The Final Measurement of ε′/ε from KTeV

Elizabeth Worcester
University of Chicago

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For the KTeV Collaboration:

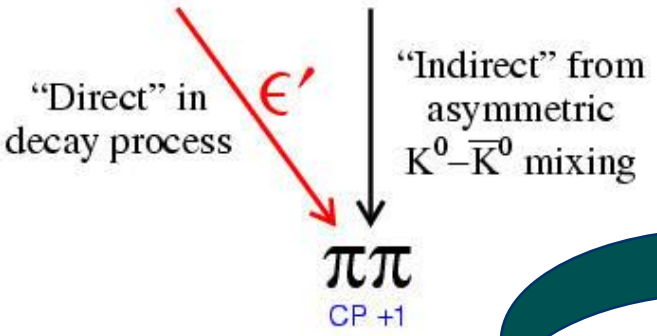
Arizona, Campinas, Chicago, Colorado, Elmhurst, FNAL, Osaka, Rice, Sao Paulo, UCLA, Virginia, Wisconsin

Overview

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

CP Violation in Kaon System

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



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

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

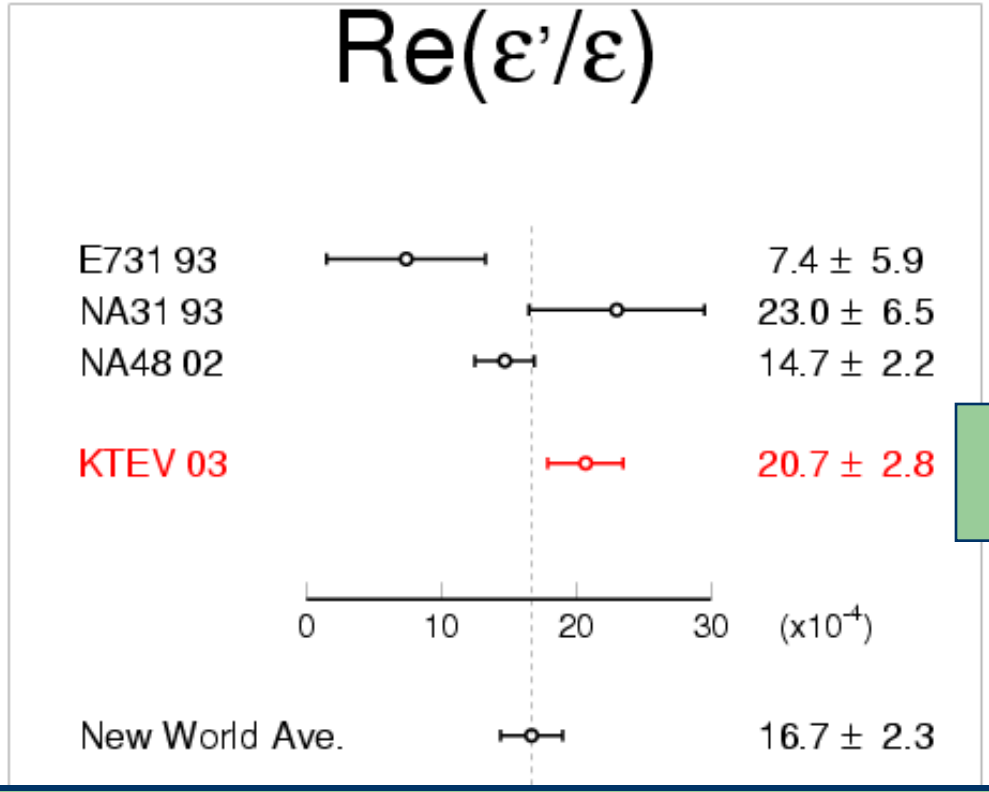
If CPT: $\phi_\varepsilon \approx \phi_{\varepsilon'}$

Re(ε′/ε) → direct CP violation

Im(ε′/ε) → CPT violation

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

Previous Results



Data from 1996 and 1997

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

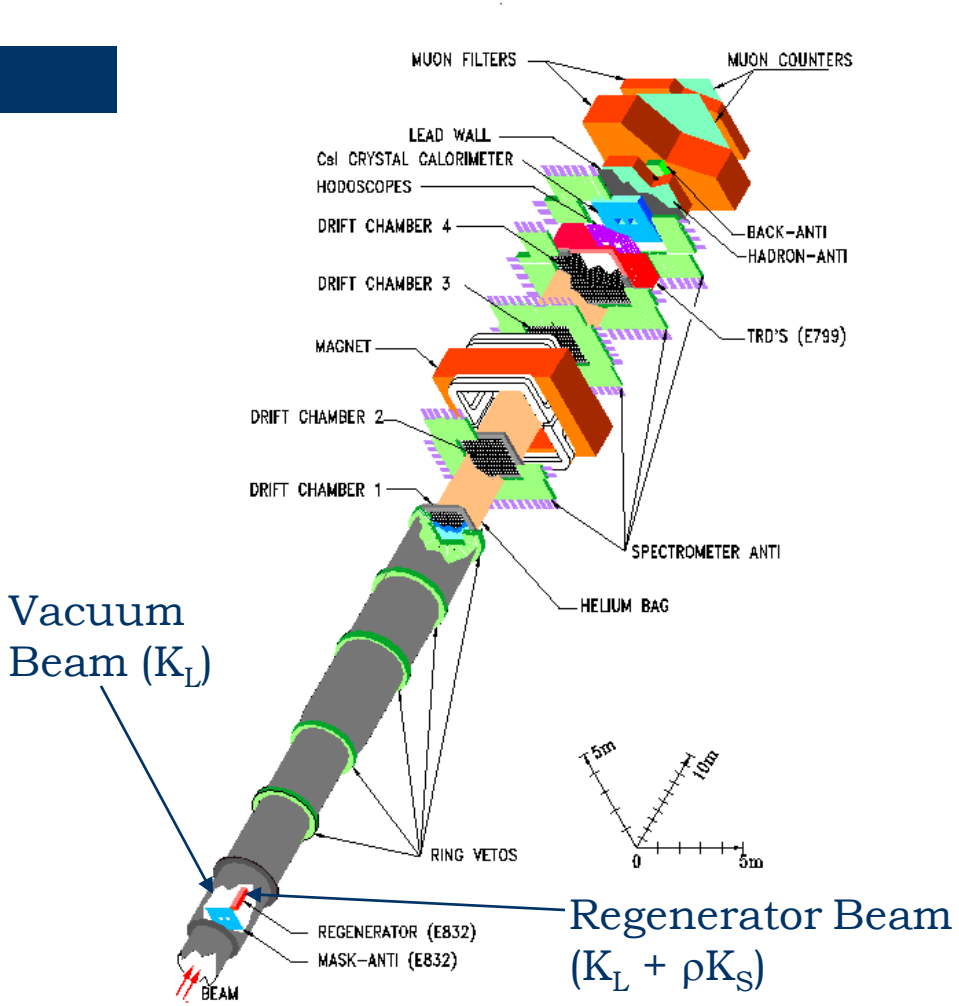
Re(ε′/ε) Uncertainties (2003)

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	

Statistical Uncertainty: 1.5×10^{-4}

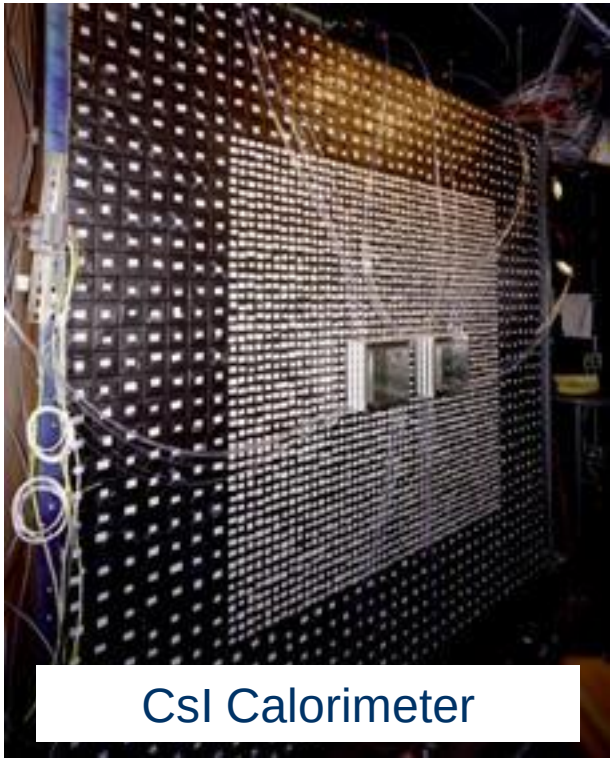
The KTeV Detector

- 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



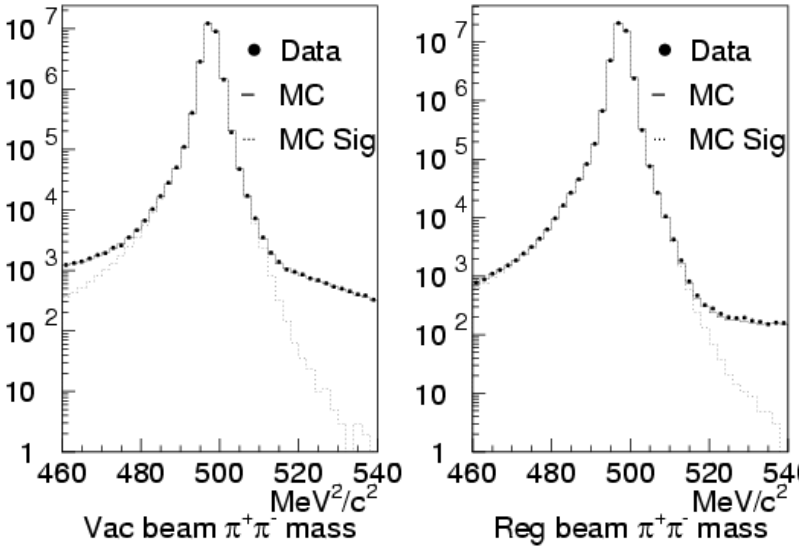
The KTeV Detector

- 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 ~0.3%
    - absolute momentum scale ~0.01%
- CsI Calorimeter
  - 3100 CsI crystals
    - small blocks 2.5 × 2.5 × 50 cm^3
    - large blocks 5.0 × 5.0 × 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 ~0.6%
    - absolute energy scale ~0.05%



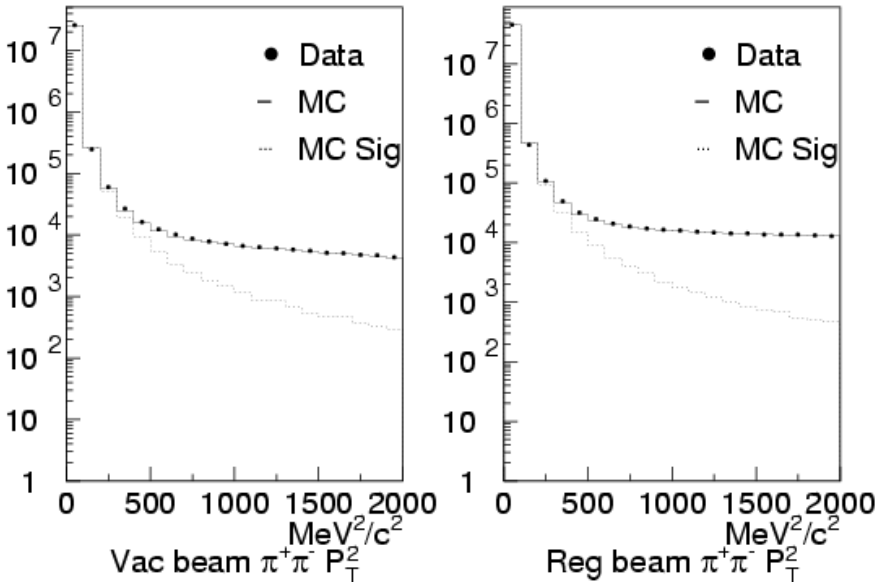
CsI Calorimeter

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



Reconstructed Mass

Transverse Momentum

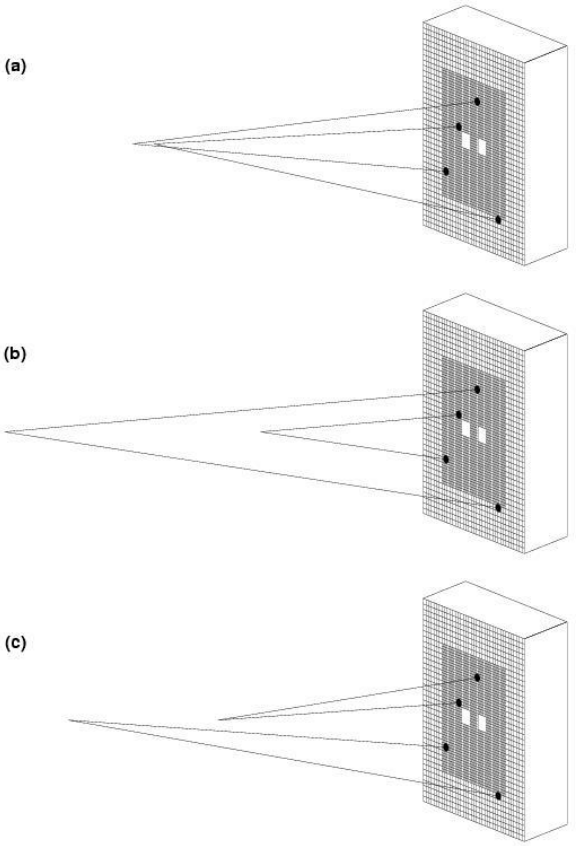


Photon Pairing

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

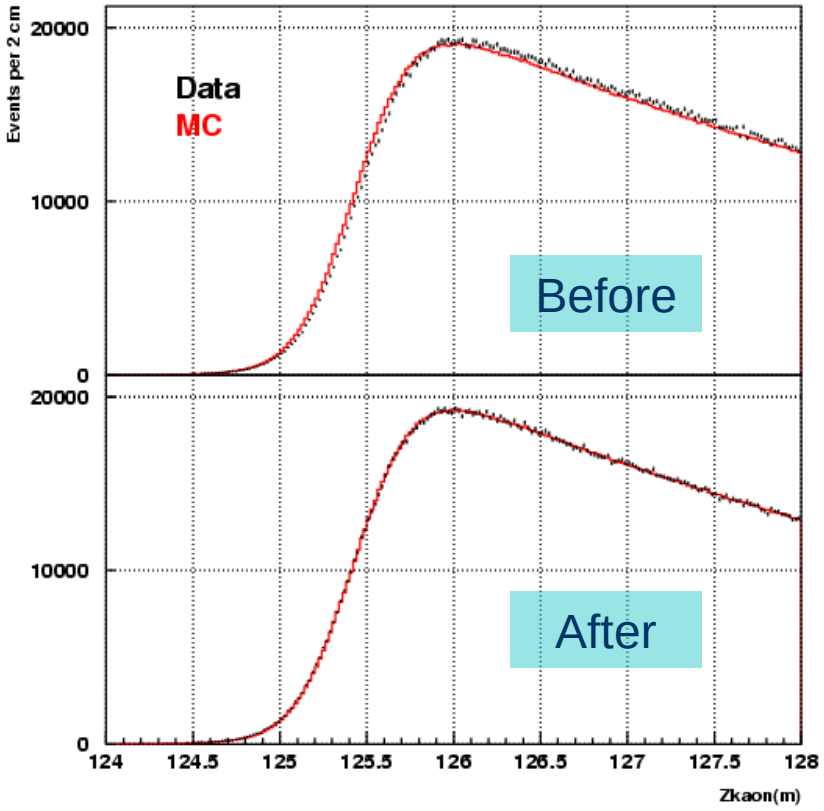
$$z_{12} \approx \frac{\sqrt{E_1 E_2}}{m_{\pi^0}} r_{12}$$

- 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

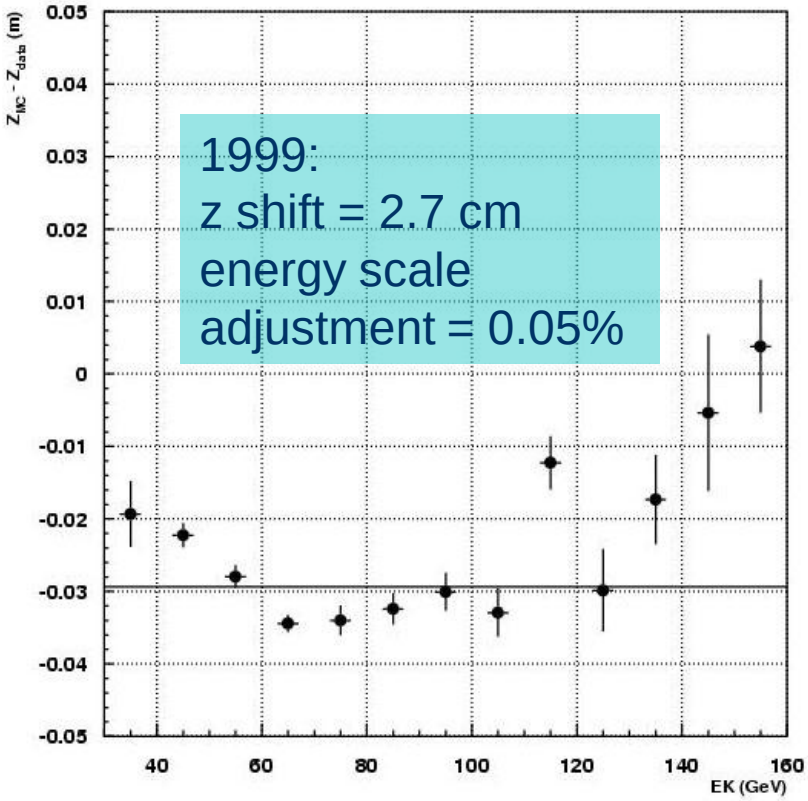


Final Energy Scale

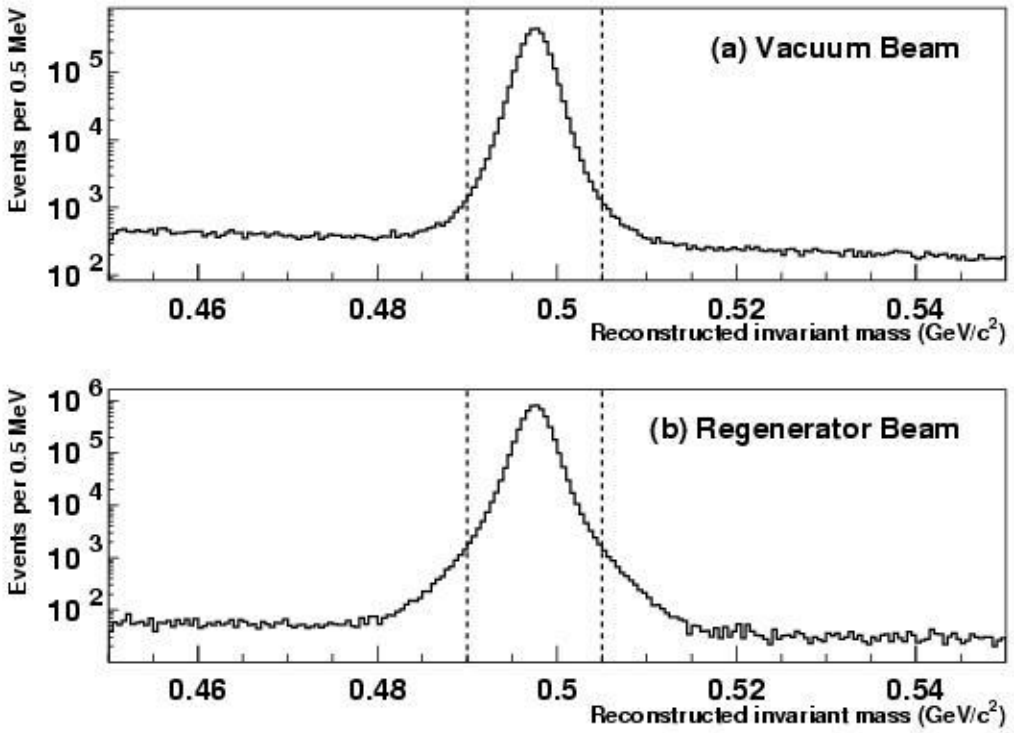
z vertex at regenerator edge



z shift to match data to MC

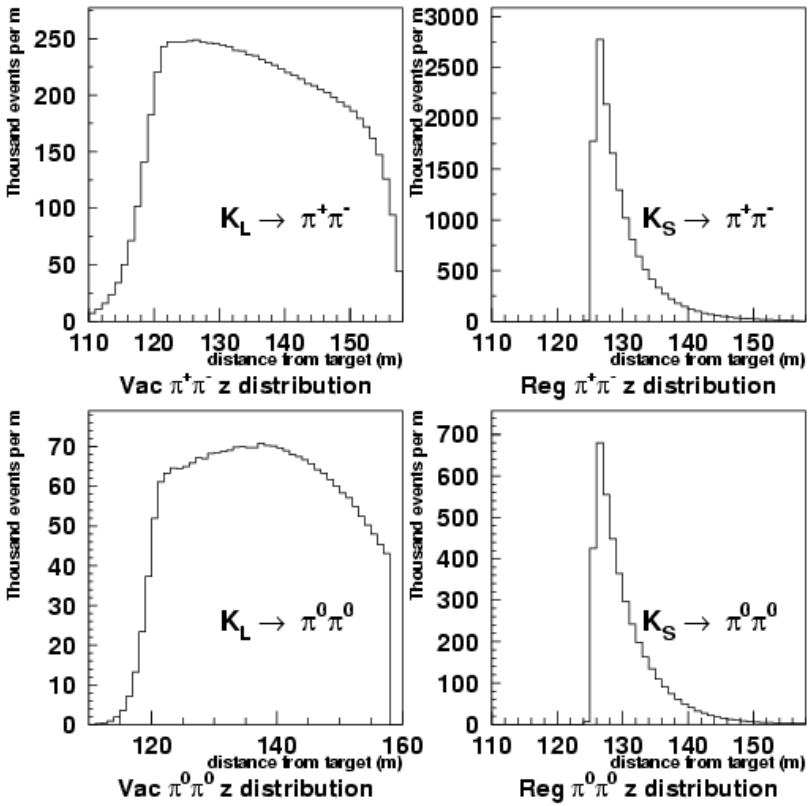


$K \rightarrow \pi^0\pi^0$ Analysis



Reconstructed Mass

Monte Carlo Simulation

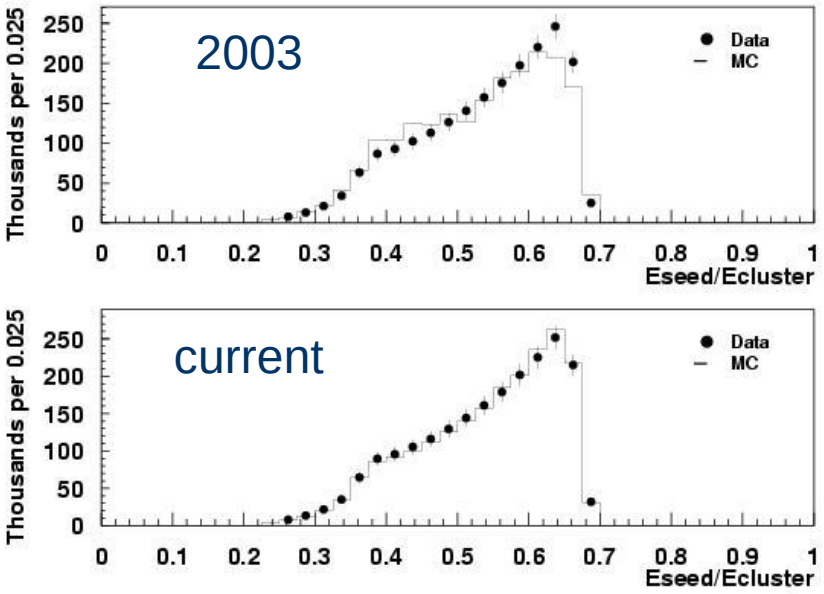


- MC used to make acceptance correction and simulate backgrounds to signal modes
  - simulates kaon generation, propagation, and decay
  - simulates detector geometry and response
  - includes the effect of “accidental” activity by overlaying data events from accidental trigger

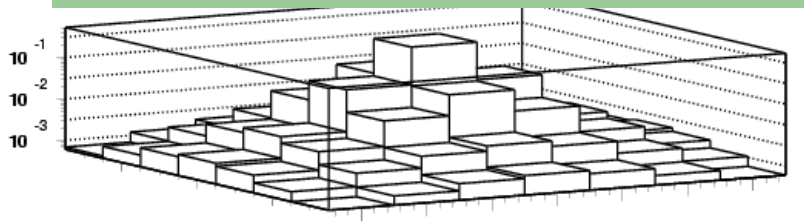
Improvements to MC

- 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

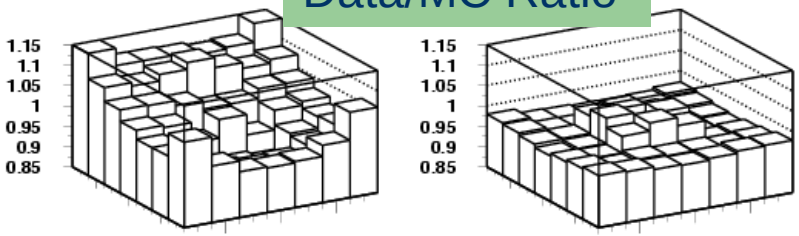
Improvements: Transverse Shower Shape



Fraction of energy per CsI block



Data/MC Ratio

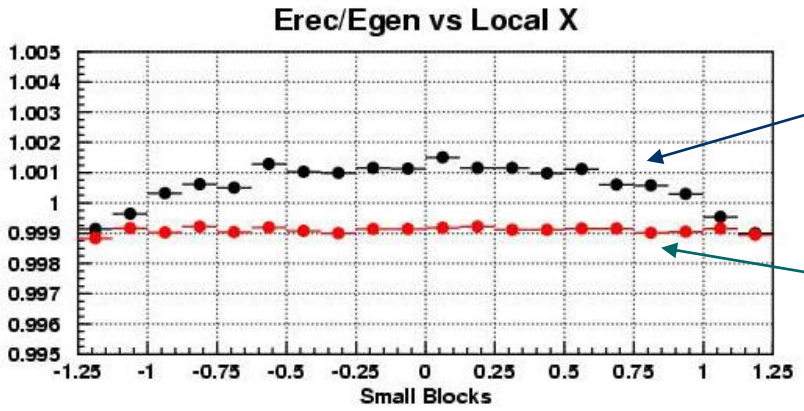


2003 current

2003: Includes transverse energy correction to match data and MC

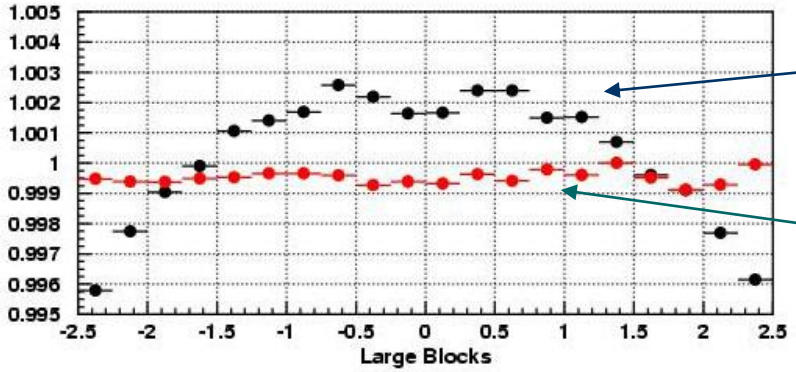
Current: No transverse energy correction required

Improvements: Reconstructed Energy



2003

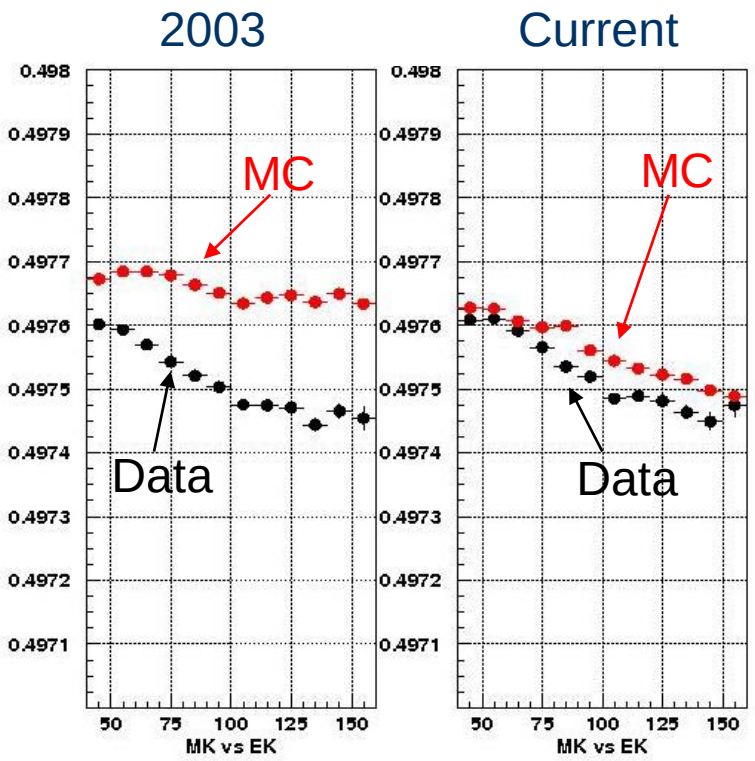
Current



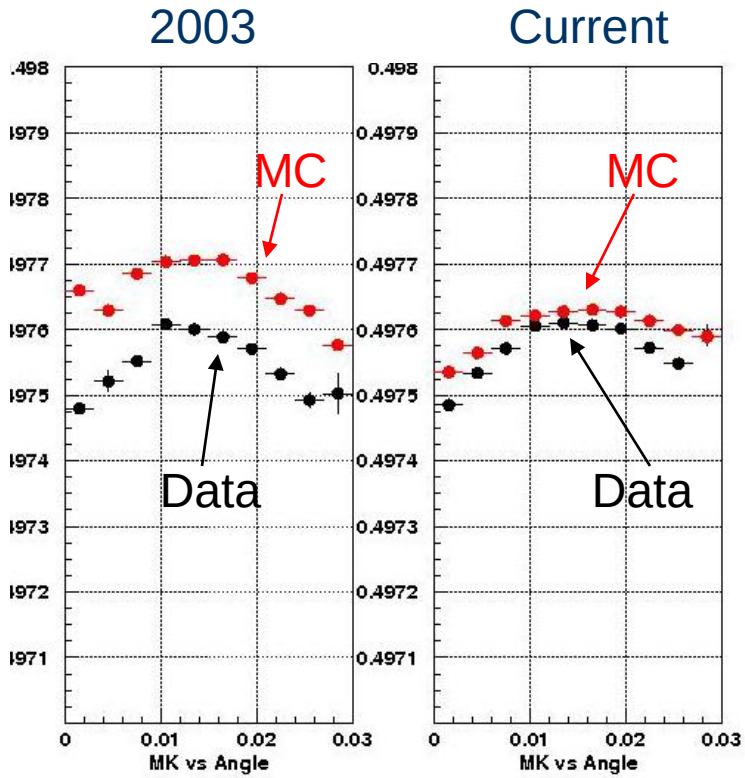
2003

Current

Improvements: Energy Linearity

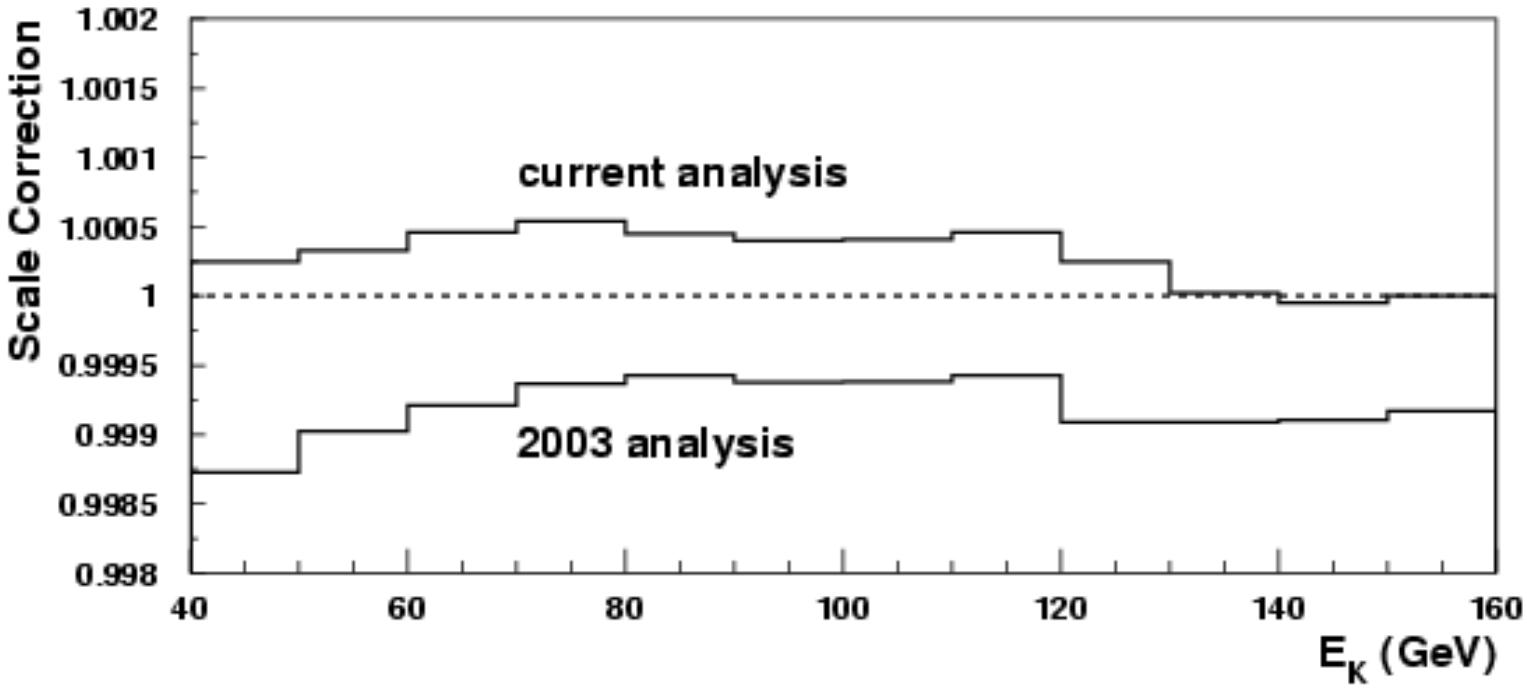


Mass vs. Energy



Mass vs. Photon Angle

Improvements: Energy Scale

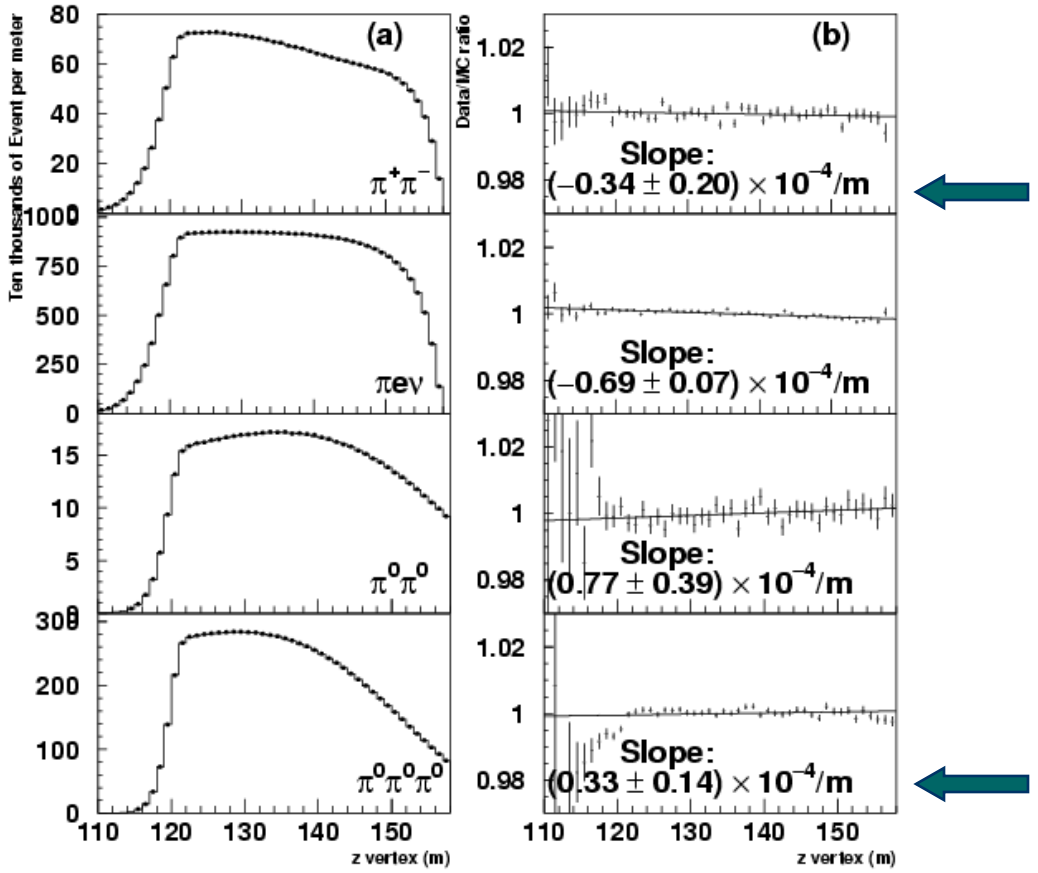


Backgrounds

- 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

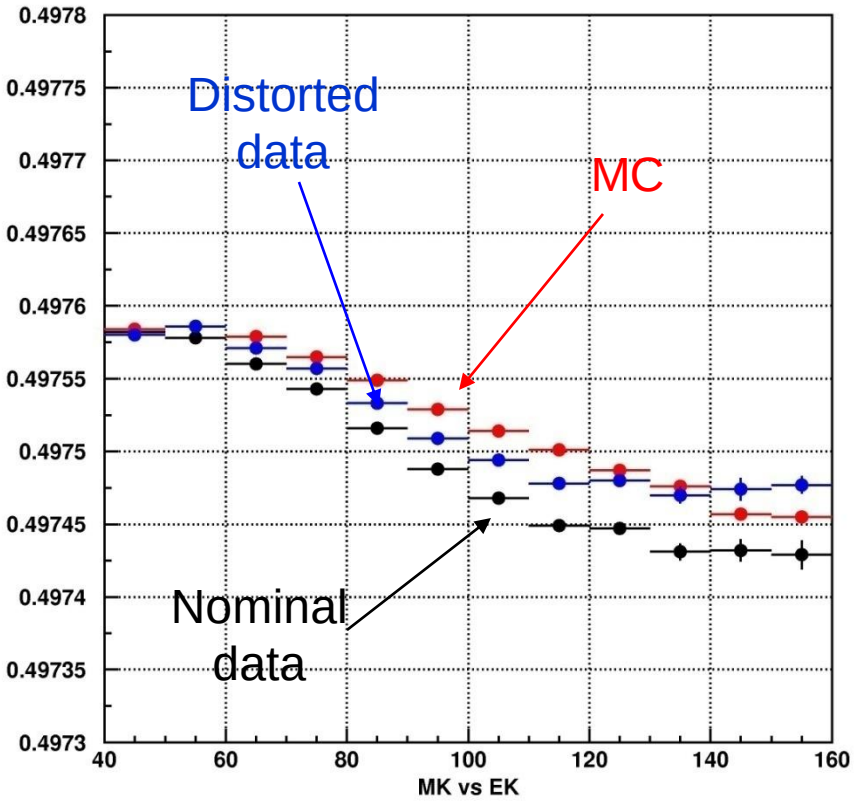
Uncertainty from Acceptance

- Quality of MC simulation evaluated by comparing vacuum beam z vertex distributions between data and MC
- Bias on Re(ε′/ ε) given by sΔz/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

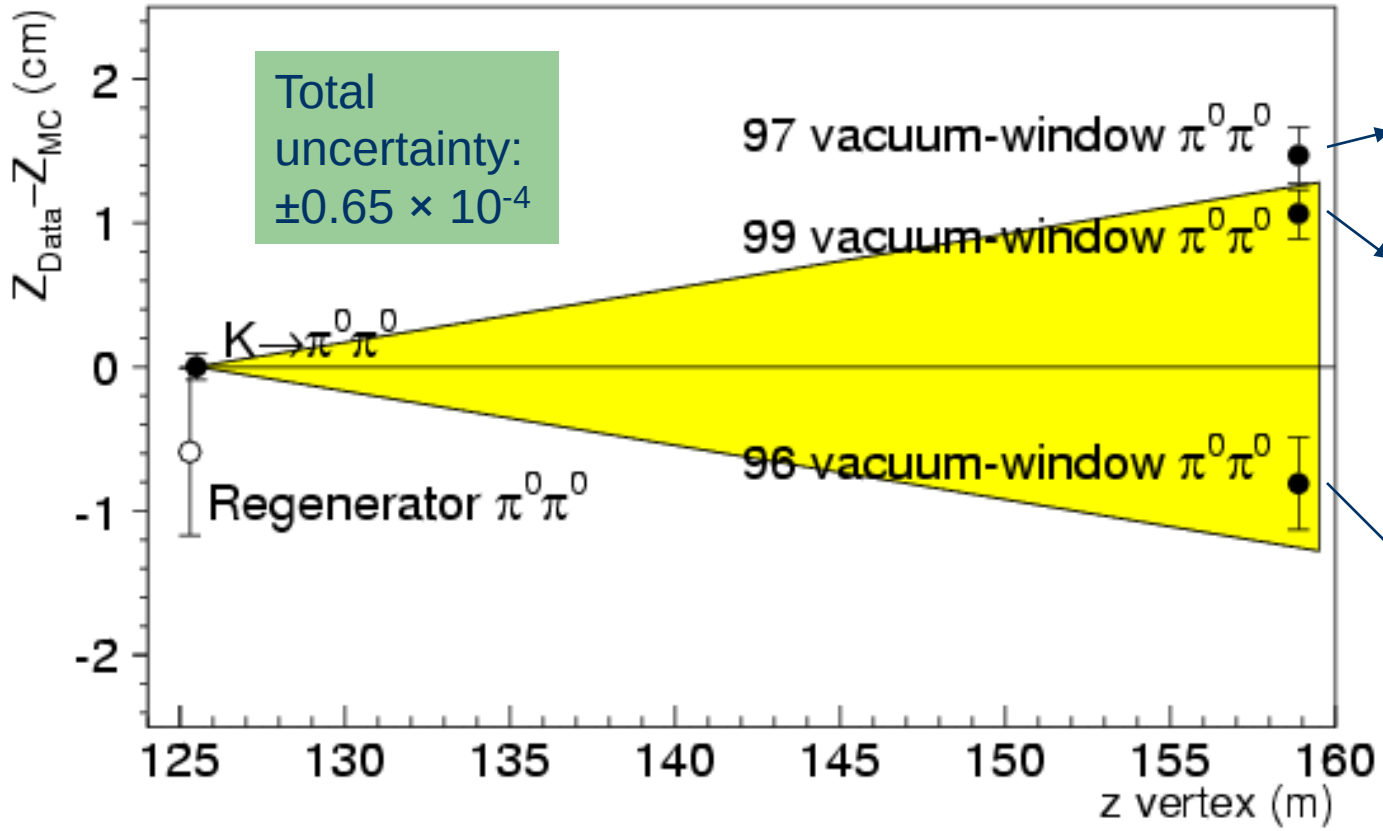


Uncertainty from Energy Non-linearity

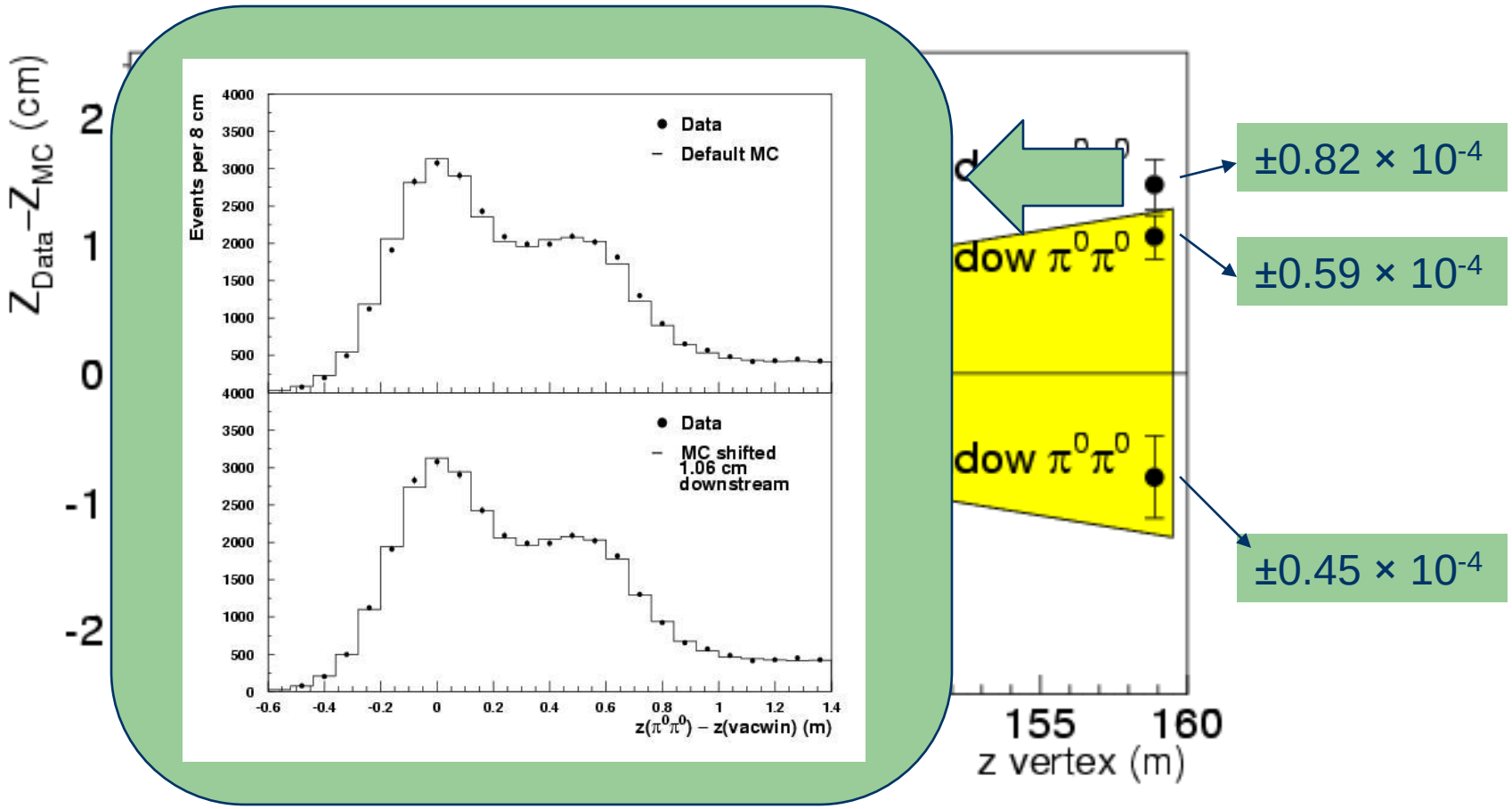
- Use M_K vs E_K plot to determine distortion which provides best data-MC match
- 0.1%/100 GeV nonlinearity applied to data for 1997 and 1999
- 0.3%/100 GeV nonlinearity for 1996
- Change in Re(ε'/ε)
  - 1996: -0.1×10^{-4}
  - 1997: -0.1×10^{-4}
  - 1999: $+0.2 \times 10^{-4}$
- Systematic error: $\pm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



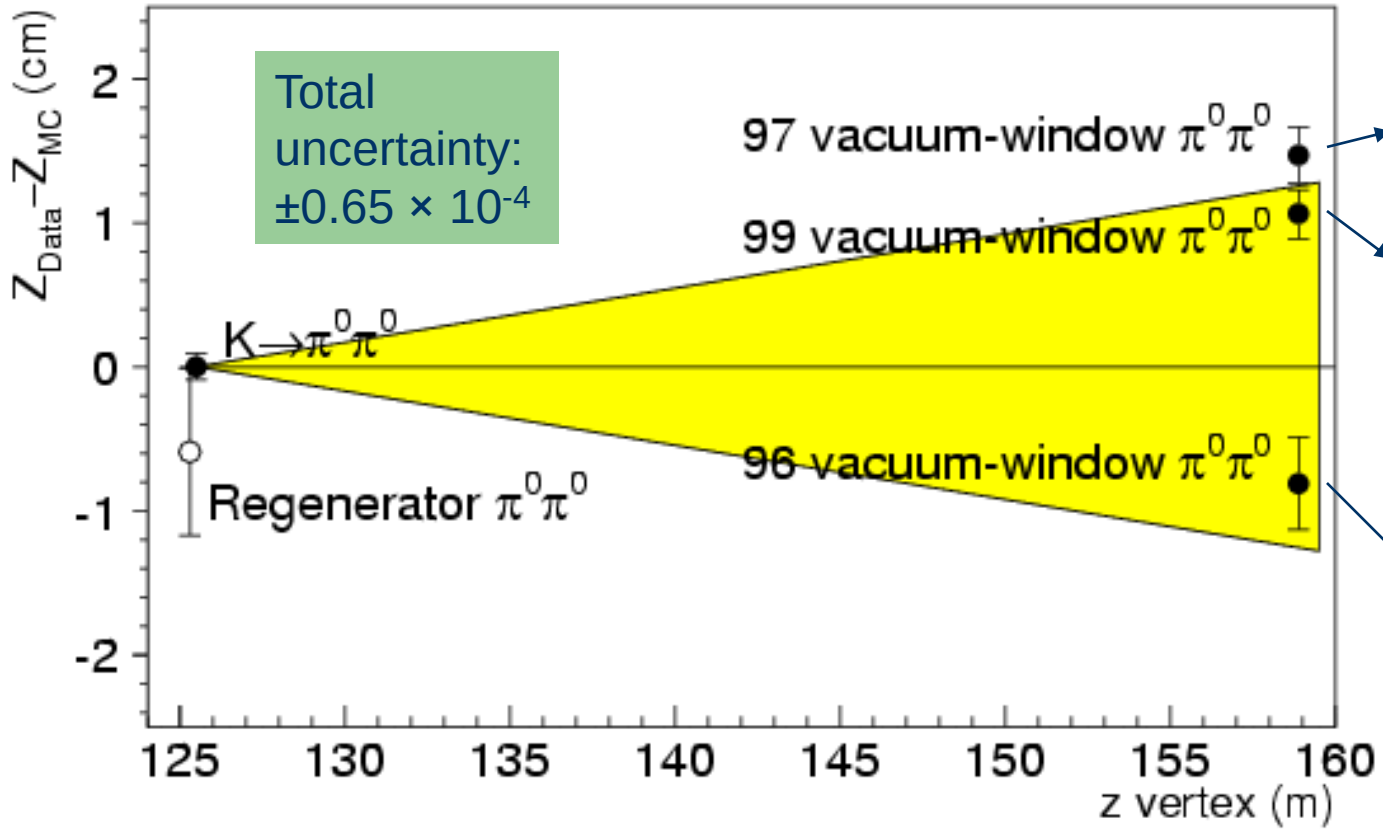
Uncertainty from Energy Scale



Uncertainty from Energy Scale



Uncertainty from Energy Scale



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

Statistical Uncertainty: 1.1×10^{-4}

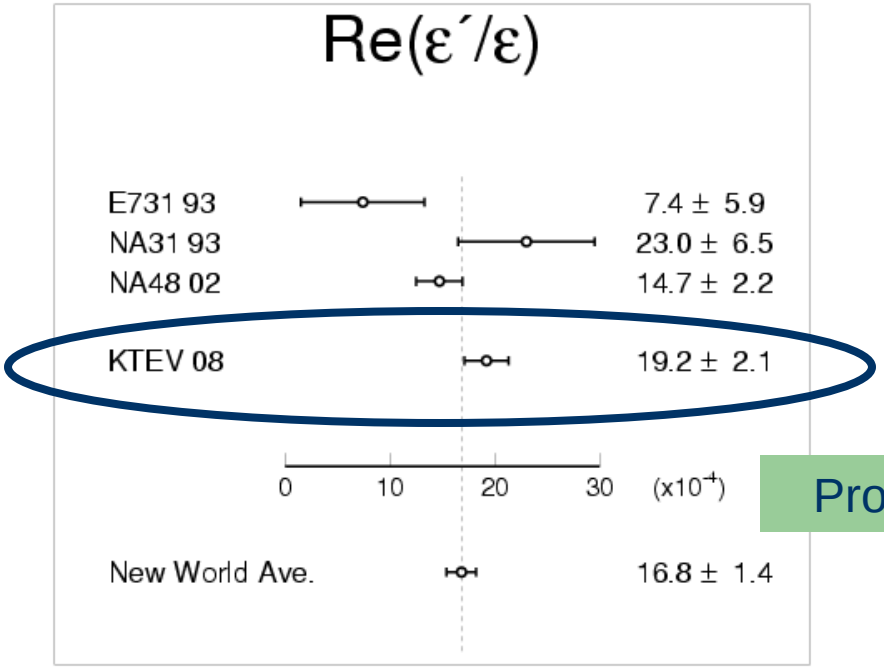
Results

The final KTeV measurement of Re($\boldsymbol{\varepsilon'/\varepsilon}$) . . .

Results: Re(ε′/ ε)

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

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

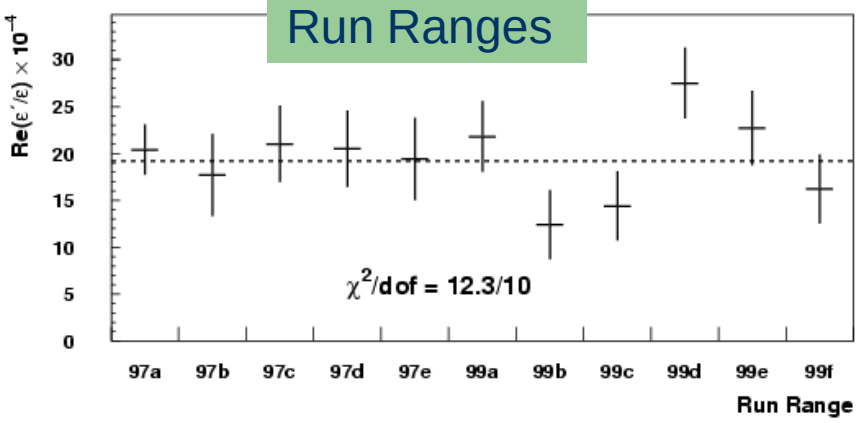


Probability = 13%

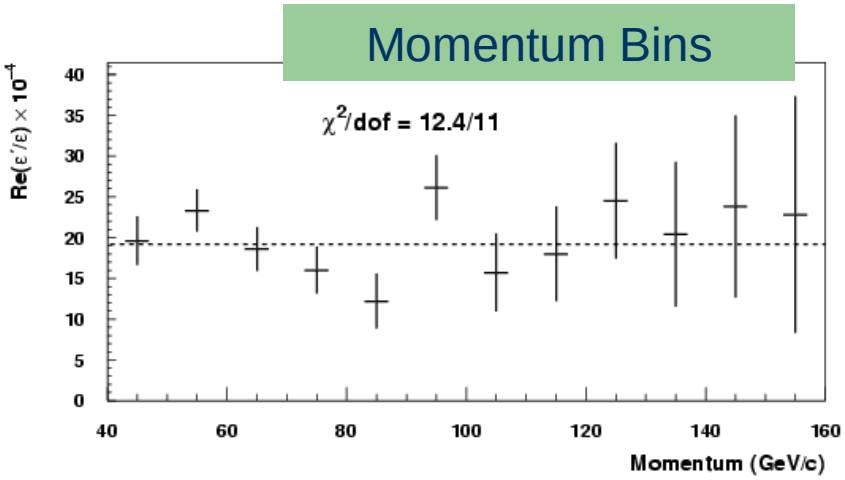
KTeV 2003: $\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\mathrm{stat}) \pm 2.4\ (\mathrm{syst})] \times 10^{-4}$

Results: Re(ε′/ ε) Crosschecks

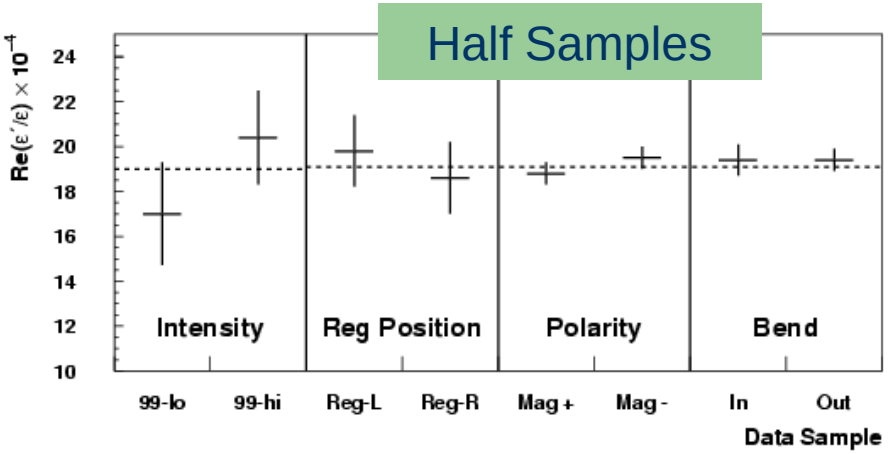
Run Ranges



Momentum Bins



Half Samples



Kaon Parameters: z-binned fit

- Fit for Δm, τ_S, ϕ_ε, Re(ε'/ε), Im(ε'/ε)
- Systematic uncertainties evaluated using same methods as Re(ε'/ε) 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*

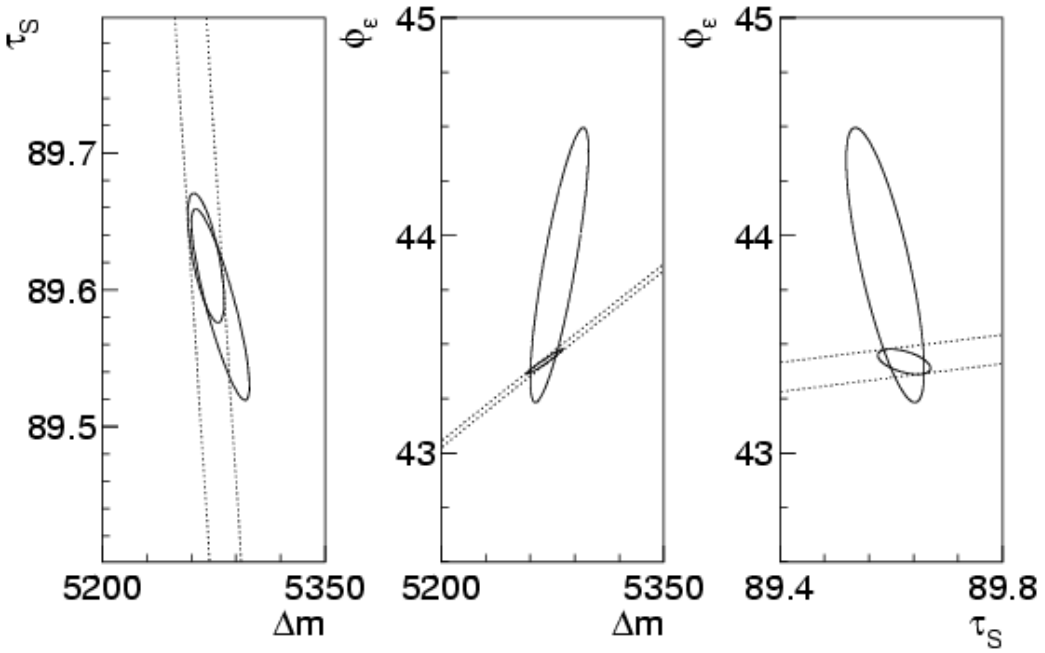
$$\Phi_{+-} \approx \Phi_\varepsilon + \mathrm{Im}(\varepsilon'/\varepsilon)$$

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

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

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

Results: z-binned Fit



No CPT assumption:

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

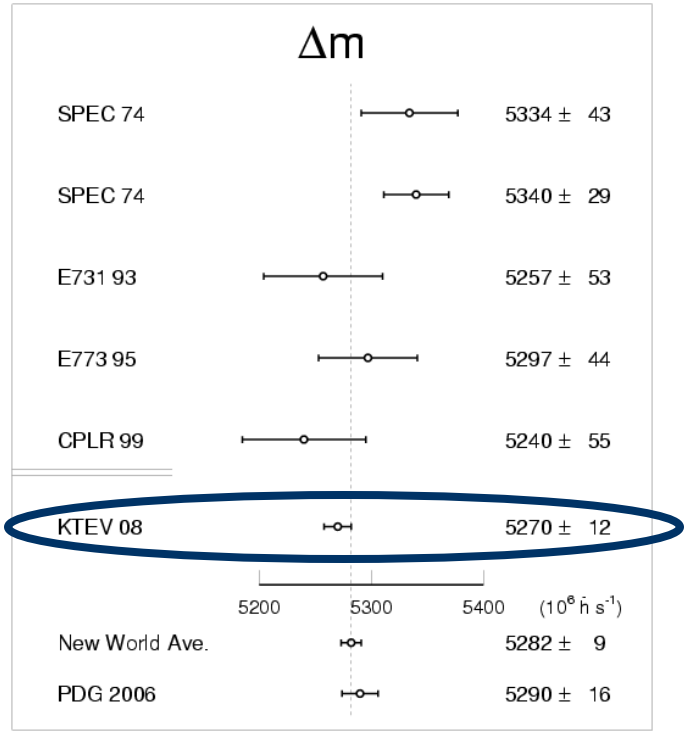
$\tau_S = (89.589 \pm 0.070) \times 10^{-12}$ s

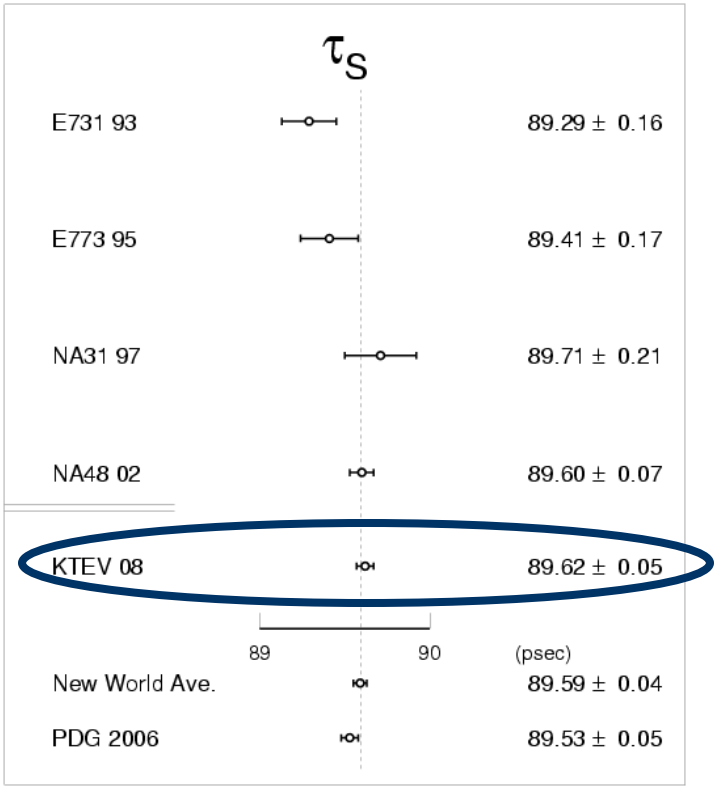
CPT assumption applied:

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

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

Results: Δm and τ_S



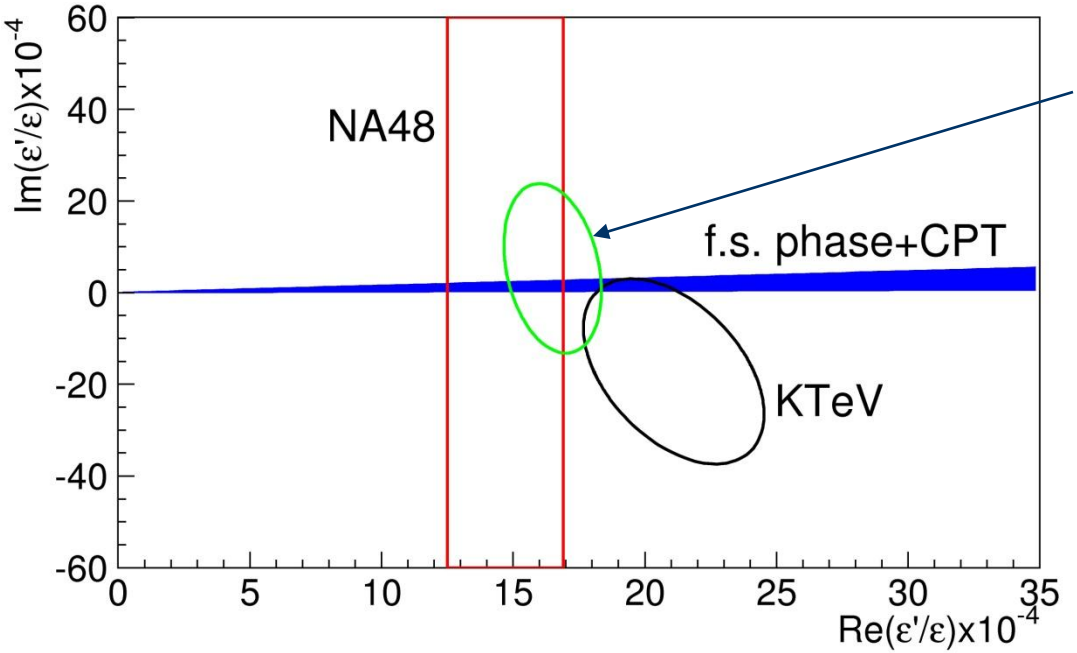


KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6\ \hbar s^{-1}$

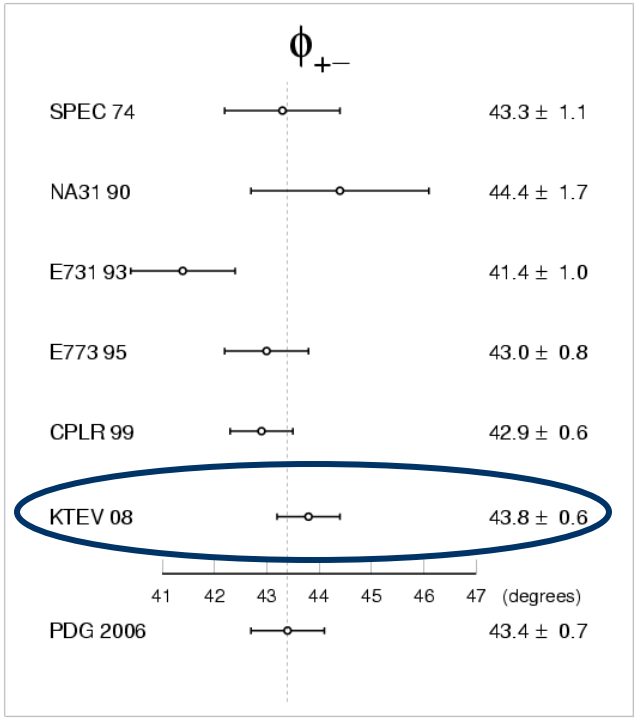
KTeV 2003: $\tau_S = (89.65 \pm 0.07) \times 10^{-12}$ s

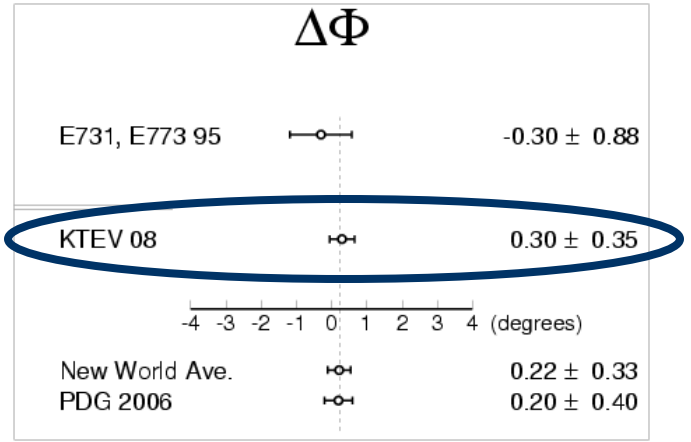
Results: z-binned fit

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



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 Final Results

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

Assuming CPT

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

No CPT assumption

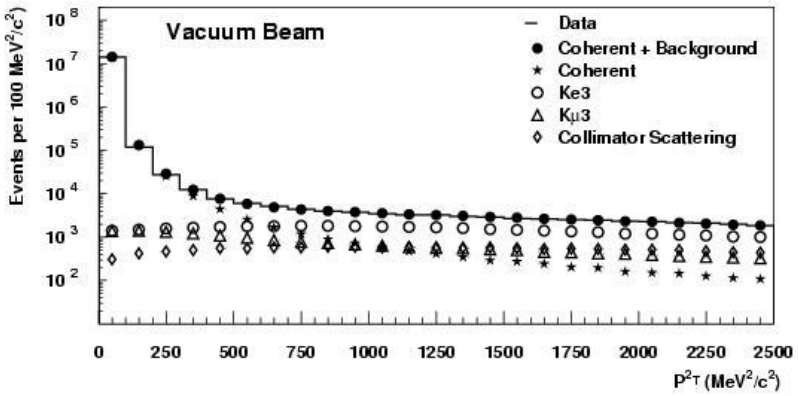
Extra Slides

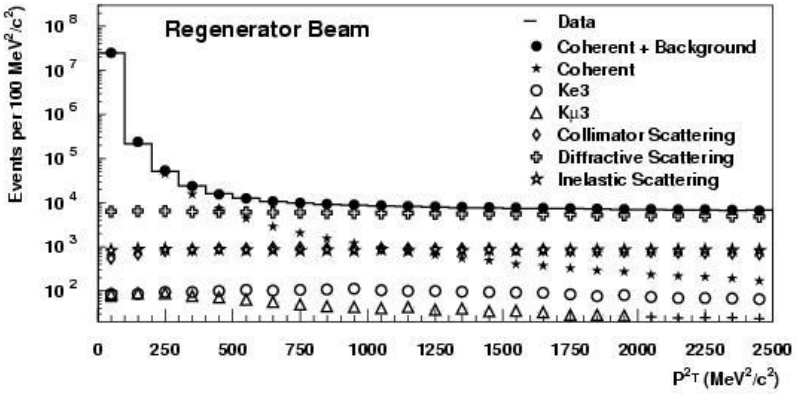
Backgrounds

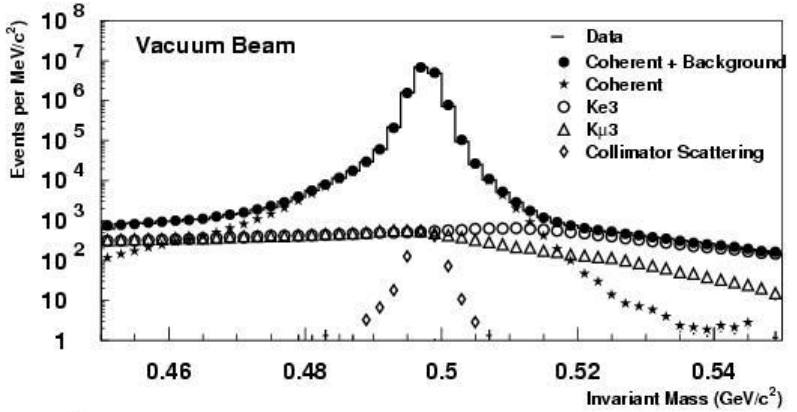
Source	Vacuum Beam	Regenerator Beam
$K \to \pi^+\pi^-$		
Regenerator Scattering	–	0.075%
Collimator Scattering	0.008%	0.008%
$K_L \to \pi^\pm e^\mp \nu$	0.032%	0.001%
$K_L \to \pi^\pm \mu^\mp \nu$	0.030%	0.001%
Total	0.070%	0.085%
$K \to \pi^0\pi^0$		
Inelastic Scattering	0.128%	0.175%
Diffractive Scattering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

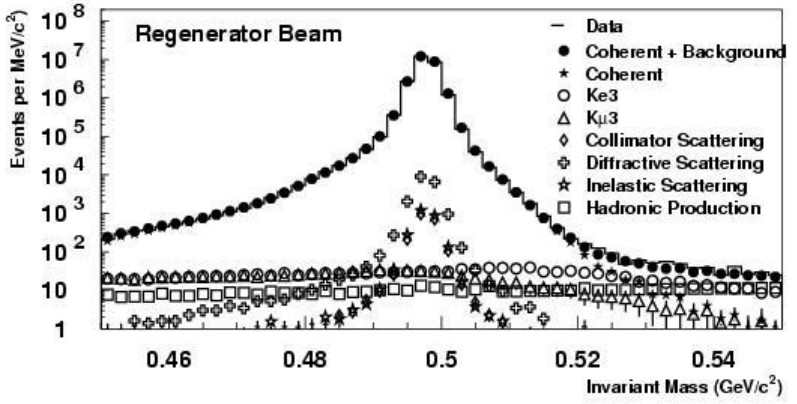
1999 backgrounds (other years vary slightly)

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

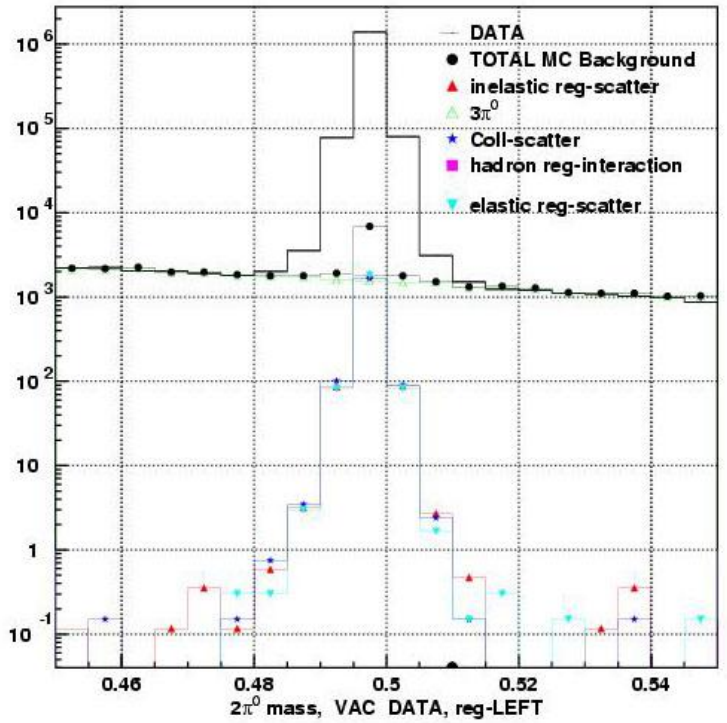




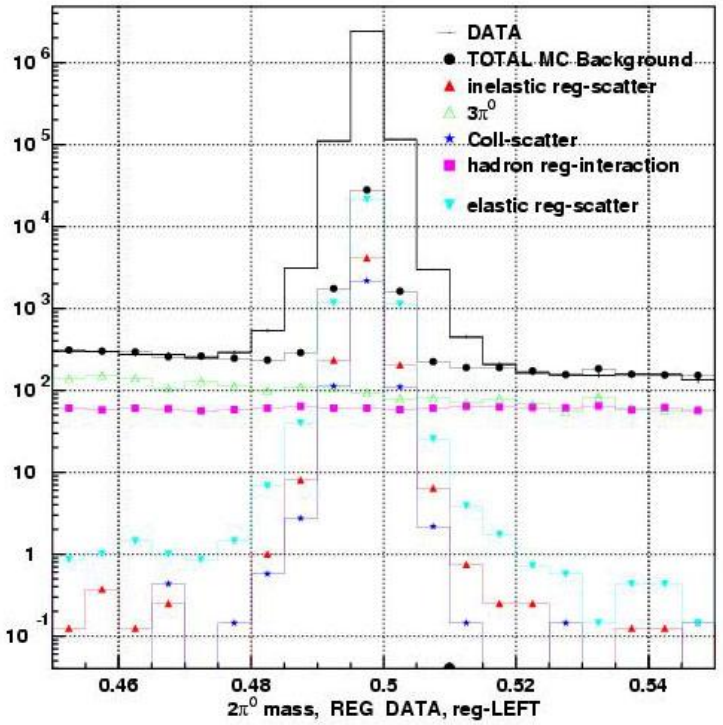




$K \rightarrow \pi^0\pi^0$ Backgrounds

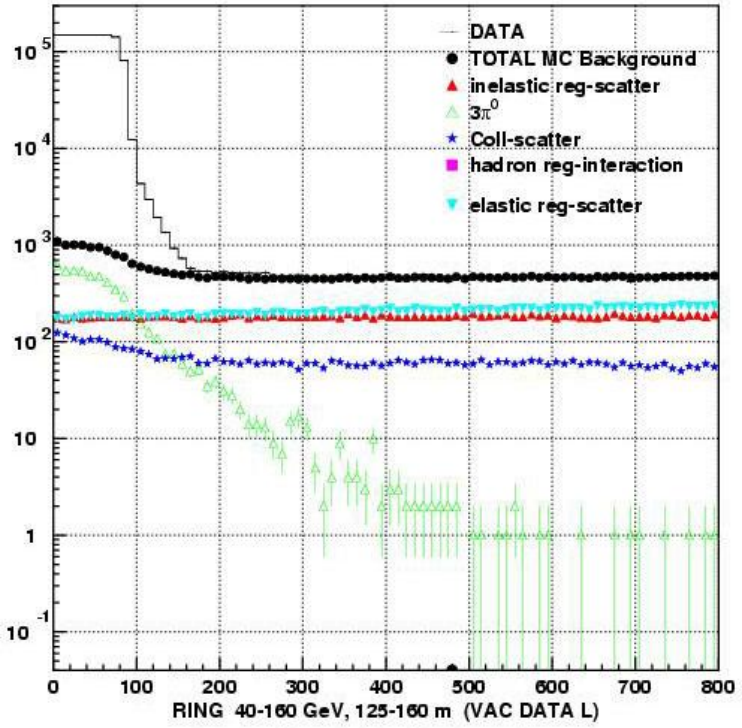


Vacuum Beam

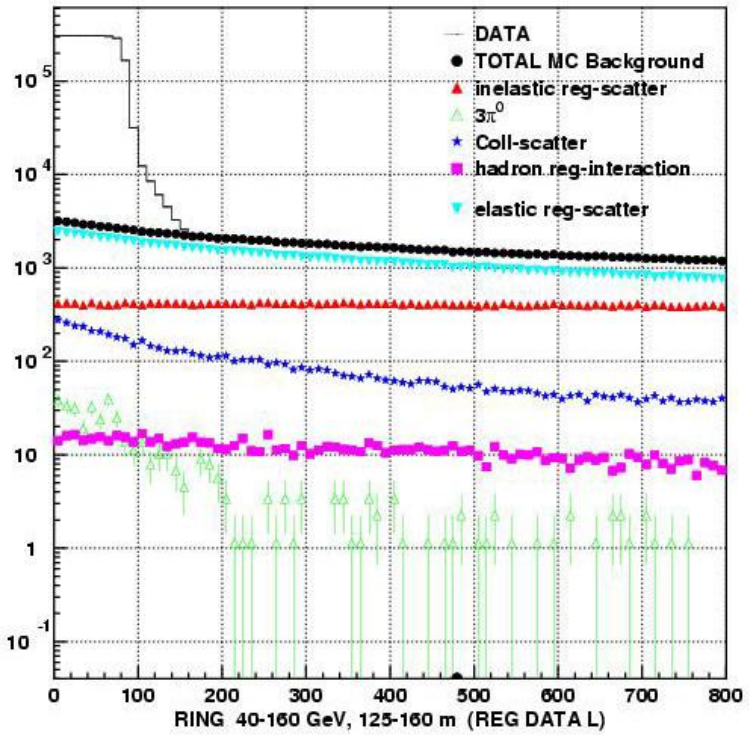


Regenerator Beam

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

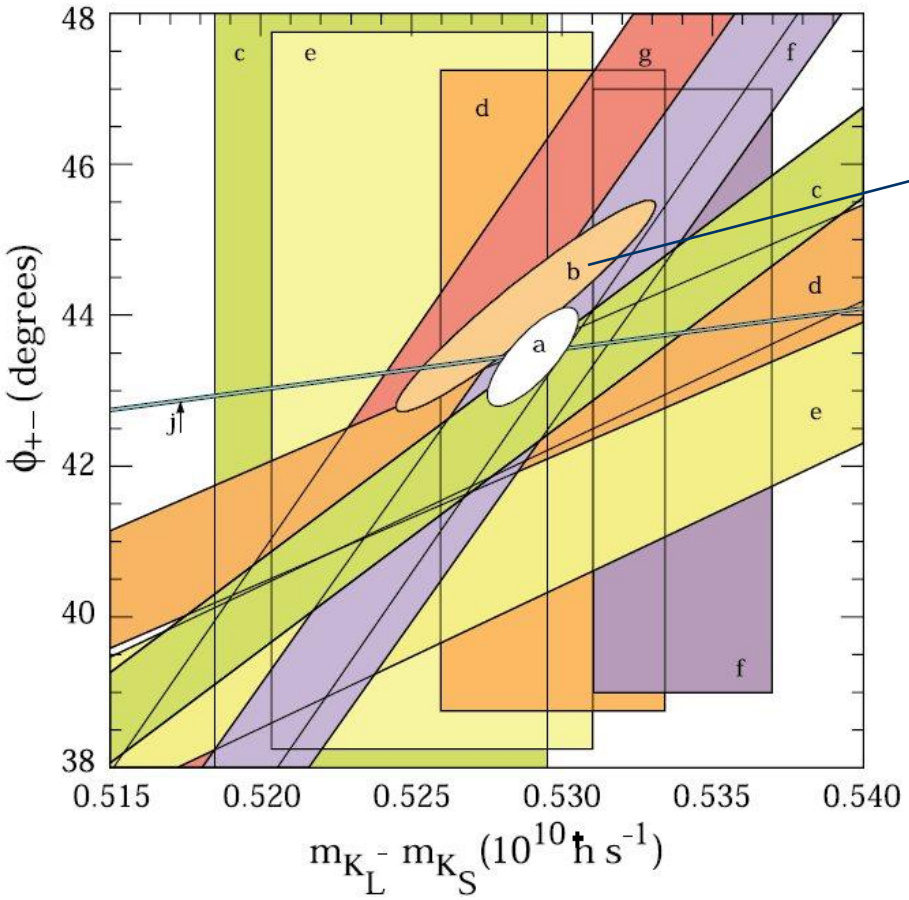


Vacuum Beam



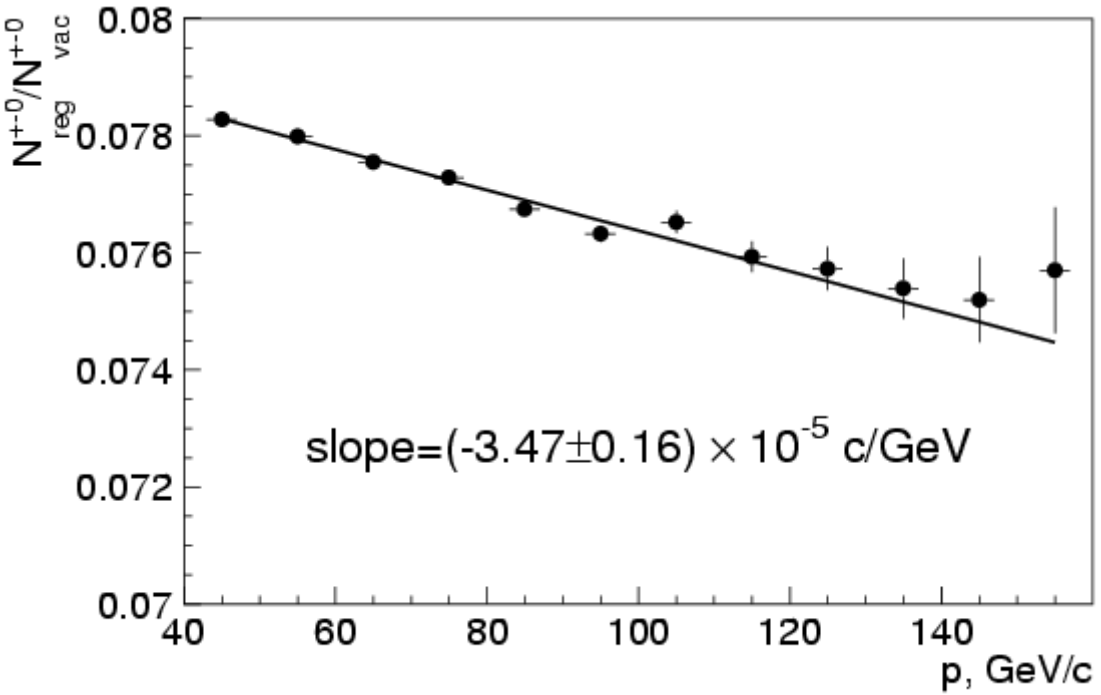
Regenerator Beam

PDG: ϕ_{+-}



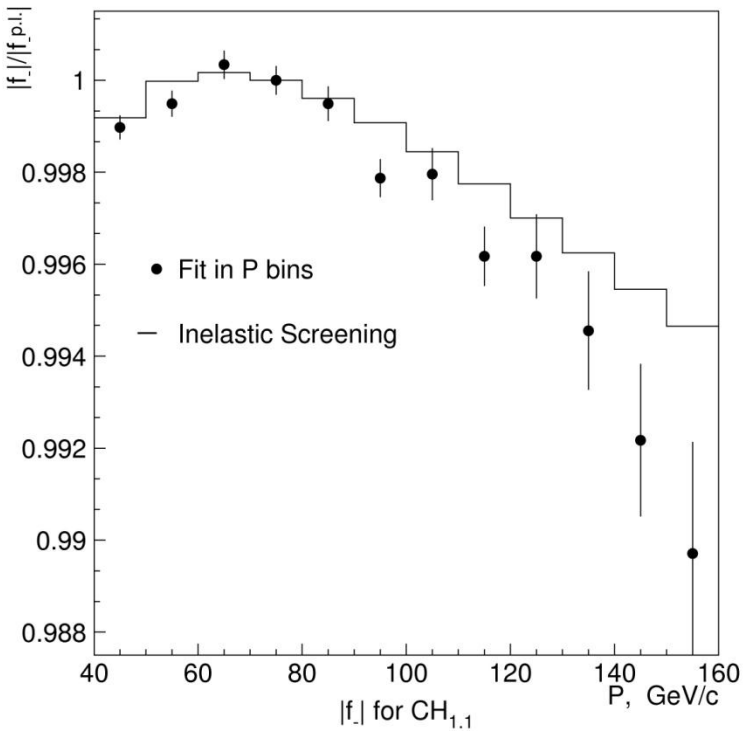
KTeV 2003

Regenerator Transmission



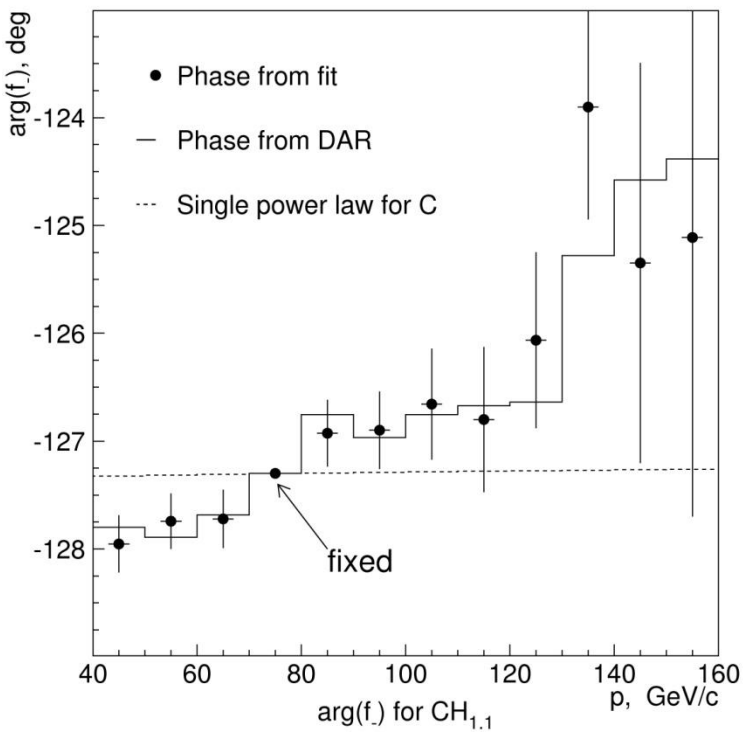
- Transmission measured from data using $K_L \rightarrow \pi^+\pi^-\pi^0$ decays
- Dedicated trigger in 1999 improved statistical precision of measurement

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