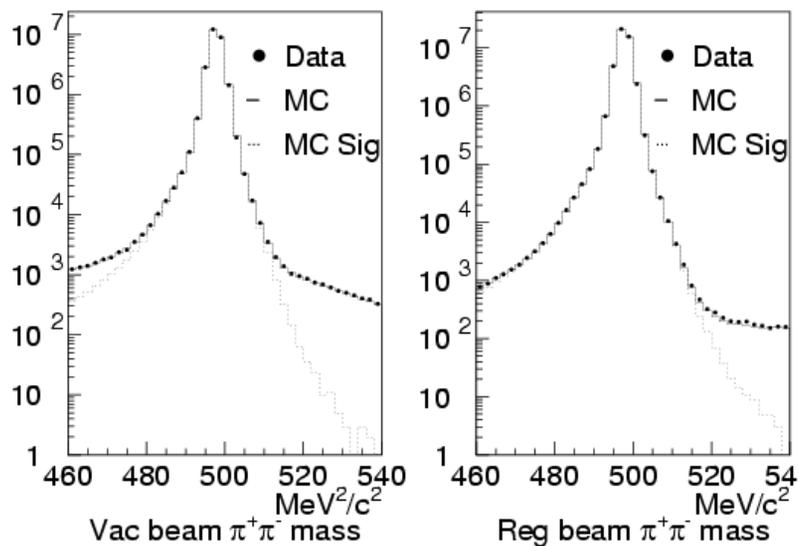
The KTeV Detector

- Spectrometer
 - 4 drift chambers
 - hexagonal cell geometry
 - 2 planes each in x and y
 - Dipole magnet
 - ~ 412 MeV/c kick in x
 - Calibrated using data and the known kaon mass
 - position resolution ~ 80 μm
 - momentum resolution $\sim 0.3\%$
 - absolute momentum scale $\sim 0.01\%$
- CsI Calorimeter
 - 3100 CsI crystals
 - small blocks $2.5 \times 2.5 \times 50$ cm^3
 - large blocks $5.0 \times 5.0 \times 50$ cm^3
 - Calibrated using in-situ laser system and momentum analyzed electrons from Ke3 decays
 - position resolution 1.2 – 2.4 mm
 - energy resolution $\sim 0.6\%$
 - absolute energy scale $\sim 0.05\%$



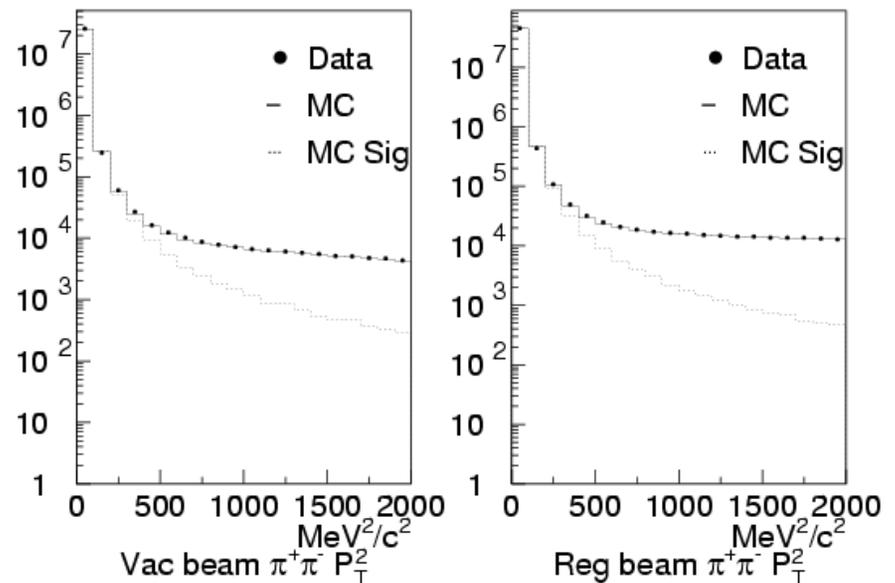
CsI Calorimeter

$K \rightarrow \pi^+\pi^-$ Analysis



Reconstructed Mass

Transverse Momentum

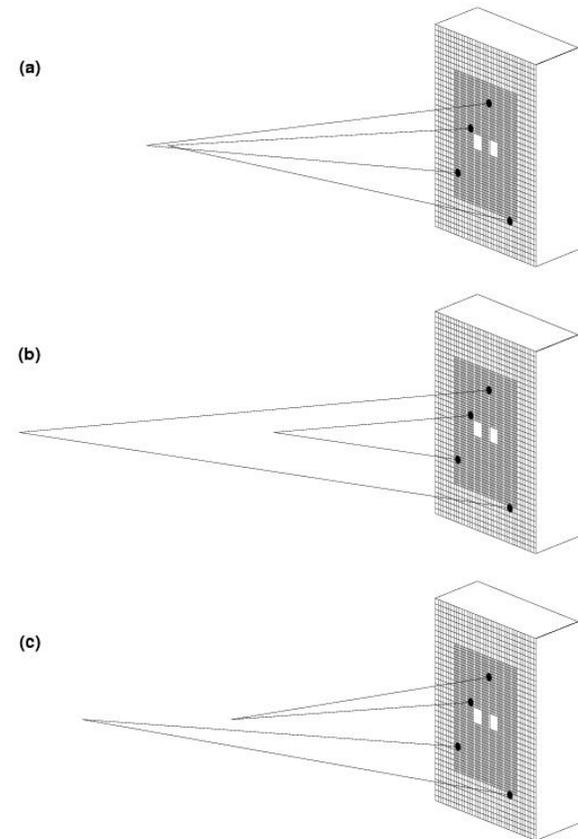


Photon Pairing

- Must determine which photons are from the same pion decay
- Pair photons and calculate z for each pair using pion mass as constraint

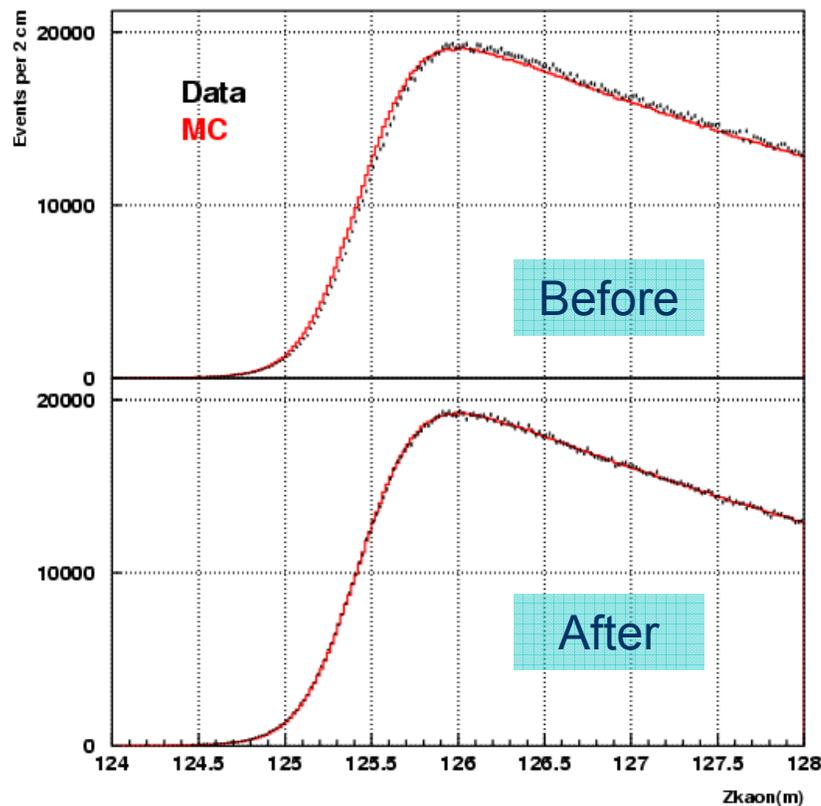
$$z_{12} \approx \frac{\sqrt{E_1 E_2}}{m_{\pi^0}} r_{12}$$

- Only correct pairing will yield consistent z for both pairs
- Consistency of measured z quantified by pairing chi-squared variable
- Choose incorrect pairing for 0.007% of $2\pi^0$ events

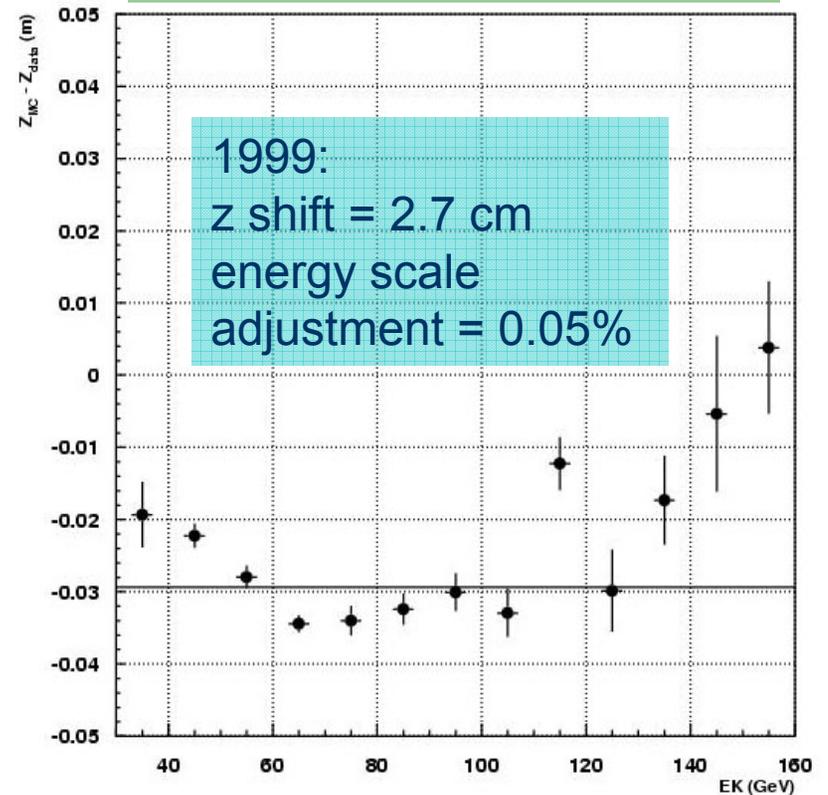


Final Energy Scale

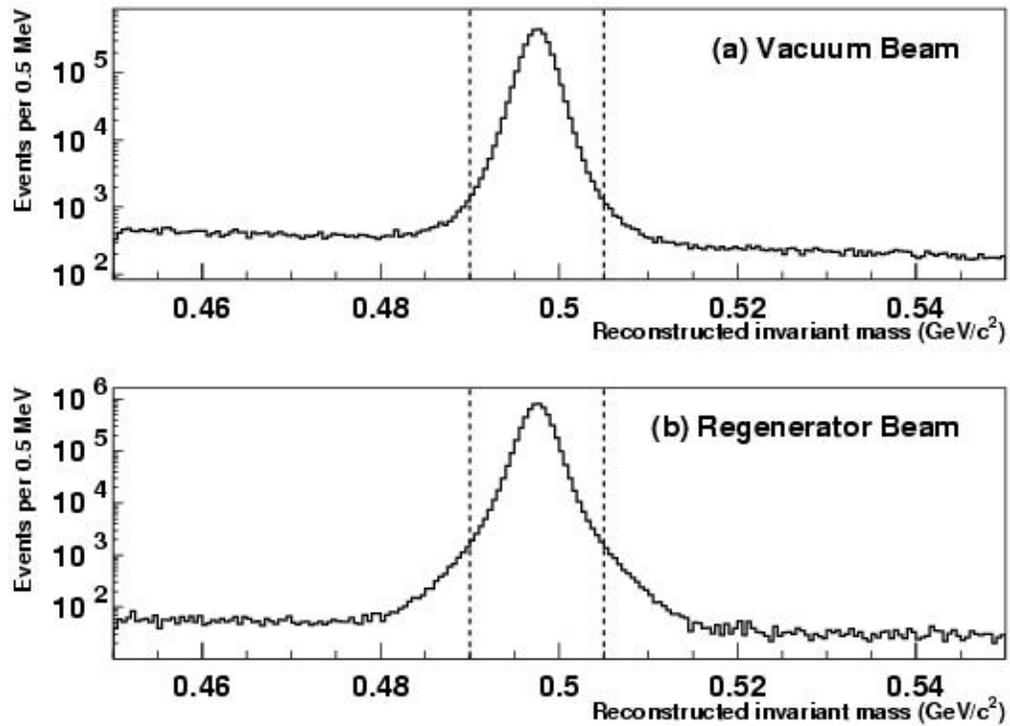
z vertex at regenerator edge



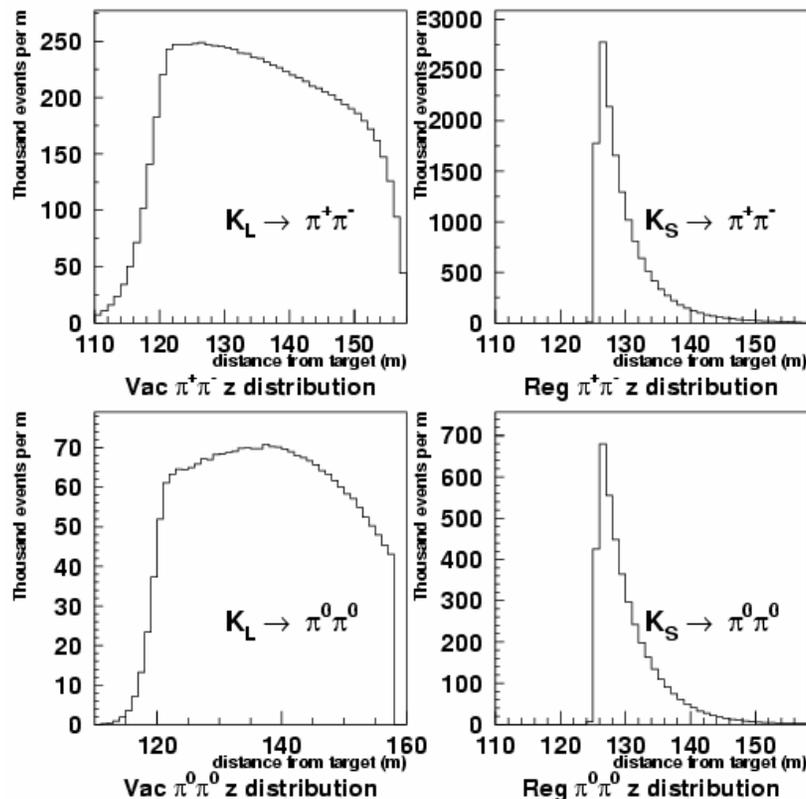
z shift to match data to MC



$K \rightarrow \pi^0\pi^0$ Analysis



Monte Carlo Simulation

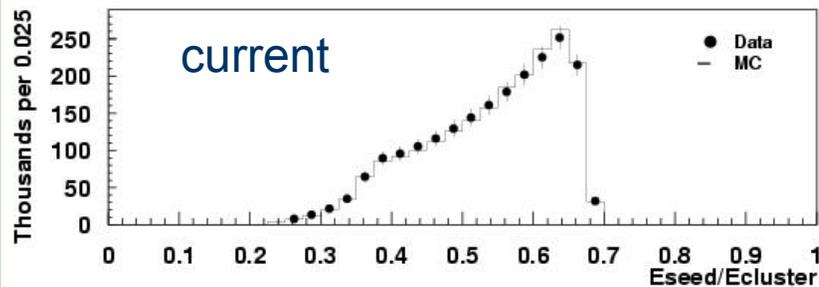
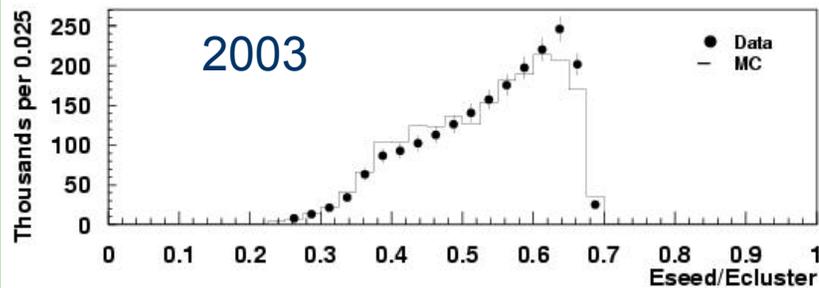


- MC used to make acceptance correction and simulate backgrounds to signal modes
 - simulates kaon generation, propagation, and decay
 - simulates detector geometry and response
 - includes the effect of “accidental” activity by overlaying data events from accidental trigger

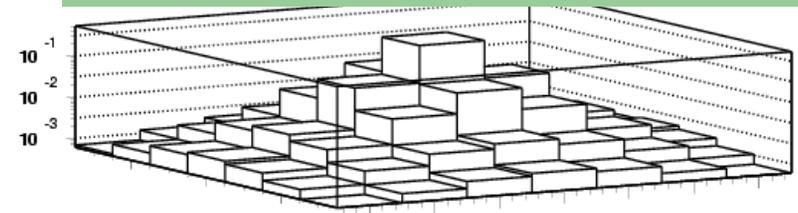
Improvements to MC

- 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

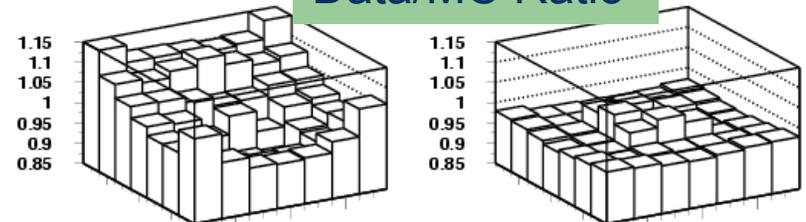
Improvements: Transverse Shower Shape



Fraction of energy per CsI block



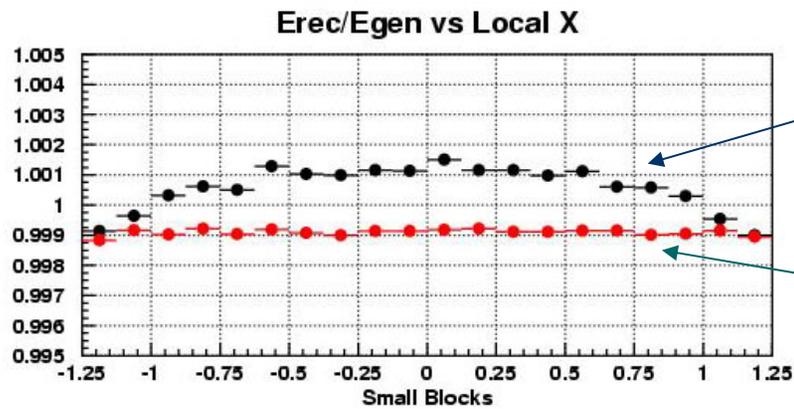
Data/MC Ratio



2003: Includes transverse energy correction to match data and MC

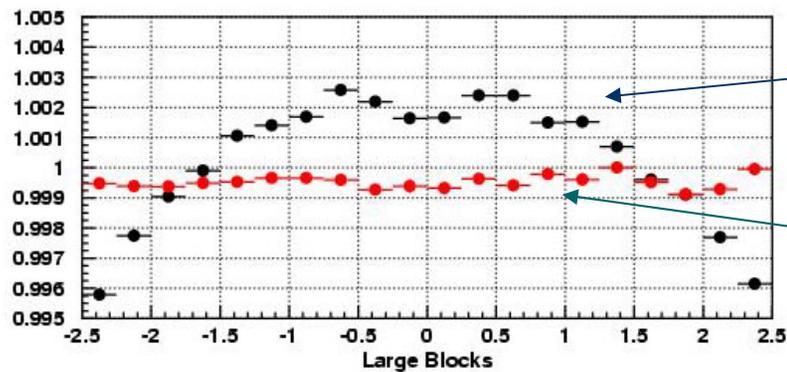
Current: No transverse energy correction required

Improvements: Reconstructed Energy



2003

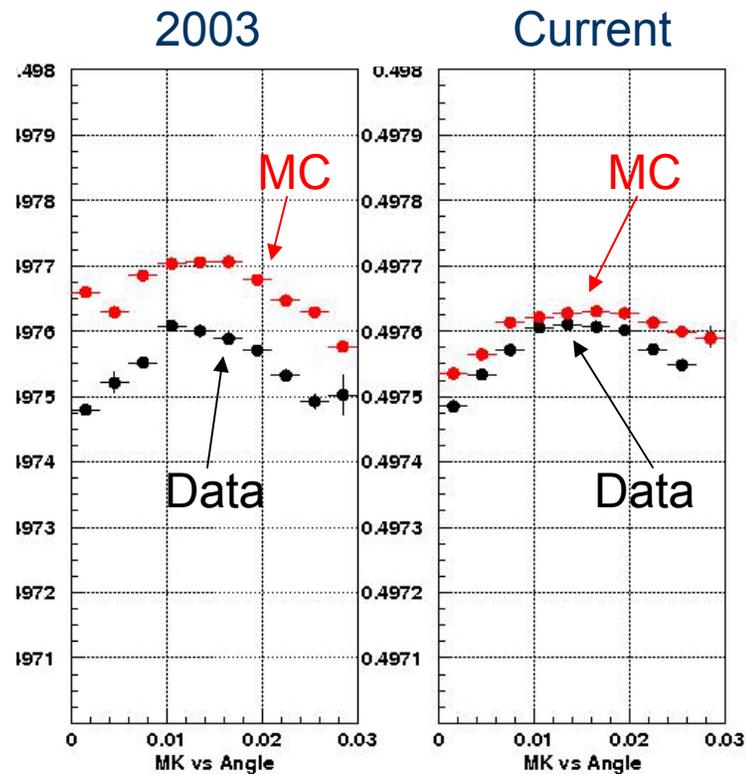
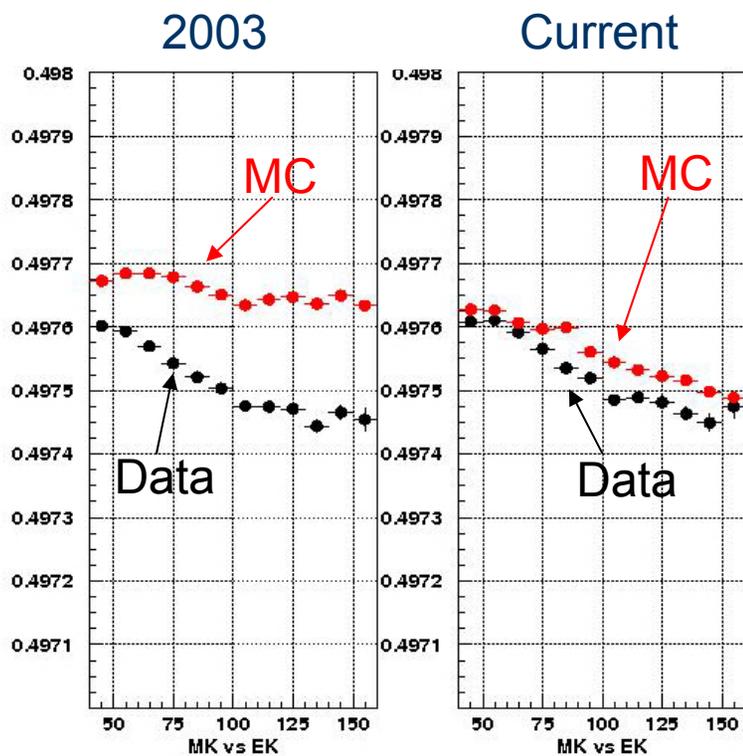
Current



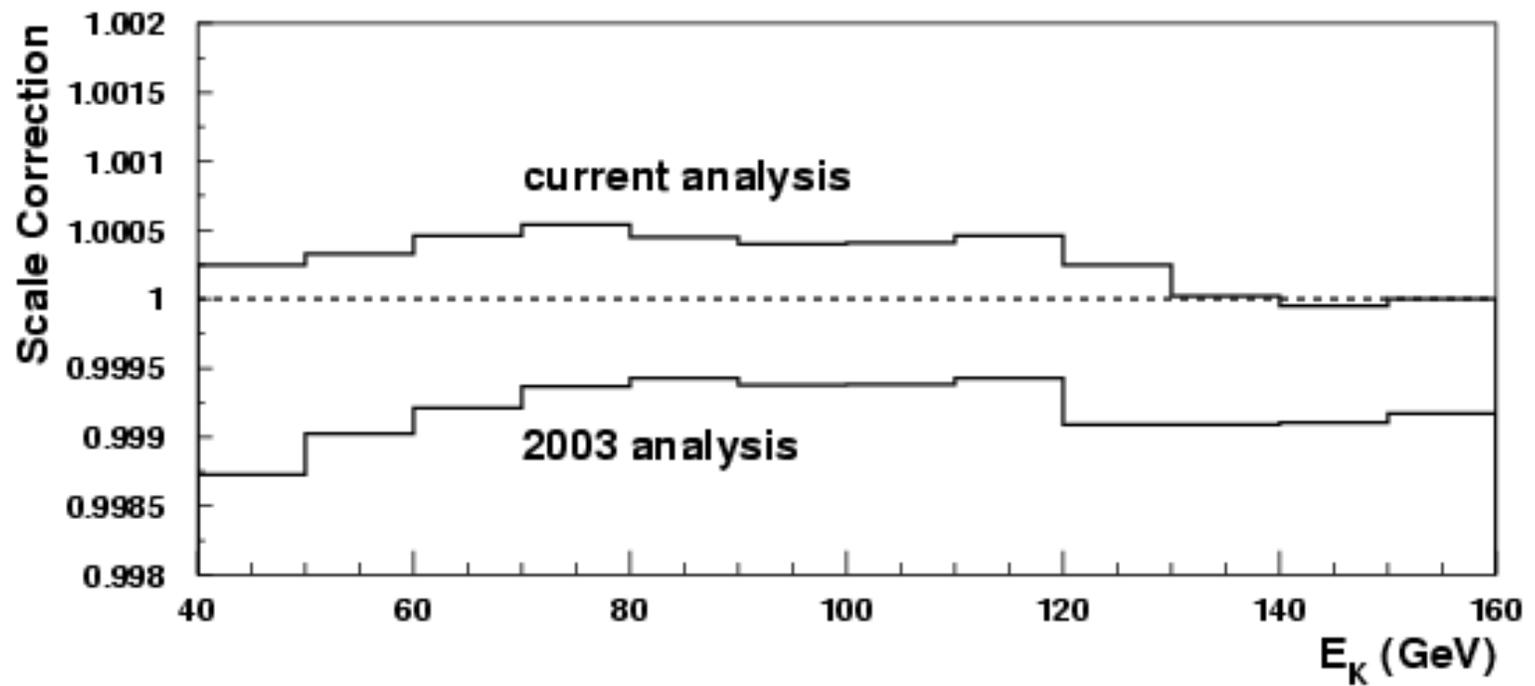
2003

Current

Improvements: Energy Linearity



Improvements: Energy Scale



Backgrounds

- Scattering backgrounds
 - Scattering in defining collimator
 - Diffractive and inelastic scattering in regenerator treated as background
 - Characterized using $\pi^+\pi^-$ events with large p_T^2
 - Common to charged and neutral signal modes
 - Level higher in neutral mode because no cut on p_T^2
 - Use RING variable instead
- Non $\pi\pi$ backgrounds
 - Semileptonic decays in charged mode
 - $K \rightarrow 3\pi^0$ decays and hadronic production in neutral mode
- Backgrounds simulated by MC, normalized to data sidebands, and subtracted
- Total background levels
 - ~0.1% in charged mode
 - ~1% in neutral mode

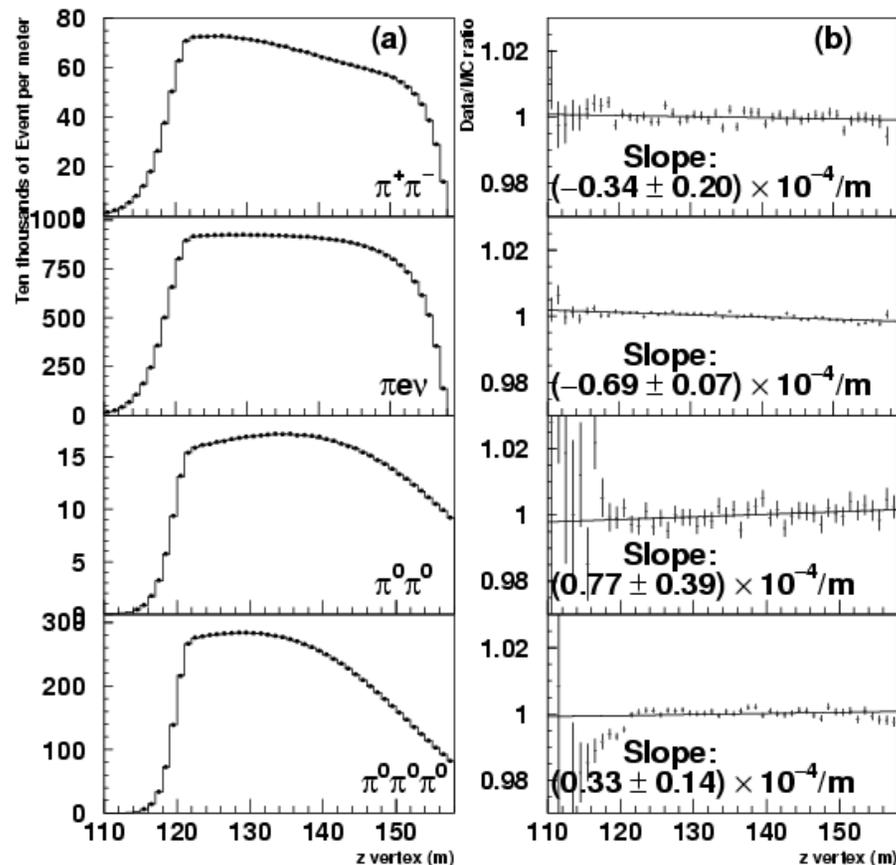
Systematic Uncertainties in $\text{Re}(\epsilon'/\epsilon)$

Source	Error on $\text{Re}(\epsilon'/\epsilon)$ ($\times 10^{-4}$)	
	$K \rightarrow \pi^+\pi^-$	$K \rightarrow \pi^0\pi^0$
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

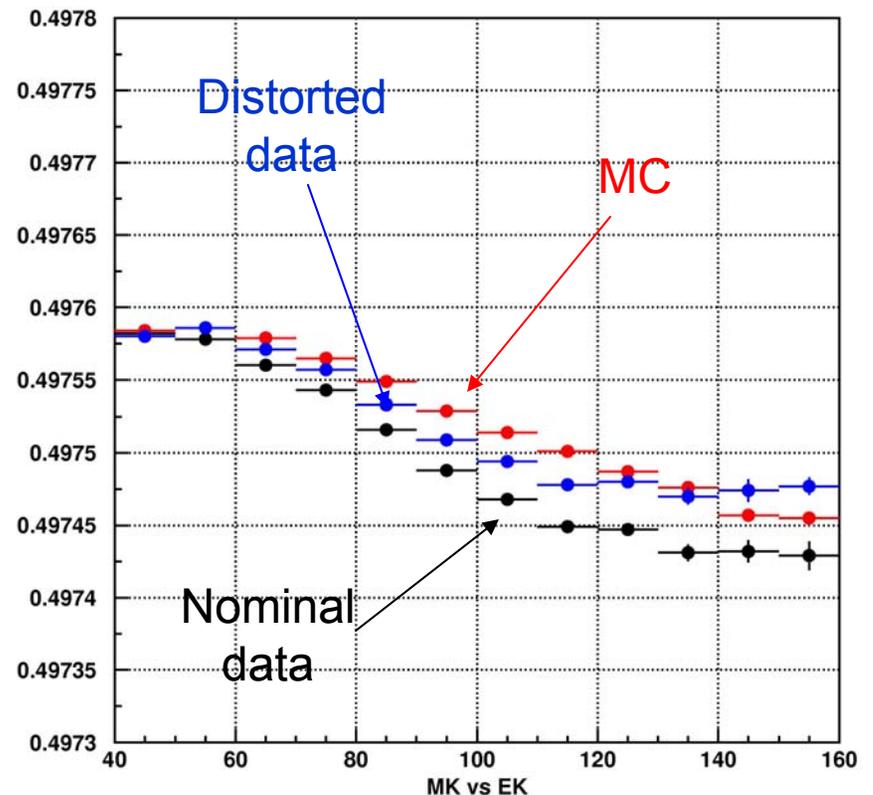
Uncertainty from Acceptance

- Quality of MC simulation evaluated by comparing vacuum beam z vertex distributions between data and MC
- Bias on $\text{Re}(\epsilon'/\epsilon)$ given by $s\Delta z/6$
 - s is slope of data-MC ratio
 - Δz is difference between mean z value for vacuum and regenerator beams
- Use $\pi^+\pi^-$ and $\pi^0\pi^0\pi^0$ slopes to determine systematic uncertainty

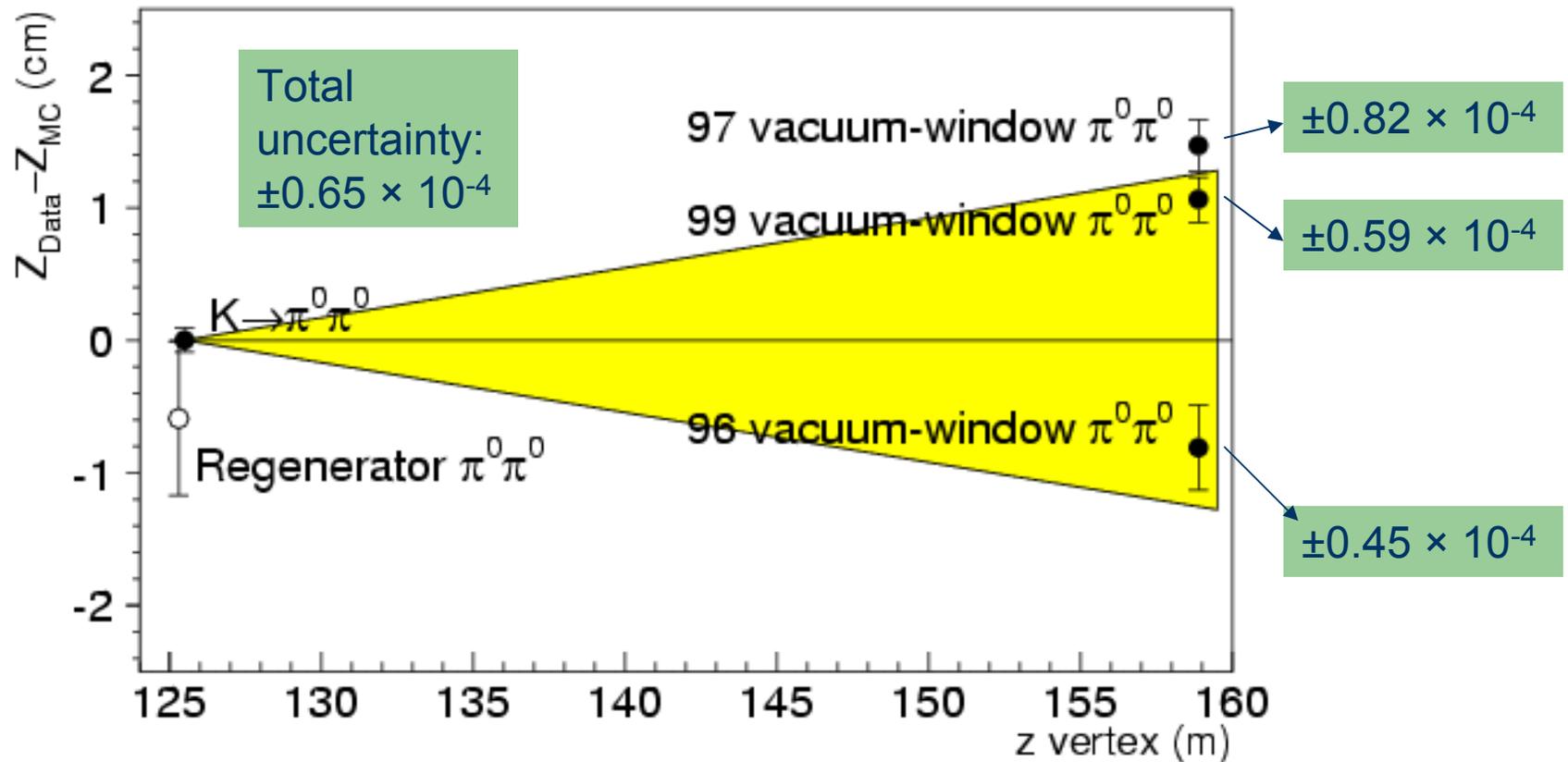


Uncertainty from Energy Non-linearity

- Use M_K vs E_K plot to determine distortion which 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 $\text{Re}(\varepsilon'/\varepsilon)$
 - 1996: -0.1×10^{-4}
 - 1997: -0.1×10^{-4}
 - 1999: $+0.2 \times 10^{-4}$
- Systematic error: $\pm 0.15 \times 10^{-4}$



Uncertainty from Energy Scale



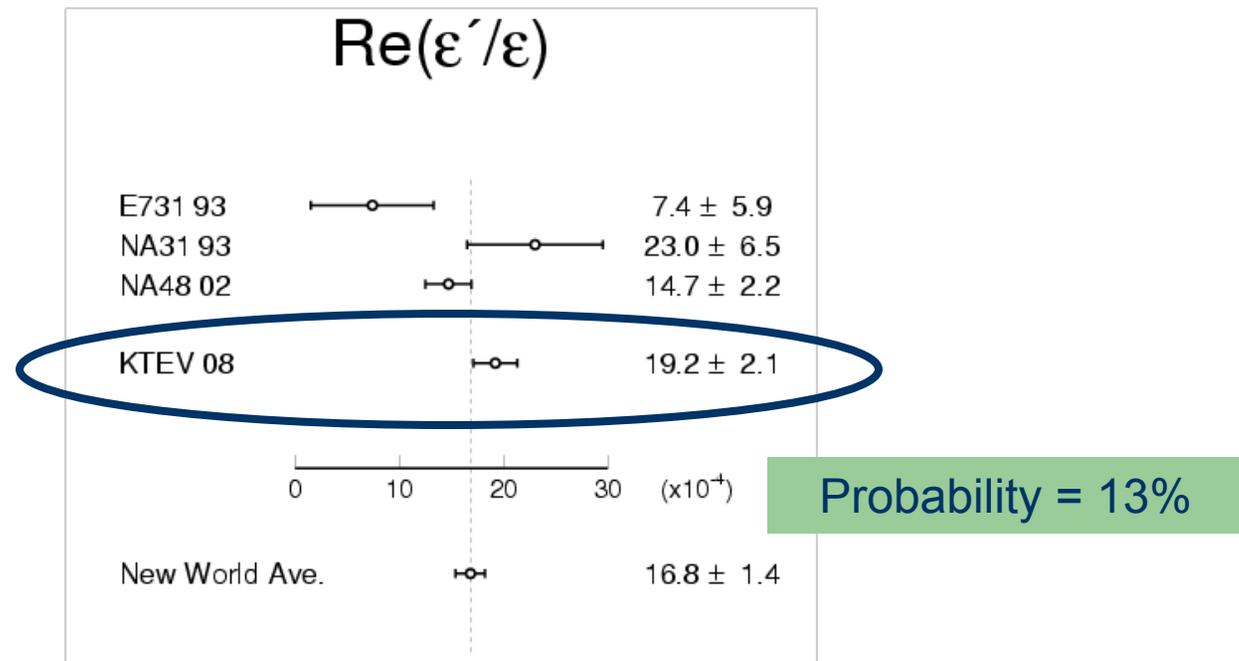
Results

The final KTeV measurement
of $\text{Re}(\epsilon'/\epsilon)$. . .

Results: $\text{Re}(\epsilon'/\epsilon)$

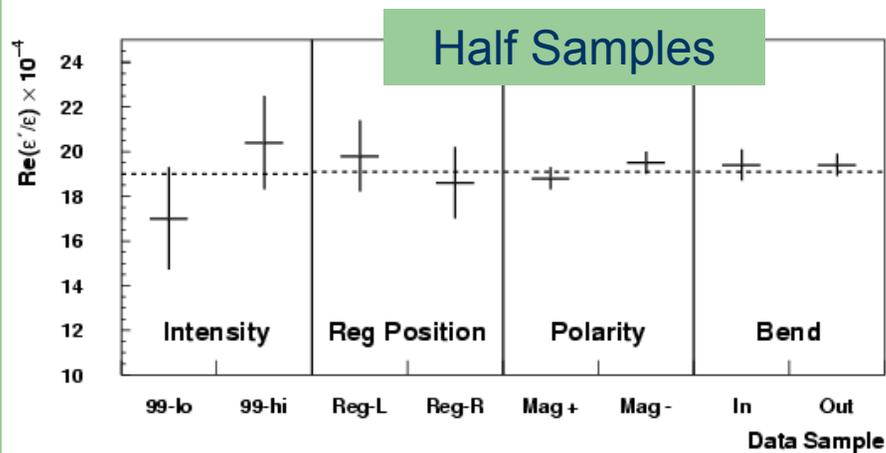
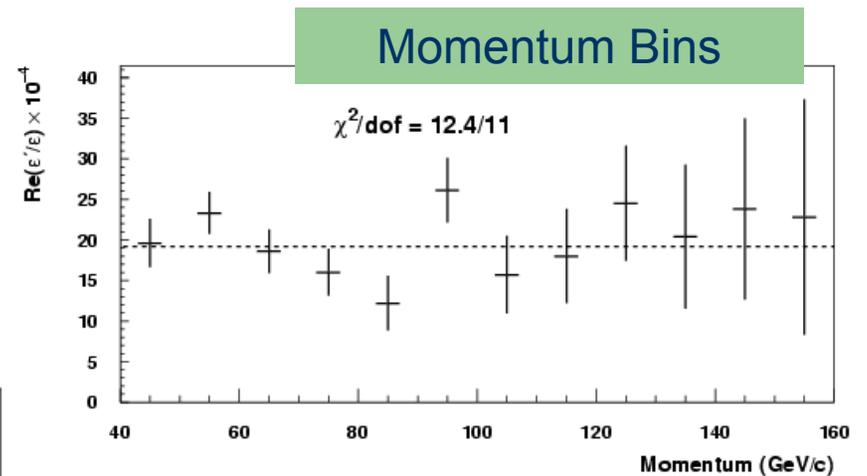
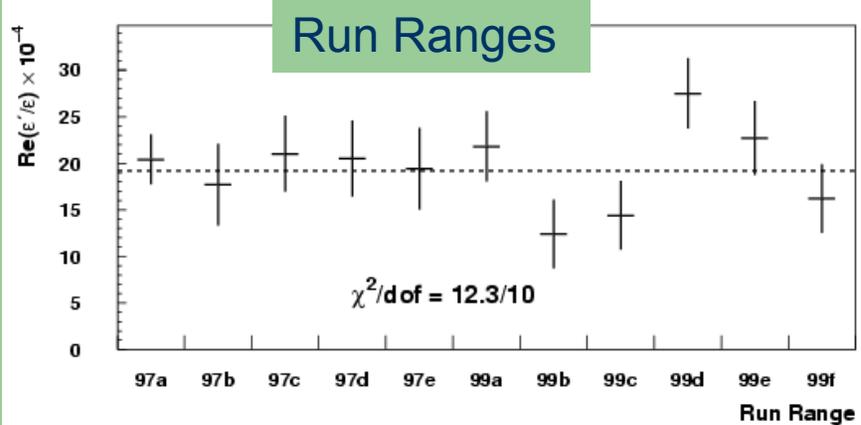
$$\text{Re}(\epsilon'/\epsilon) = [19.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \times 10^{-4}$$

$$\text{Re}(\epsilon'/\epsilon) = (19.2 \pm 2.1) \times 10^{-4}$$



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

Results: $\text{Re}(\epsilon'/\epsilon)$ Crosschecks



Kaon Parameters: z-binned fit

- Fit for Δm , τ_S , ϕ_ε , $\text{Re}(\varepsilon'/\varepsilon)$, $\text{Im}(\varepsilon'/\varepsilon)$
- Systematic uncertainties evaluated using same methods as $\text{Re}(\varepsilon'/\varepsilon)$ analysis
- Significant reduction in systematic uncertainties for ϕ_ε and $\Delta\phi$
 - Improved measurements of regenerator properties
 - Nuclear screening effects (ϕ_ε)
 - Energy scale ($\Delta\phi$)
- CPT assumption applied a *posteriori*

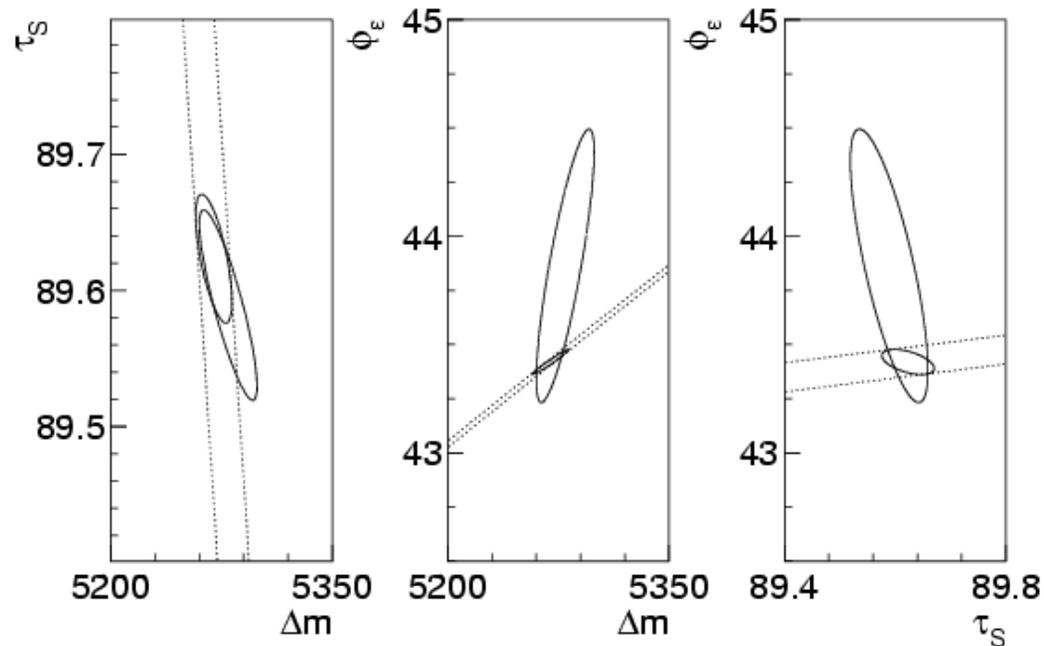
$$\Phi_{+-} \approx \Phi_\varepsilon + \text{Im}(\varepsilon'/\varepsilon)$$

$$\Phi_{00} \approx \Phi_\varepsilon - 2\text{Im}(\varepsilon'/\varepsilon)$$

$$\Delta\Phi = \Phi_{00} - \Phi_{+-} \approx -3\text{Im}(\varepsilon'/\varepsilon)$$

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

Results: z-binned Fit



No CPT assumption:

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

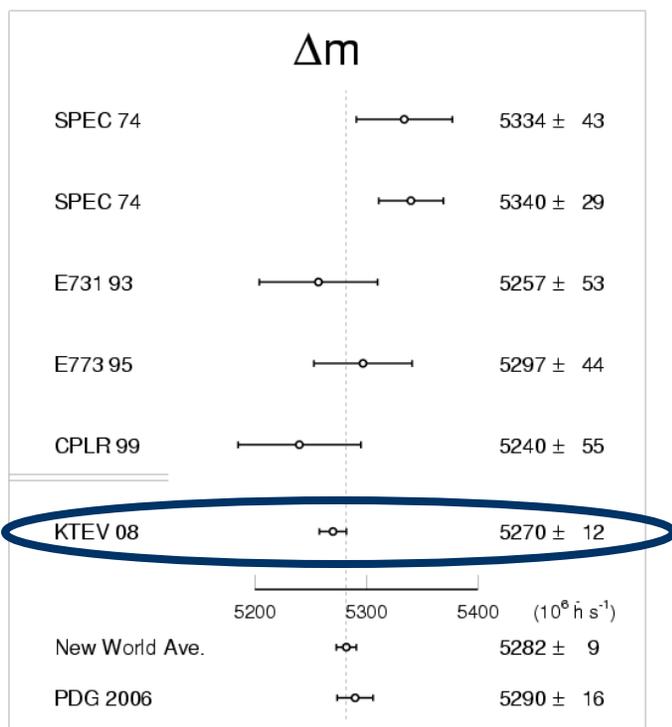
$$\tau_S = (89.589 \pm 0.070) \times 10^{-12} \text{ s}$$

CPT assumption applied:

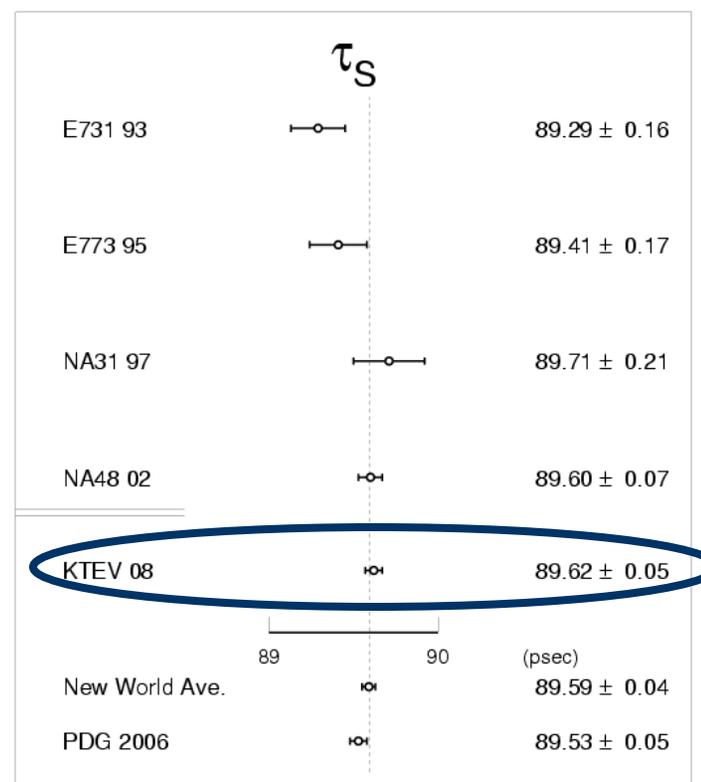
$$\Delta m = (5269.9 \pm 12.3) \times 10^6 \text{ } \hbar\text{s}^{-1}$$

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

Results: Δm and τ_S



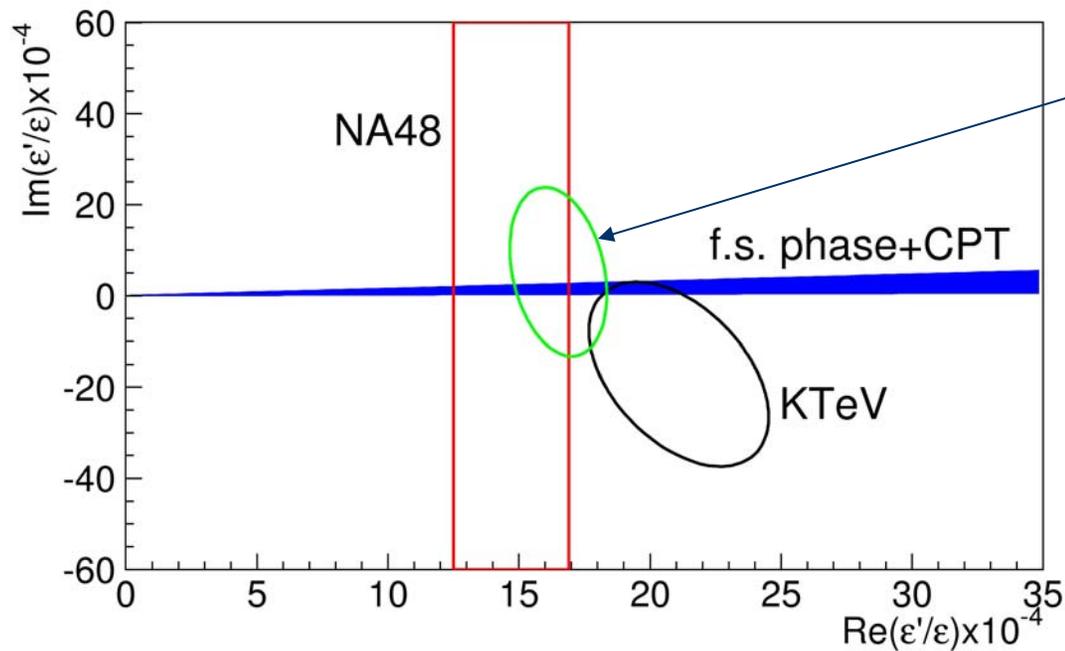
KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6 \hbar s^{-1}$



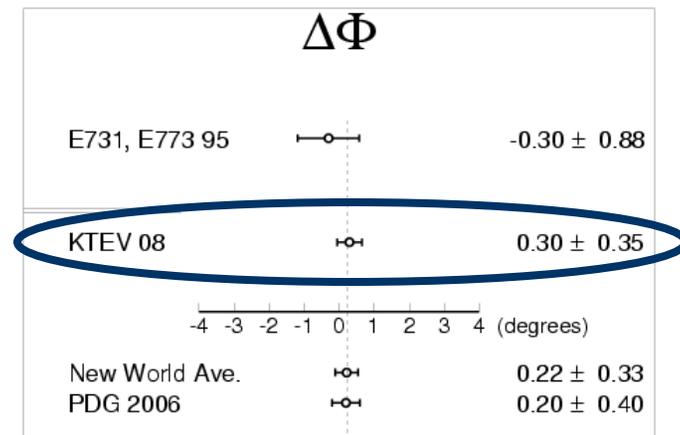
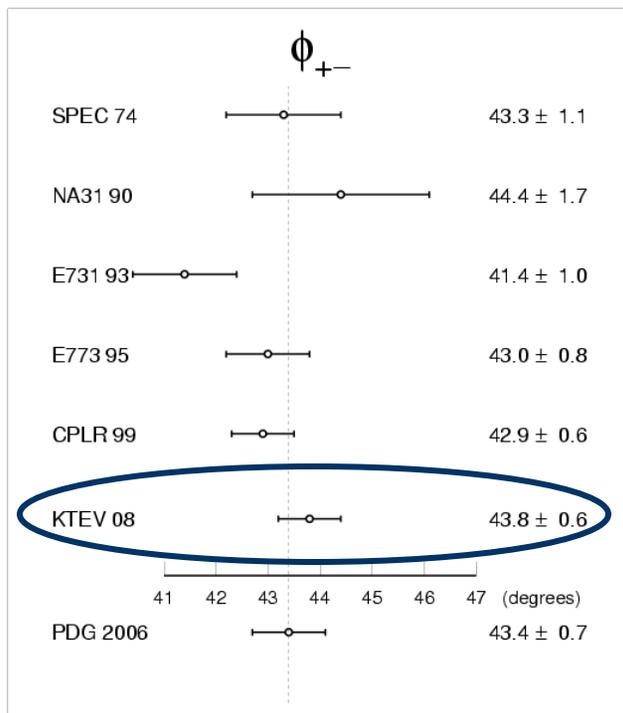
KTeV 2003: $\tau_S = (89.65 \pm 0.07) \times 10^{-12} s$

Results: z-binned fit

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



Results: CPT Tests



Consistent with CPT symmetry

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

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

KTeV Results

- $\text{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
 - $\Delta m = (5269.9 \pm 12.3) \times 10^6 \text{ } \hbar\text{s}^{-1}$
 - $\tau_S = (89.623 \pm 0.047) \times 10^{-12} \text{ s}$
 - $\phi_\varepsilon = (43.86 \pm 0.63)^\circ$
 - $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)^\circ$
 - $\Delta\phi = (0.30 \pm 0.35)^\circ$
- Assuming CPT
- No CPT assumption

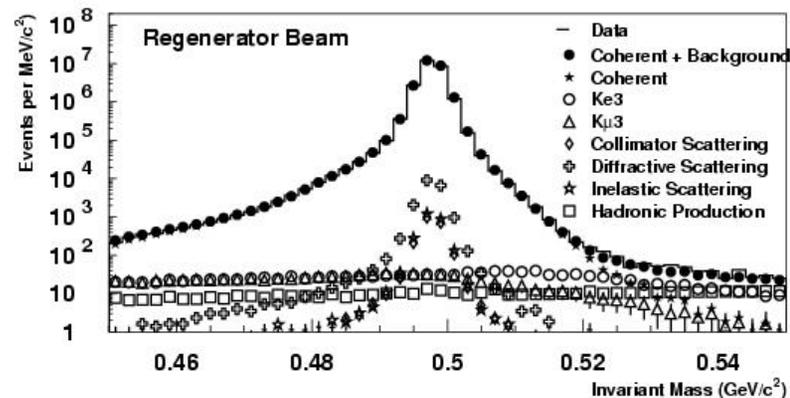
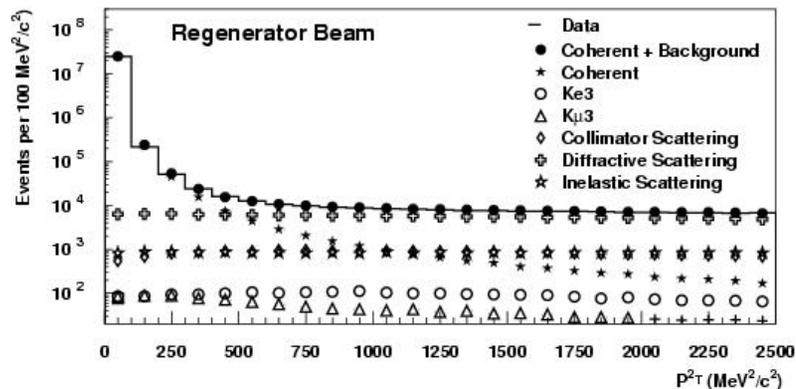
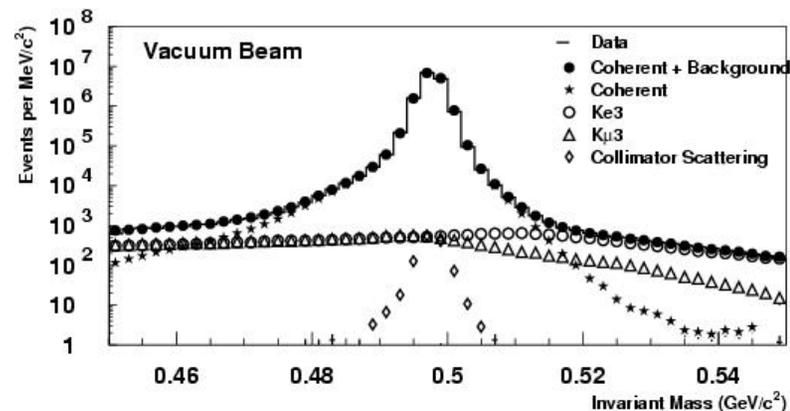
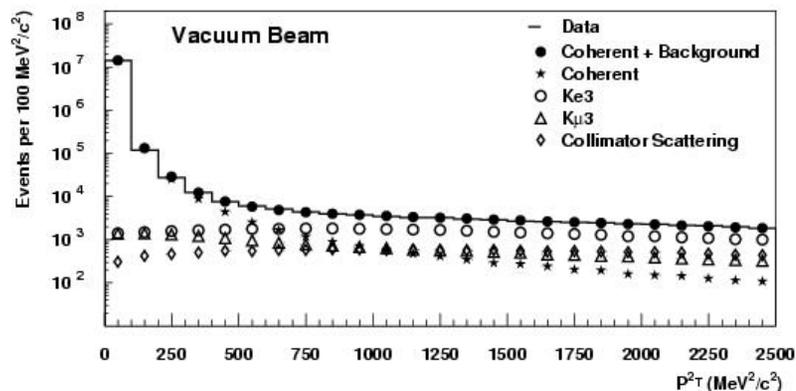
Extra Slides

Backgrounds

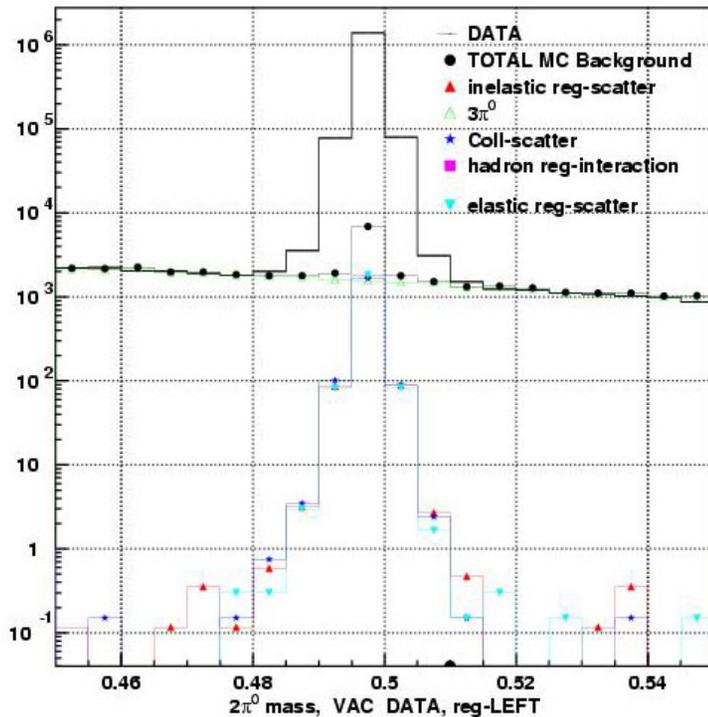
Source	Vacuum Beam	Regenerator Beam
$K \rightarrow \pi^+ \pi^-$		
Regenerator Scattering	–	0.075%
Collimator Scattering	0.008%	0.008%
$K_L \rightarrow \pi^\pm e^\mp \nu$	0.032%	0.001%
$K_L \rightarrow \pi^\pm \mu^\mp \nu$	0.030%	0.001%
Total	0.070%	0.085%
$K \rightarrow \pi^0 \pi^0$		
Inelastic Scattering	0.128%	0.175%
Diffraction Scattering	0.130%	0.906%
Collimator Scattering	0.120%	0.091%
$K_L \rightarrow \pi^0 \pi^0 \pi^0$	0.301%	0.012%
Photon Mispairing	0.008%	0.007%
Hadronic Production	–	0.007%
Total	0.678%	1.190%

1999 backgrounds (other years vary slightly)

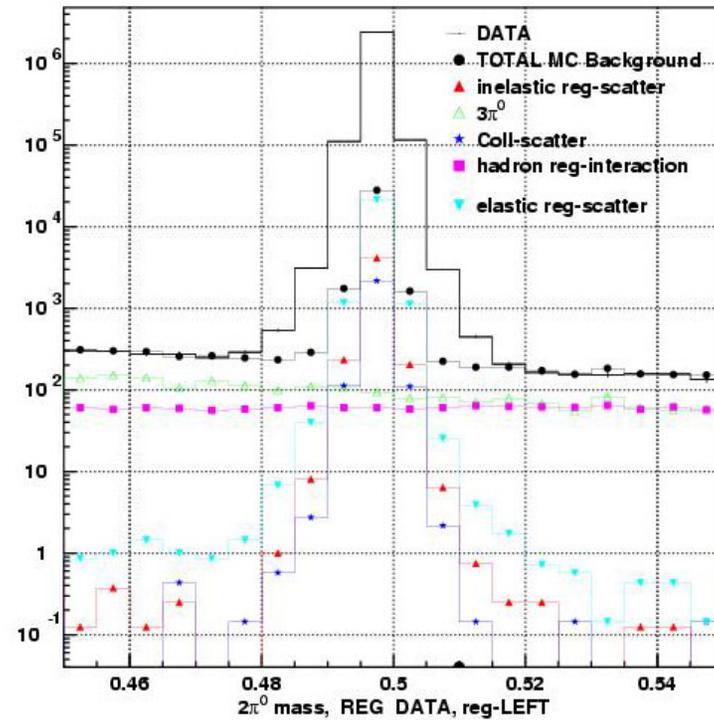
K \rightarrow $\pi^+\pi^-$ Backgrounds



$K \rightarrow \pi^0 \pi^0$ Backgrounds

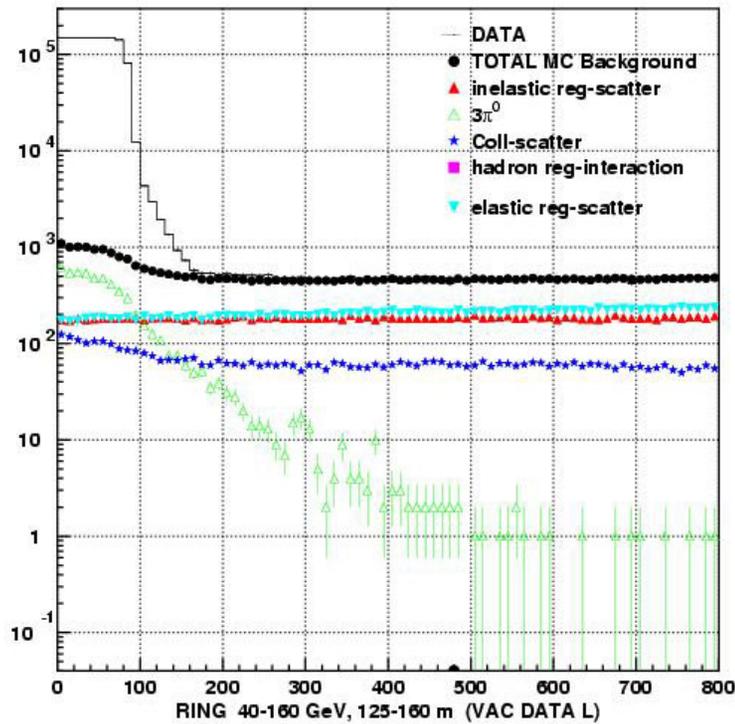


Vacuum Beam

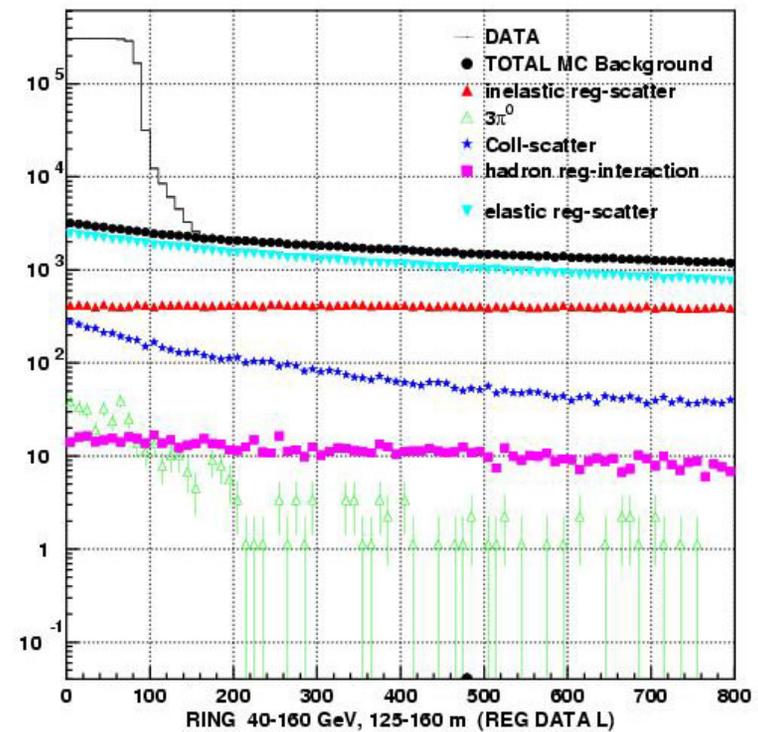


Regenerator Beam

$K \rightarrow \pi^0 \pi^0$ Backgrounds

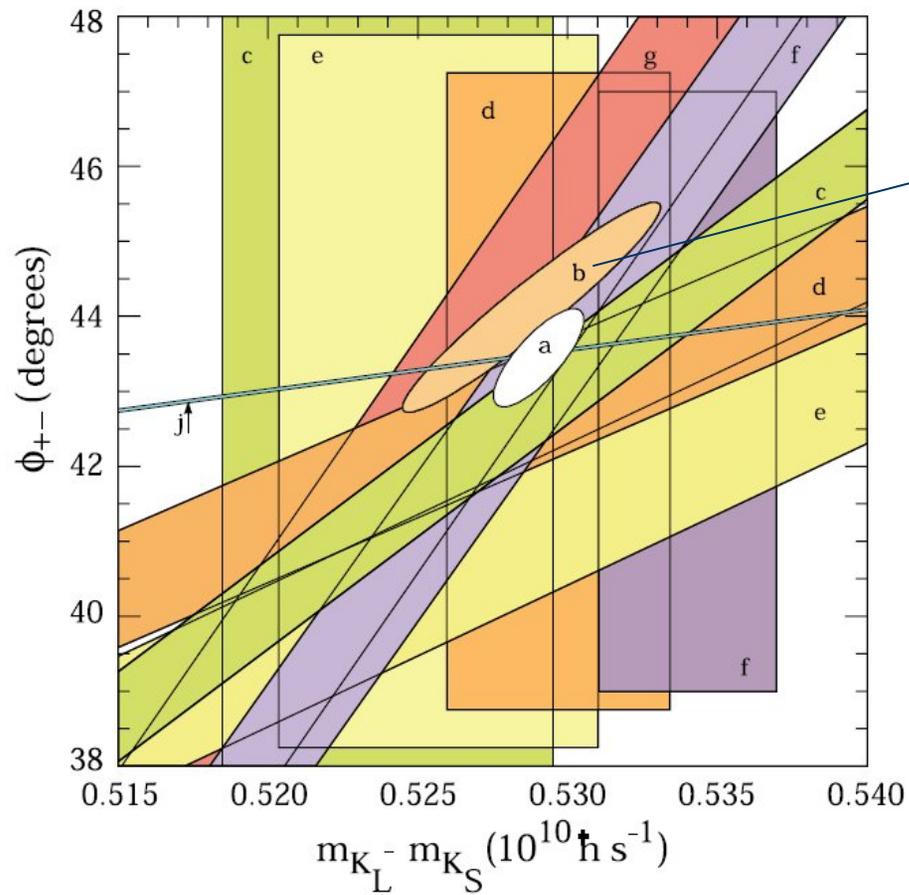


Vacuum Beam

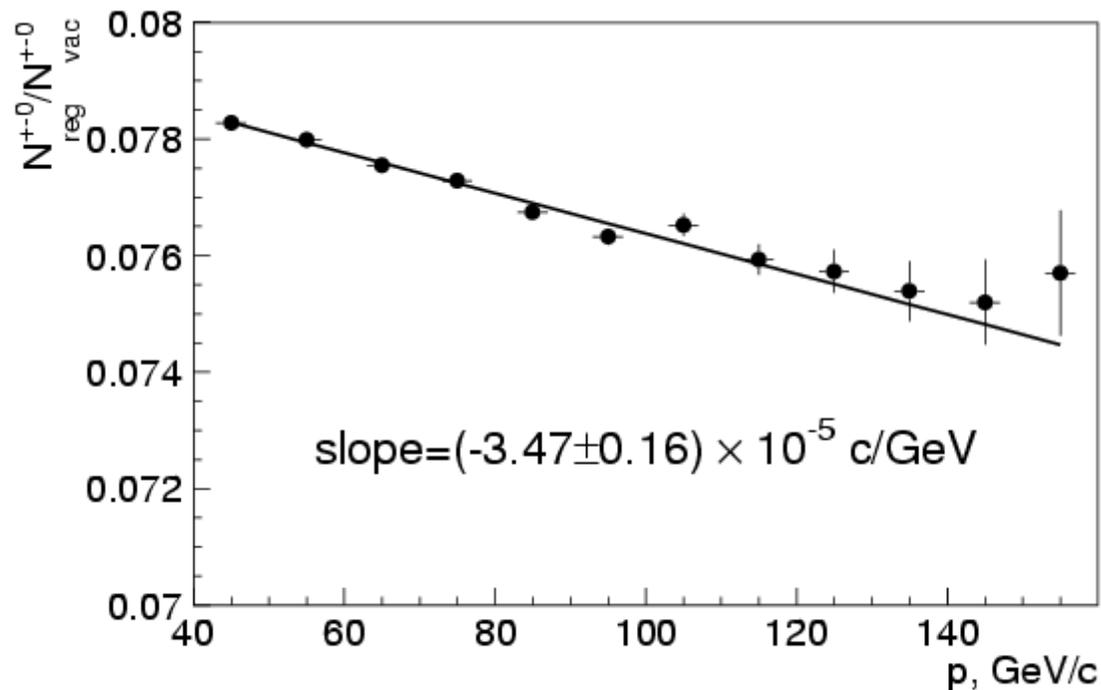


Regenerator Beam

PDG: ϕ_{+-}

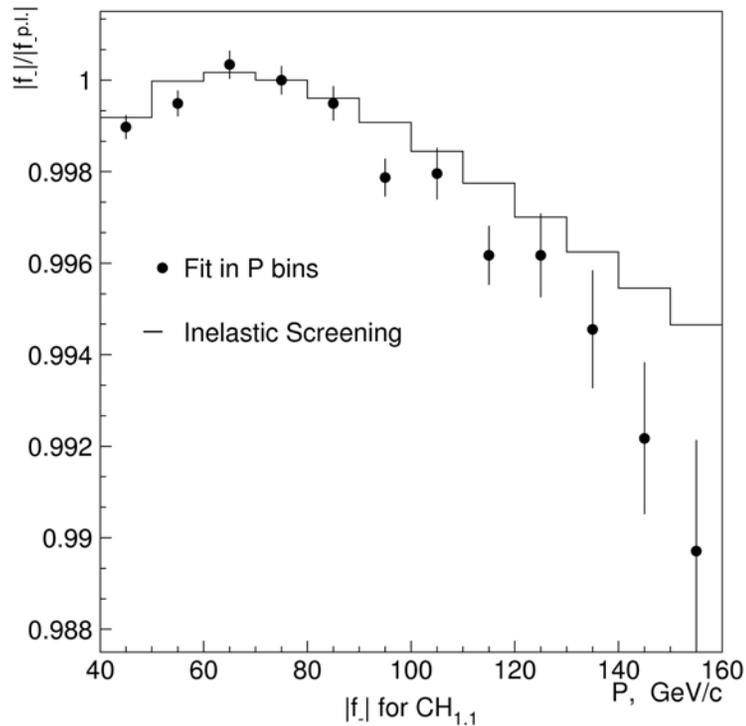


Regenerator Transmission



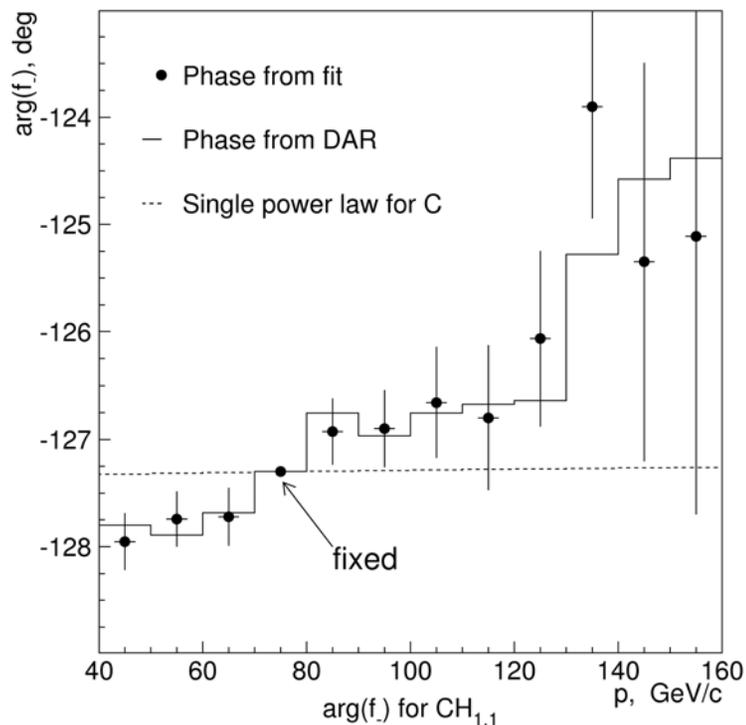
- Transmission measured from data using $K_L \rightarrow \pi^+ \pi^- \pi^0$ decays
- Dedicated trigger in 1999 improved statistical precision of measurement

Screening corrections



- Screening corrections use elastic and inelastic screening models
- Check corrections by fitting regeneration amplitude in momentum bins
- Good agreement at low momentum

Screening corrections



- For p binned fit, evaluate regeneration phase using Derivative Analyticity Relation (DAR)
- Perform fit which floats the regeneration phase in p bins, DAR agrees well with data
- Evaluate systematic uncertainty by comparing inelastic screening correction (nominal) to direct fit to data using DAR for the phase