The Final Measurement of ε′/ε from KTeV

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For the KTeV Collaboration:

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Overview

- Introduction
- The KTeV Experiment
- Data Analysis
- Monte Carlo Simulation
- Backgrounds
- Extracting Physics Parameters
- Systematic Uncertainties
- Results and Conclusion

Focus on improvements to $\mathbf{K} \rightarrow \pi^0\pi^0$ analysis

CP Violation

- Discrete symmetries: C, P, T individually invariant in strong and EM interactions
- Parity violation in weak interaction discovered in 1953
- CP violation in kaon mixing (“indirect”) discovered in 1964
- CP violation in kaon decays (“direct”) established by KTeV and NA48 in 1999
- Direct and indirect CP violation predicted by the Standard Model
- Astrophysics suggests non-SM CP violation
- CPT violation not expected

CKM Matrix

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP Violation

Neutral Kaons

Strangeness Eigenstates :

$$K^0 = \bar{s}d$$

$$\overline{K}^0 = s\bar{d}$$

CP Eigenstates :

$$\left|K_1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right) \qquad (CP+1)$$

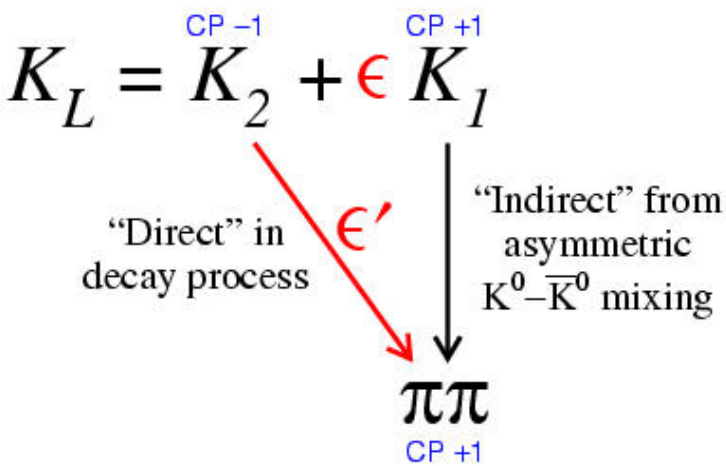
$$\left|K_2\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right) \qquad (CP-1)$$

CP Violation in Kaon System

Weak Eigenstates :

$$\left|K_L\right\rangle \approx \left|K_2\right\rangle + \varepsilon\left|K_1\right\rangle \qquad (mostly\ CP-1)$$

$$\left|K_S\right\rangle \approx \left|K_1\right\rangle + \varepsilon\left|K_2\right\rangle \qquad (mostly\ CP+1)$$



CP symmetry can be violated in the mixing and in the decay

Measuring Re(ε′/ ε)

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

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

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

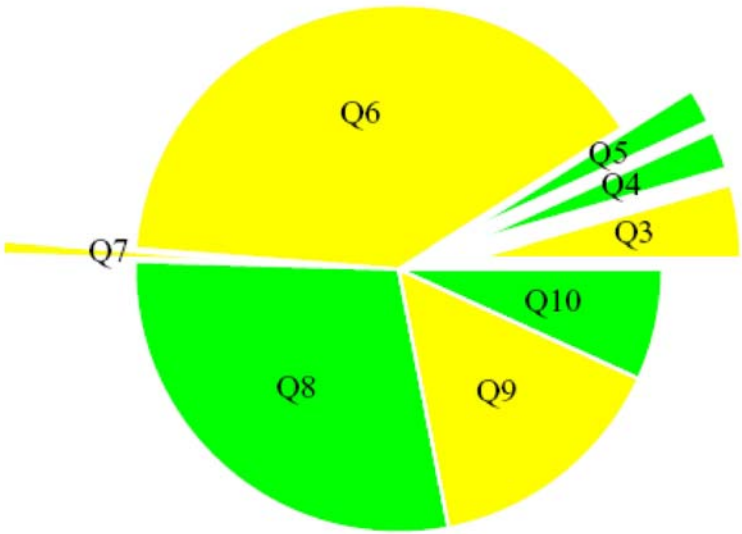
Re(ε′/ε) → direct CP violation

Im(ε′/ε) → CPT violation

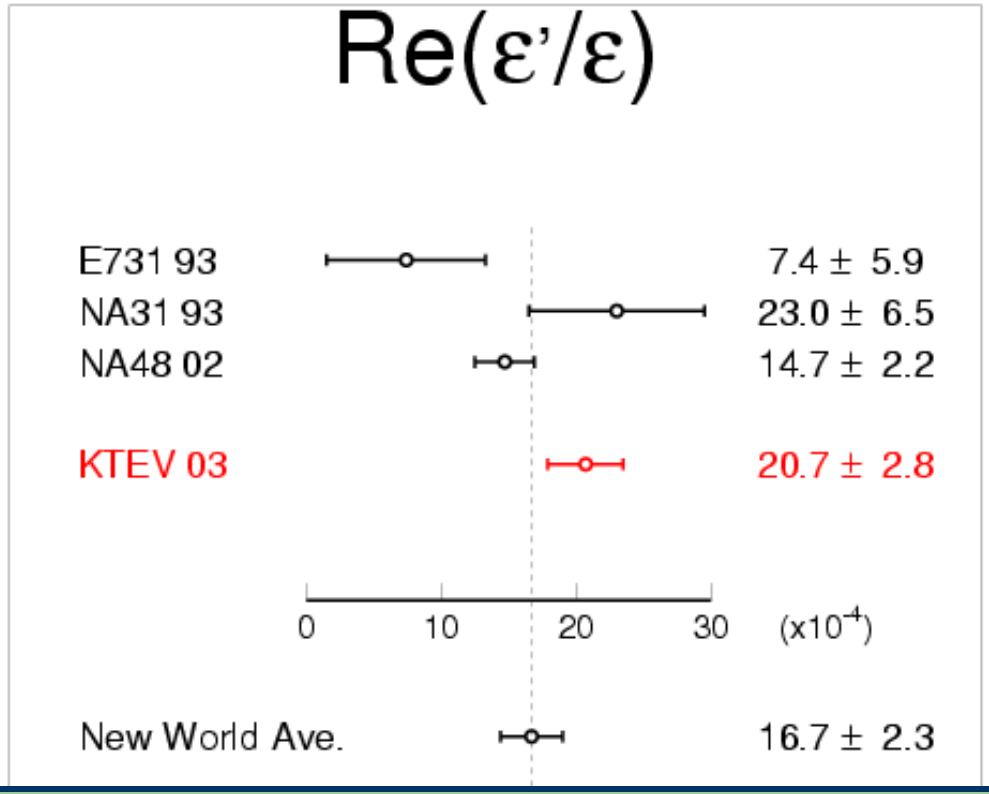
$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left(\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 - 1\right)$$

Theory Status

- Standard model predicts CP violation through a complex phase in the CKM matrix
- Amplitudes calculated using operator product expansion
- 10 operators
  - W exchange
  - QCD penguins
  - EW penguins
- Wilson coefficients (short-distance physics) well understood at NLO
- Large uncertainties in long distance physics
- Current predictions 1-30 × 10^{-4}
- Precise lattice QCD calculations expected in the future



KTeV Results (2003)



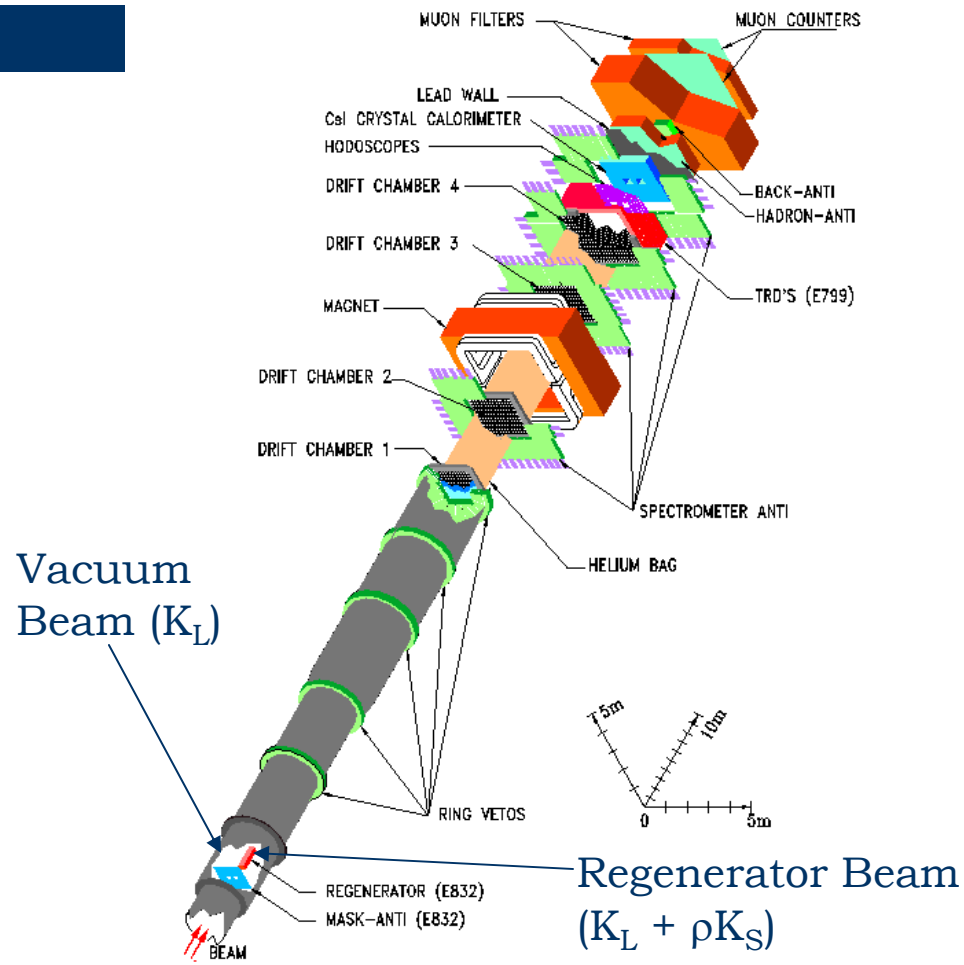
$$\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.48(\mathrm{stat}) \pm 2.39(\mathrm{syst})] \times 10^{-4}$$

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	

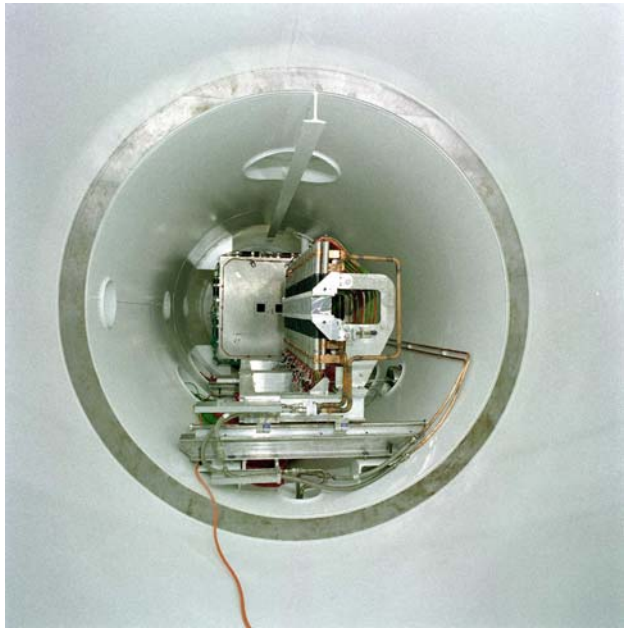
The KTeV Detector

- 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



Regenerator

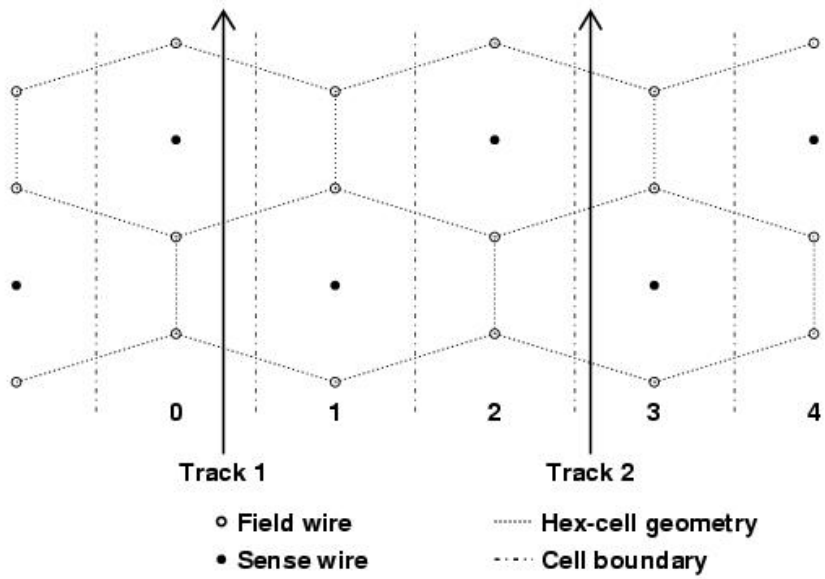
$$|K_L\rangle \rightarrow \text{Regenerator } (\rho) \quad \sigma_{\overline{K}^0} > \sigma_{K^0} \rightarrow |K_L\rangle + \rho|K_S\rangle$$



- Coherent regeneration: forward direction
- Diffractive regeneration: kaon scatters at finite angle
- Inelastic regeneration: target nucleus destroyed, secondary particles may be produced

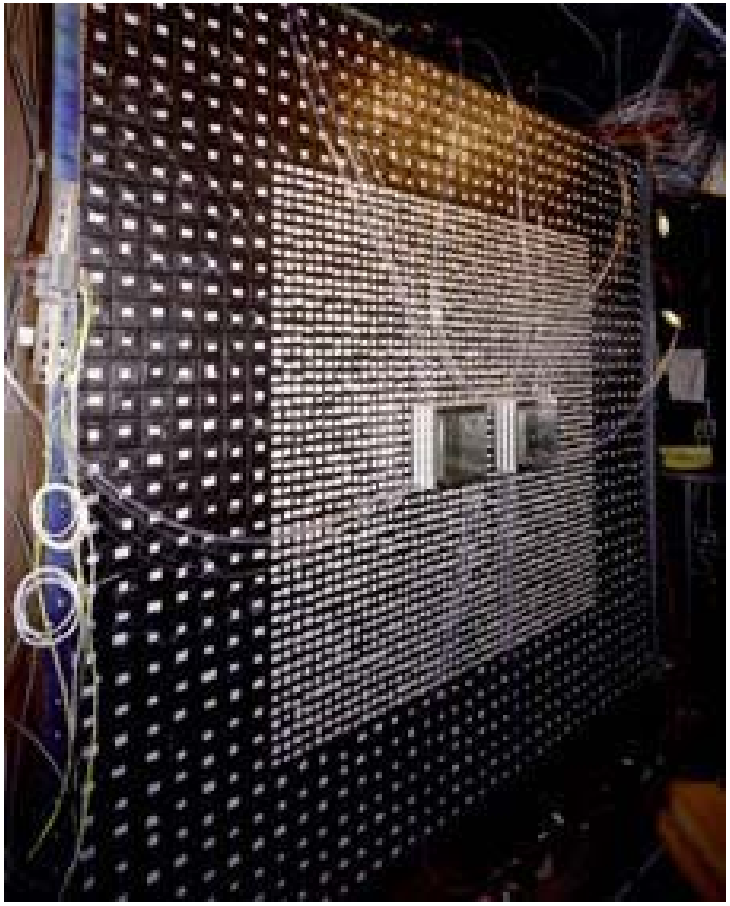
Charged Spectrometer

- 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%

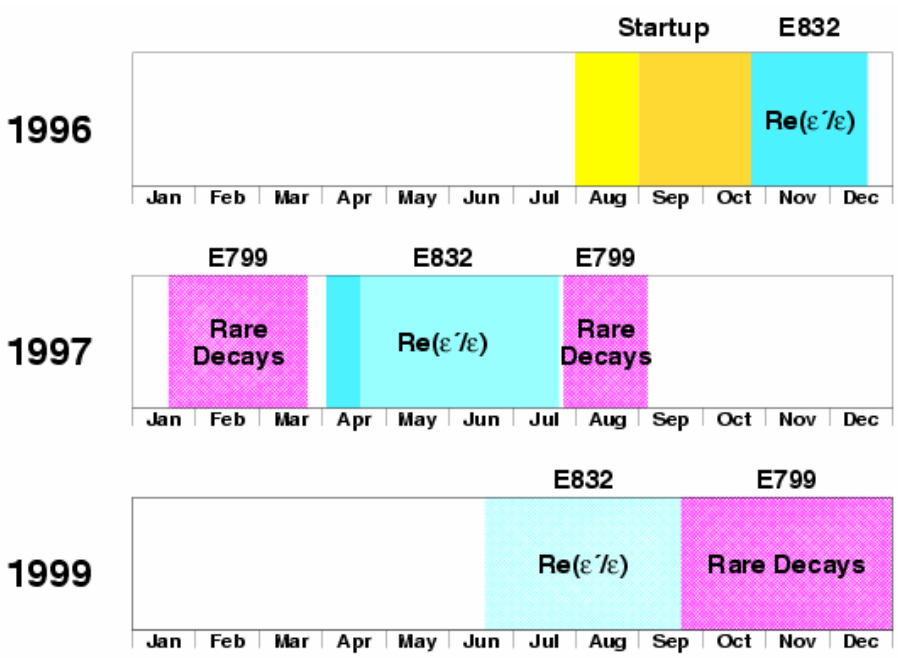


CsI Calorimeter

- 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 mm (small blocks)
    - ~2.4 mm (large blocks)
  - energy resolution ~0.6%
  - absolute energy scale ~0.05%

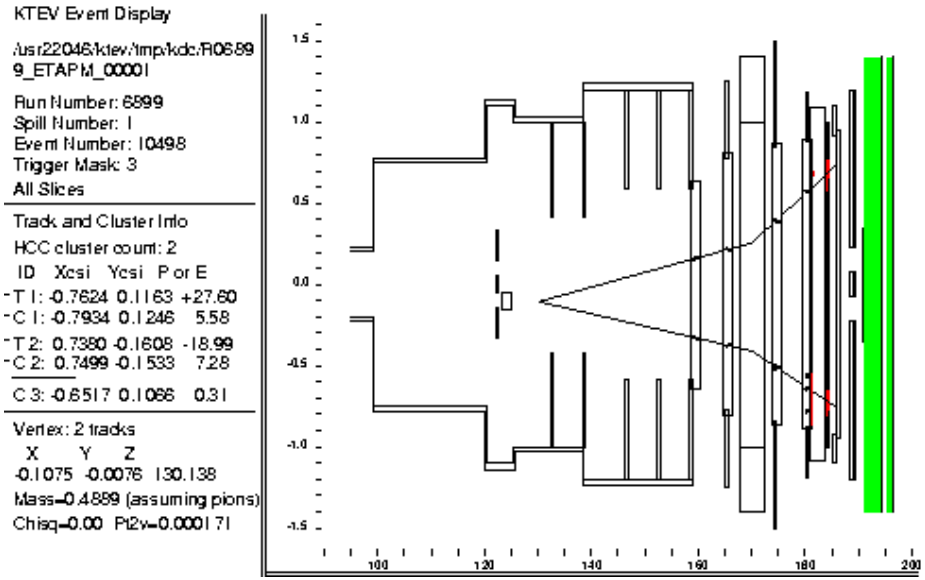


KTeV Data

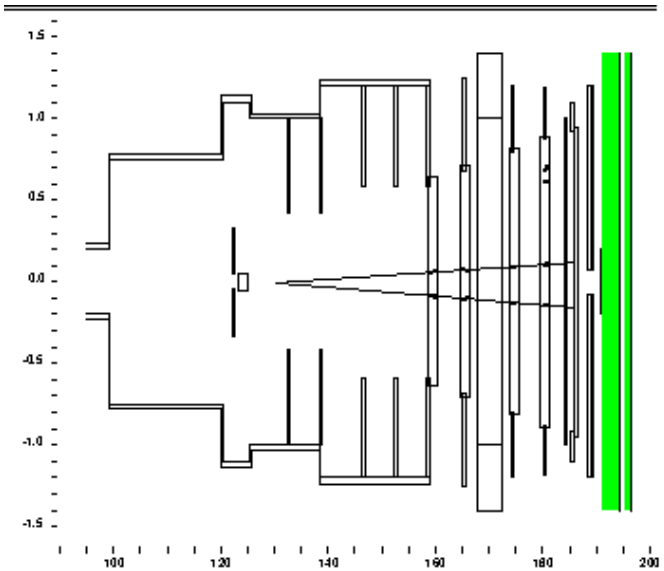


- 2003 result based on ~3 million $K_L \rightarrow \pi^0\pi^0$ decays from 1996 and 1997
  - $\sigma_{stat} = 1.6 \times 10^{-4}$
- 1999 dataset contains ~3 million $K_L \rightarrow \pi^0\pi^0$ decays
  - $\sigma_{stat} = 1.6 \times 10^{-4}$
- All data
  - $\sigma_{stat} = 1.1 \times 10^{-4}$

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

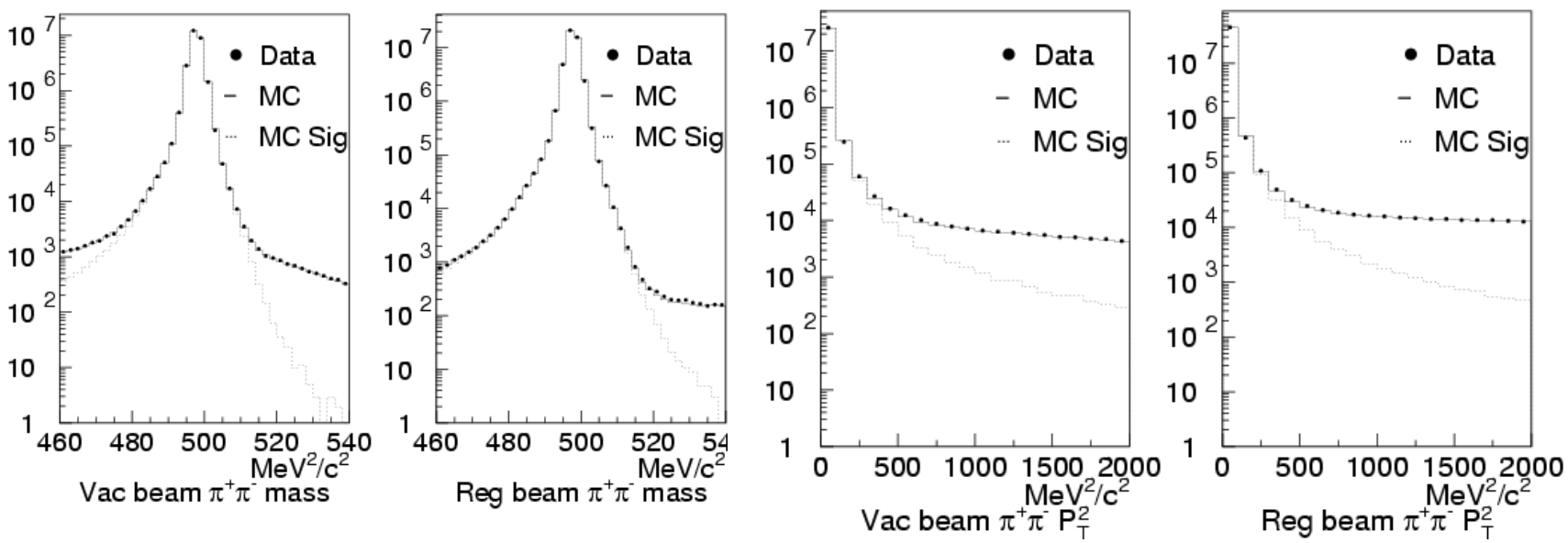


X vs Z



Y vs Z

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



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

KTEV Event Display

/ktev4a/data/E832/RAN009686.dat

Run Number: 9686
Spill Number: 3
Event Number: 534355
Trigger Mask: 8
All Slices

Track and Cluster Info

HCC cluster count: 4

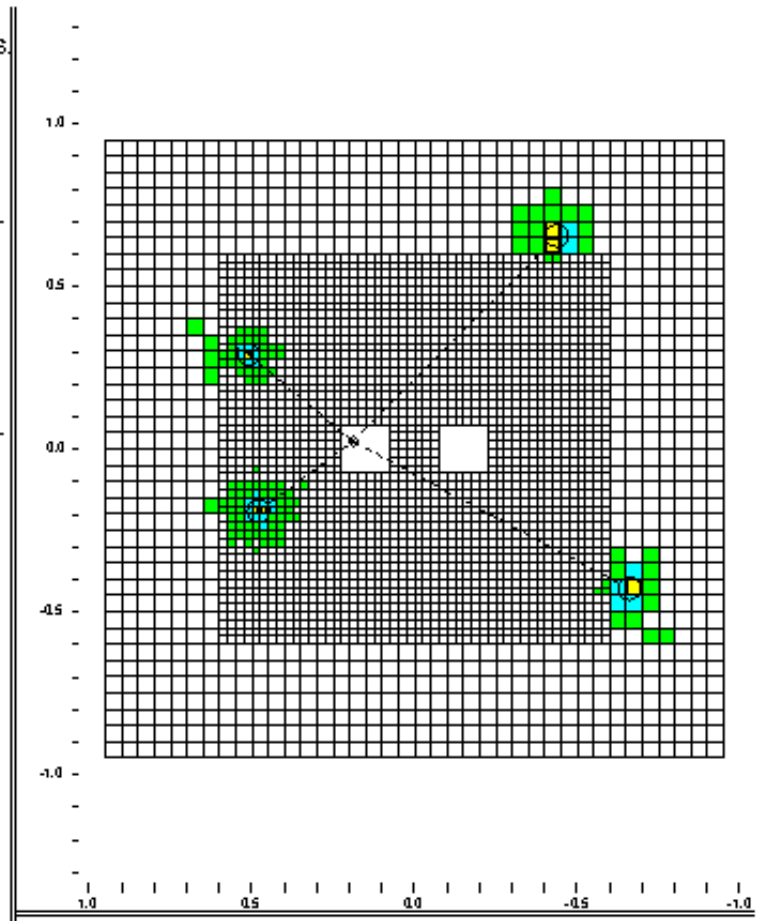
ID	Xcsi	Ycsi	P or E
C 1:	-0.4372	0.6553	6.20
C 2:	-0.6604	-0.4297	5.32
C 3:	0.4797	-0.1908	18.65
C 4:	0.5111	0.2909	9.24

Vertex: 4 clusters

X	Y	Z
0.1412	0.0171	139.139

Mass=0.4973

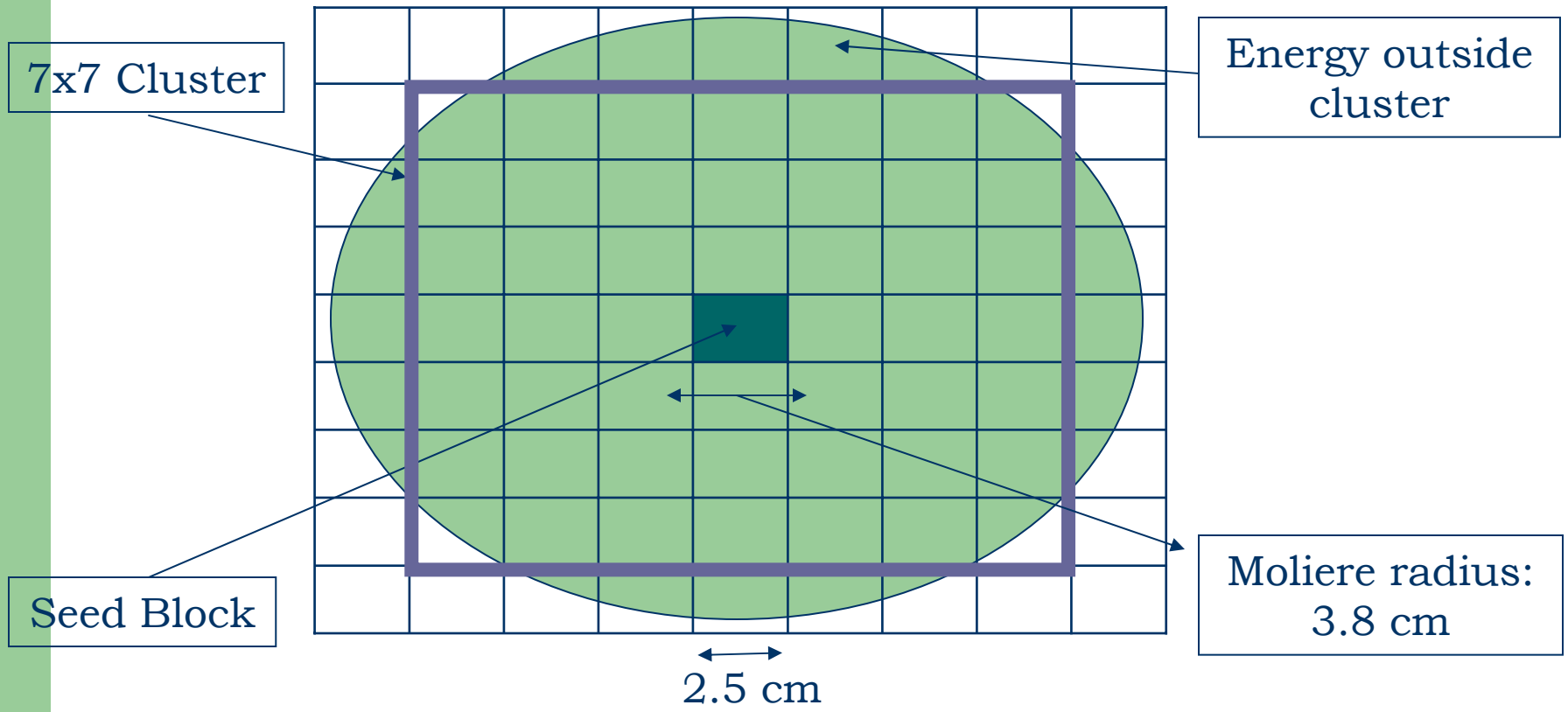
Pairing chisq=0.11



CsI Clustering

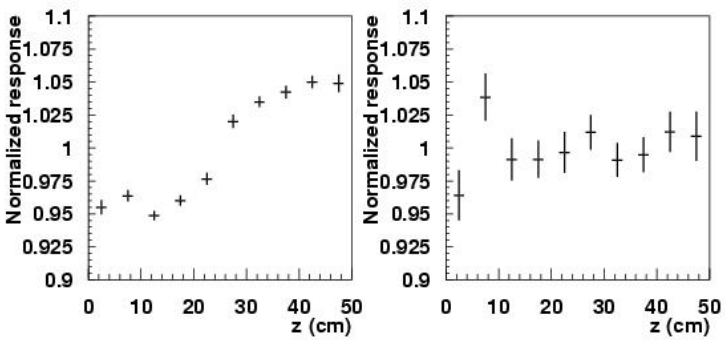
- Build clusters around local energy maxima
  - 7×7 clusters (small blocks)
  - 3×3 clusters (large blocks)
- Determine positions by comparing the fraction of energy in neighboring rows and columns
- Determine energies by summing block energies and applying corrections
  - Energy outside cluster
  - Energy shared between clusters
  - Variations of CsI response
  - Photon-electron differences

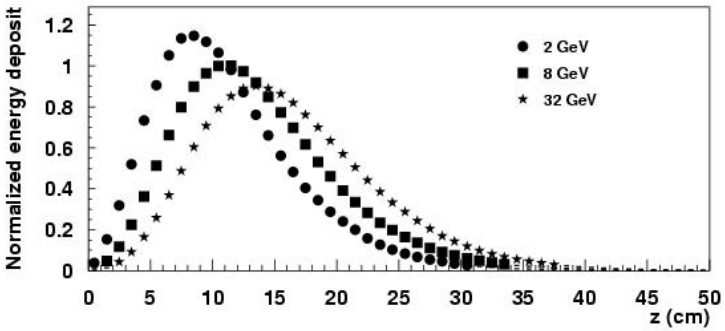
Clustering Lingo



Longitudinal Uniformity Correction

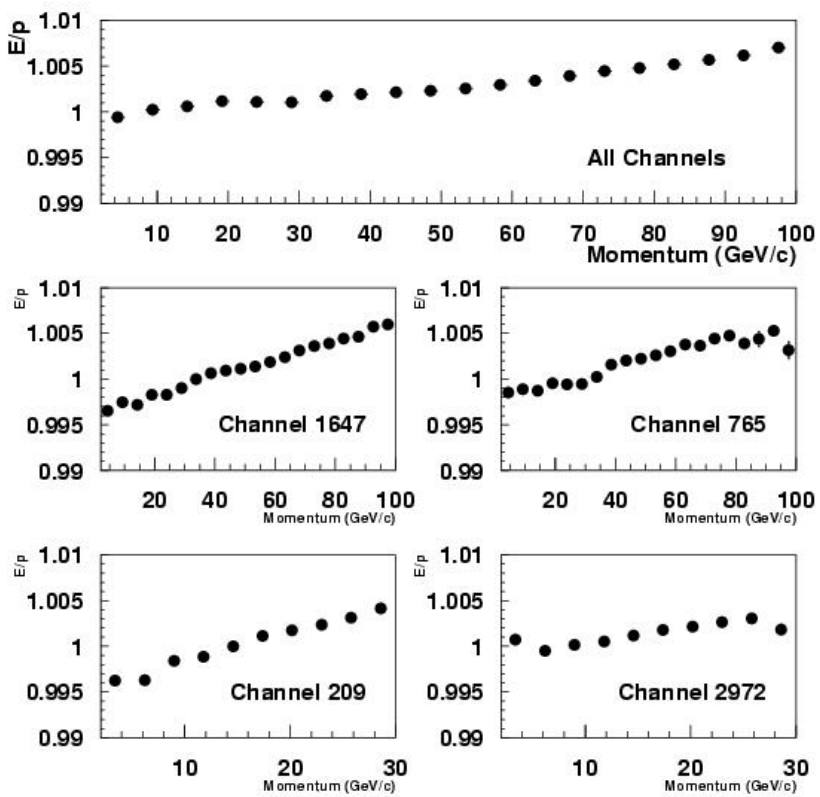
- Longitudinal response of CsI crystals uniform to ~5%
- Response of individual crystals measured in 10 bins using cosmic ray muons passing vertically through CsI
- Longitudinal shower profiles generated using GEANT
- Longitudinal response of CsI convoluted with predicted shower profile for each block
- Individual block energies corrected



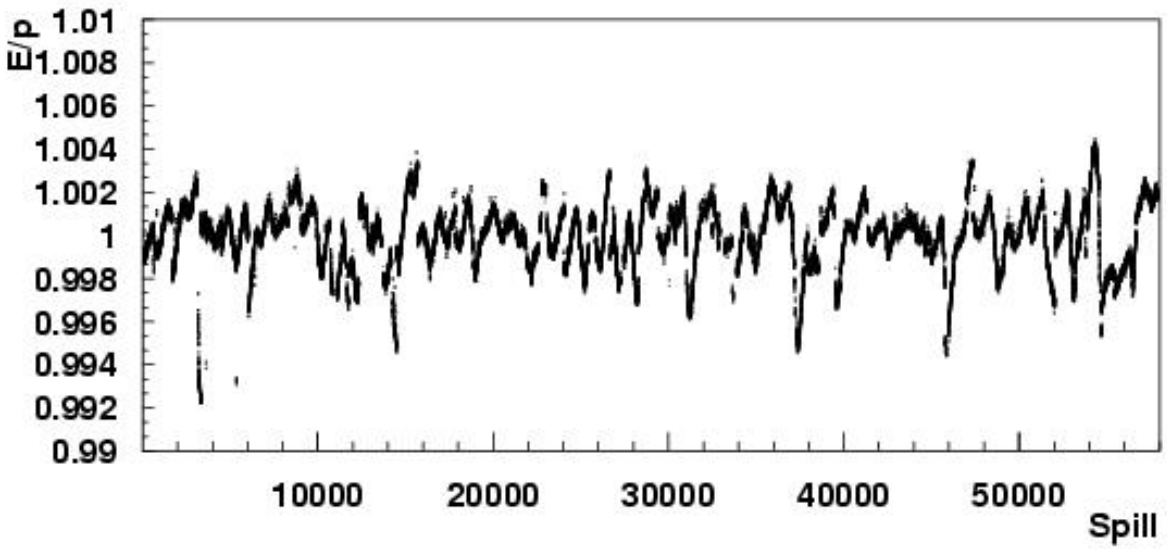


Channel-by-Channel Linearity Correction

- Removes residual energy non-linearity
- Measured separately for each crystal using E/p of electrons from calibration sample
- Applied multiplicatively to each cluster
  - based on seed block
  - applied as function of cluster energy
- Correction generally less than 1%

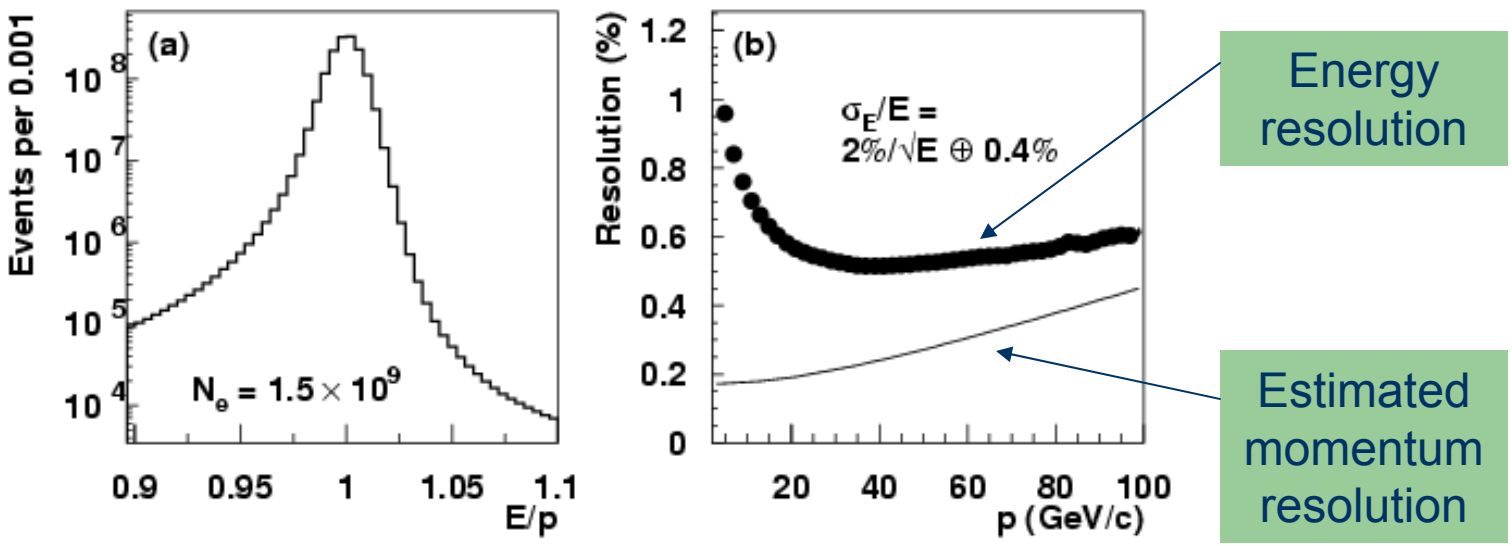


Spill-by-Spill Correction



- Corrects for global fluctuations in CsI response over time
  - Eg: small temperature changes affect CsI scintillation properties
- Measured using E/p of electrons from calibration sample
- Correction less than ~0.5%

CsI Performance



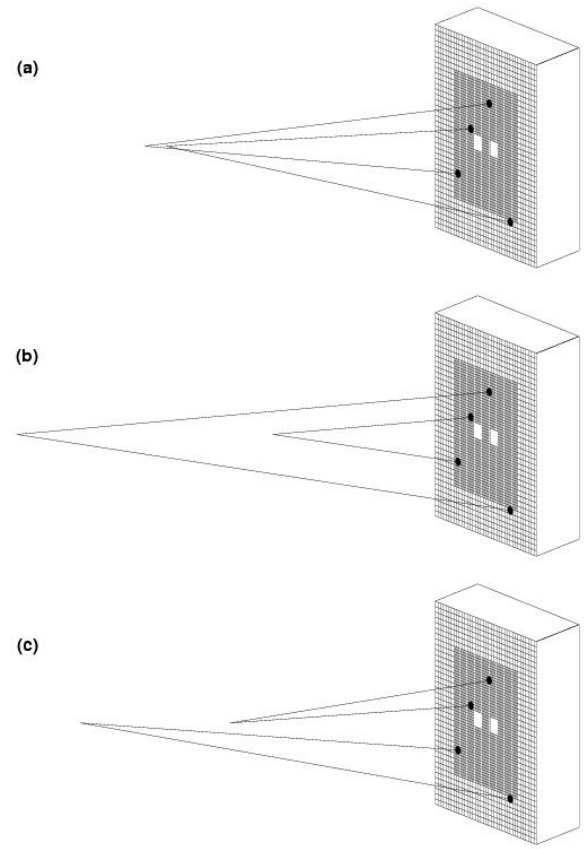
- Calibration based on 1.5 billion Ke3 electrons
- Final E/p resolution after all corrections: ~0.6%

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

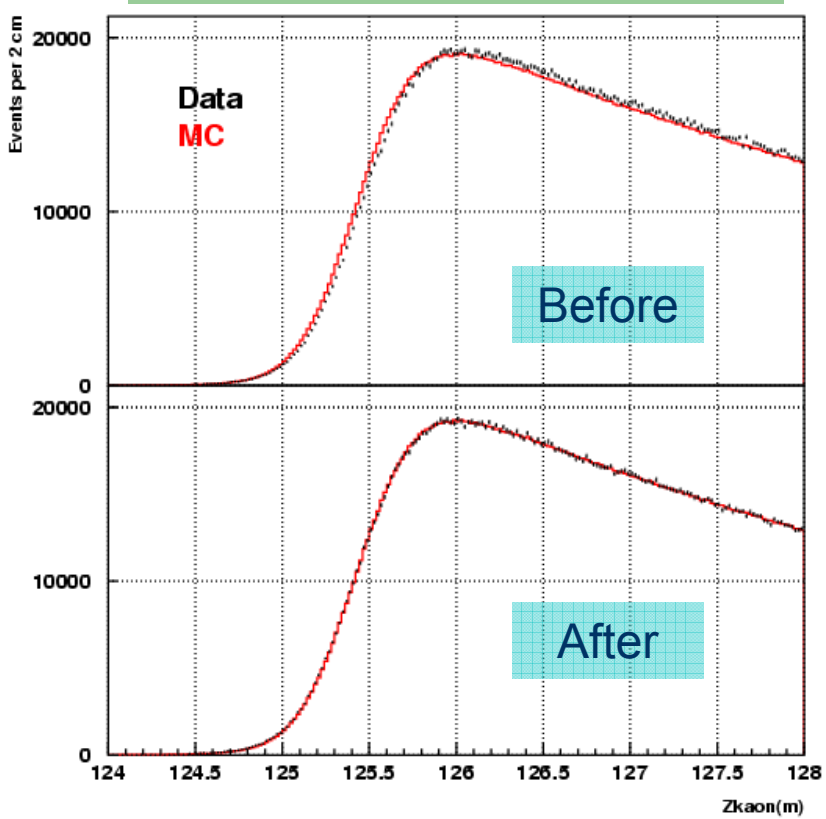
$$z_{12} \approx \frac{\sqrt{E_1 E_2}}{m_{\pi^0}} r_{12}$$

- 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

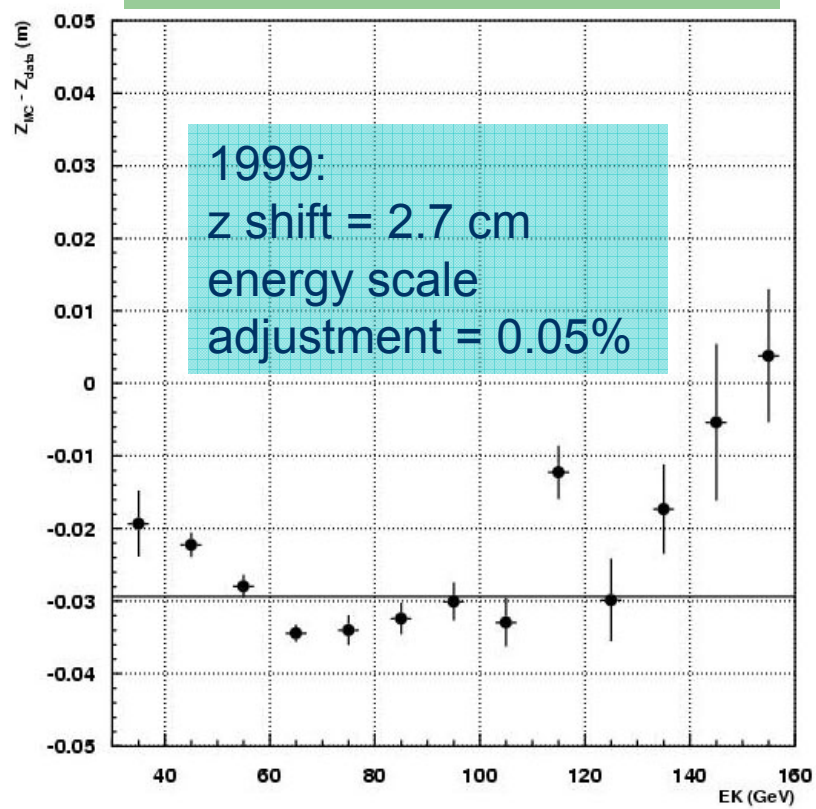


Final Energy Scale

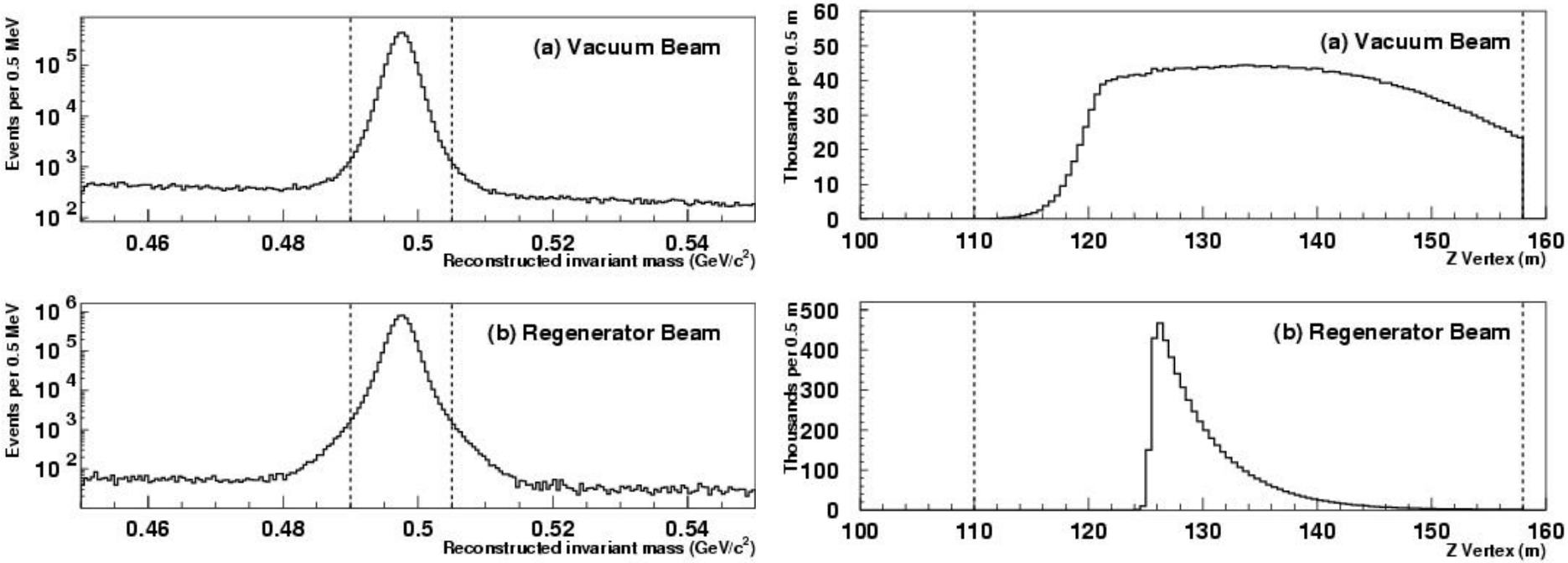
z vertex at regenerator edge



z shift to match data to MC



$K \rightarrow \pi^0\pi^0$ mass and z vertex distributions

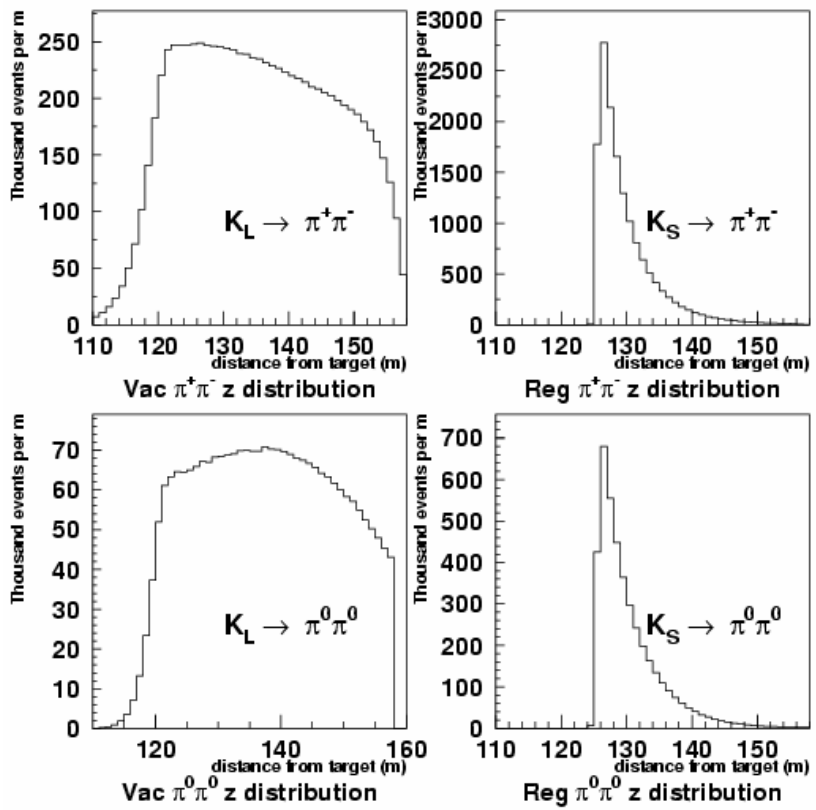


Mass resolution ~1.5 MeV/c²

K_L and K_S lifetime difference → very different z vertex distributions

Monte Carlo Simulation

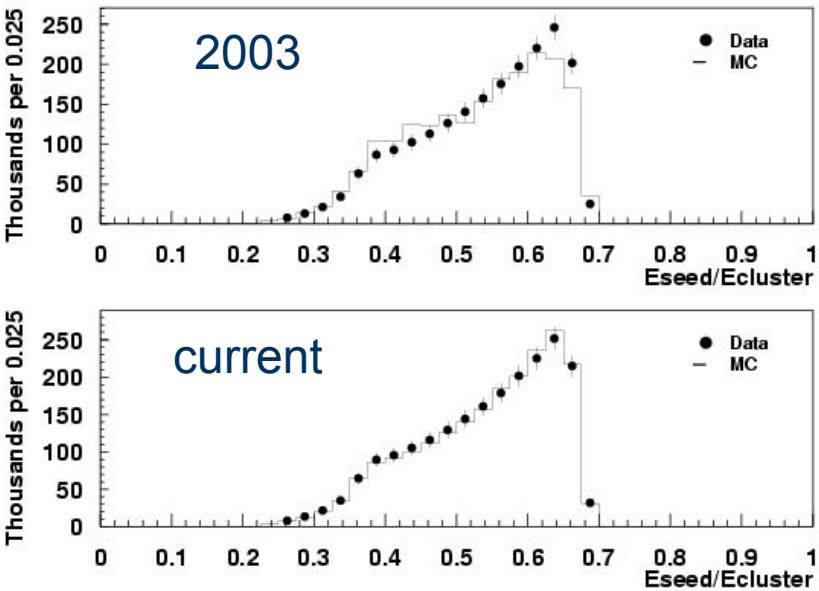
- MC used to make acceptance correction and simulate backgrounds to signal modes
  - simulates kaon generation, propagation, and decay
  - simulates detector geometry and response
  - includes the effect of “accidental” activity by overlaying data events from accidental trigger



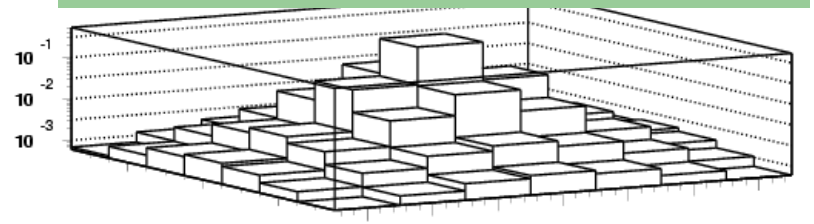
Improvements to MC

- 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

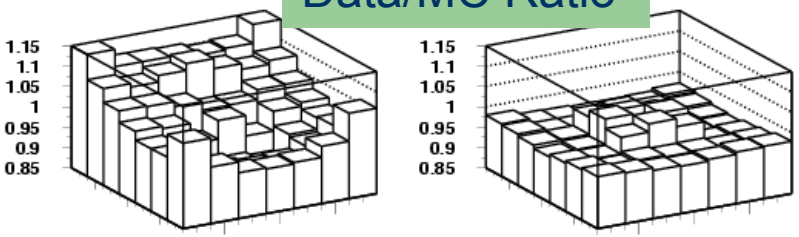
Improvements: Transverse Shower Shape



Fraction of energy per CsI block



Data/MC Ratio

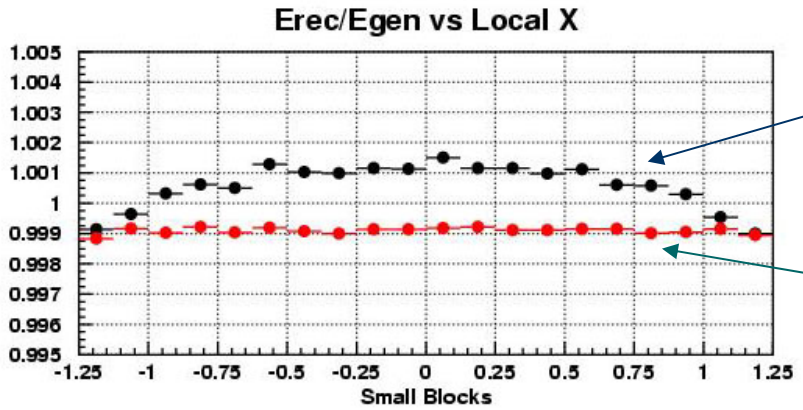


2003 current

2003: Includes transverse energy correction to match data and MC

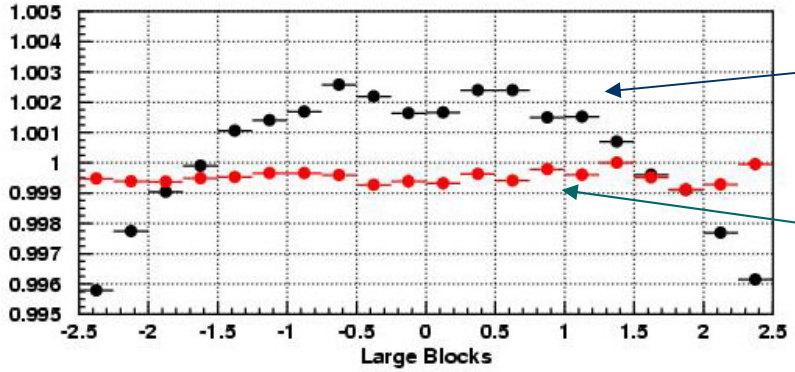
Current: No transverse energy correction required

Improvements: Reconstructed Energy



2003

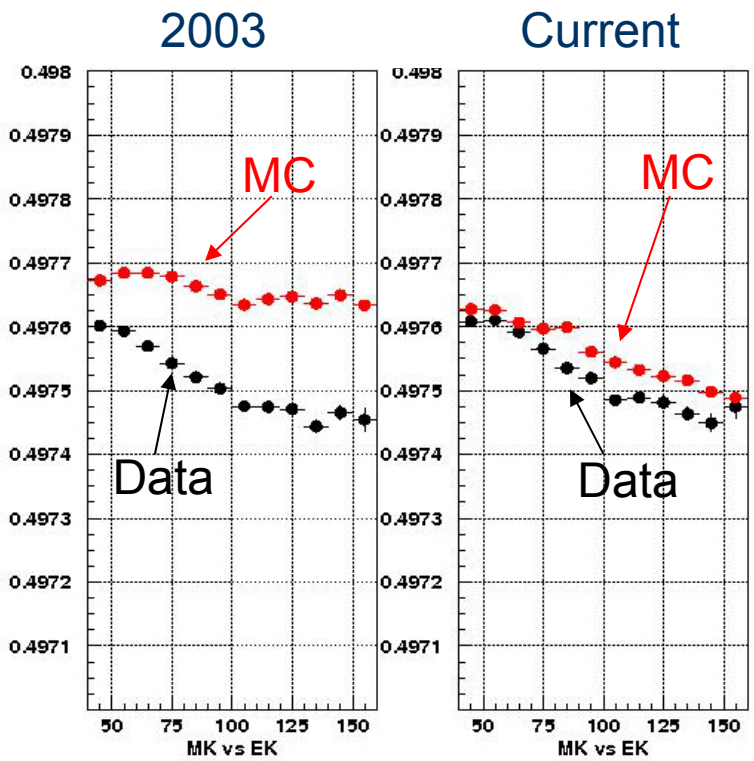
Current



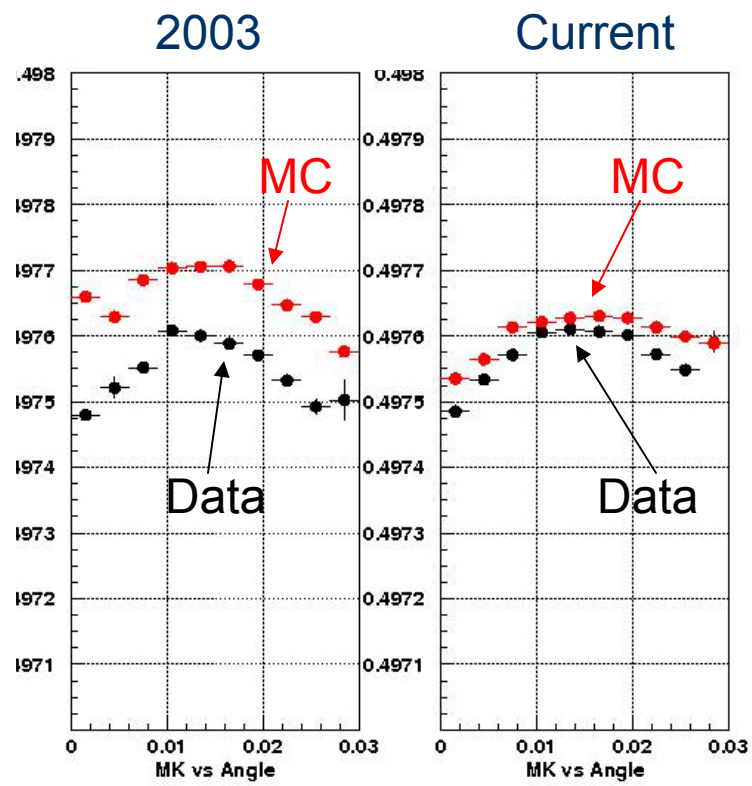
2003

Current

Improvements: Energy Linearity

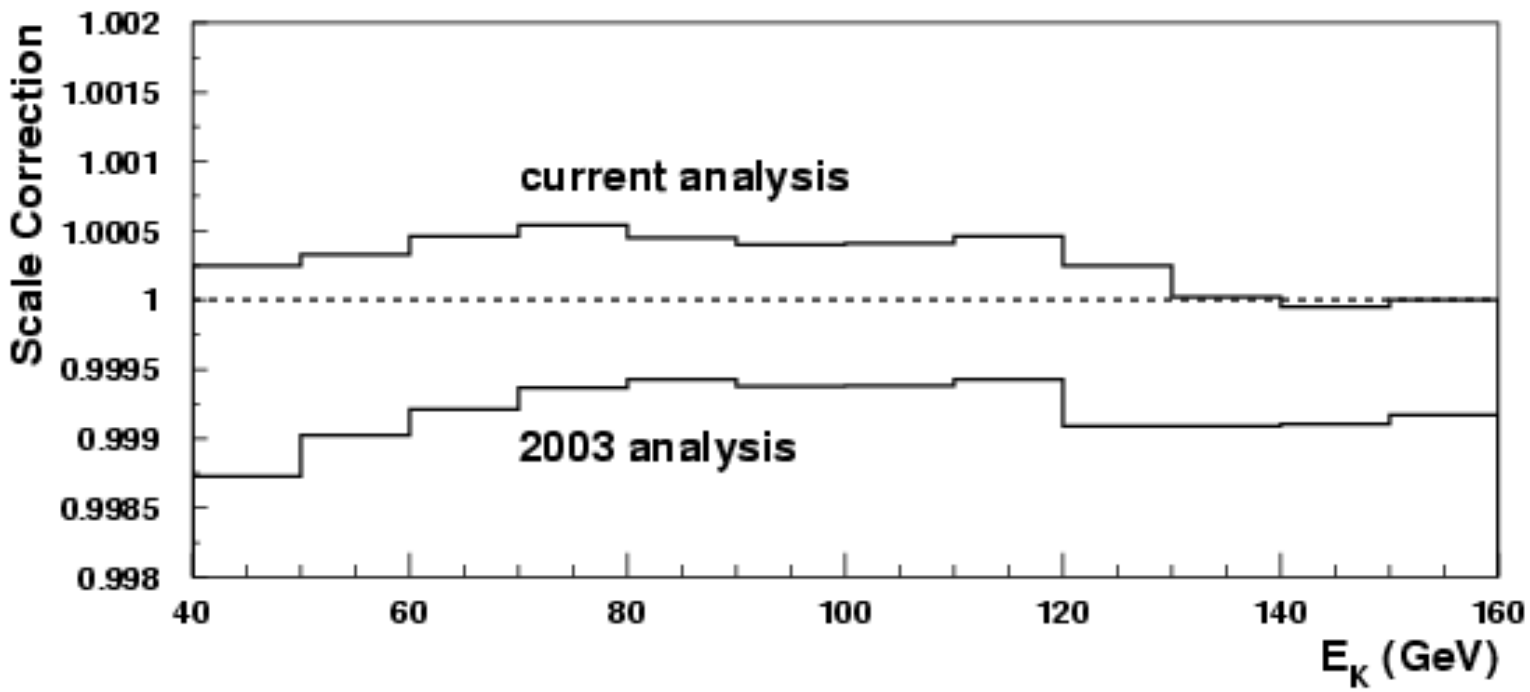


Mass vs. Energy



Mass vs. Photon Angle

Improvements: Energy Scale

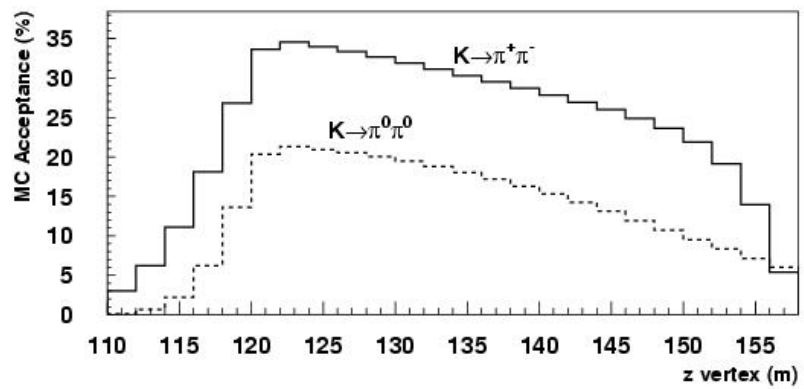


Backgrounds

- 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

Extracting Physics Parameters

- Fitter used to apply MC acceptance correction and treat K_L-K_S interference in regenerator beam
- Acceptance correction binned in p,z
  - large correction
  - ~85% from geometry
- Prediction function calculates decay distributions – nearly identical to MC treatment
- Acceptance corrected prediction function compared to background subtracted data using a χ^2
- Minimize χ^2 using MINUIT



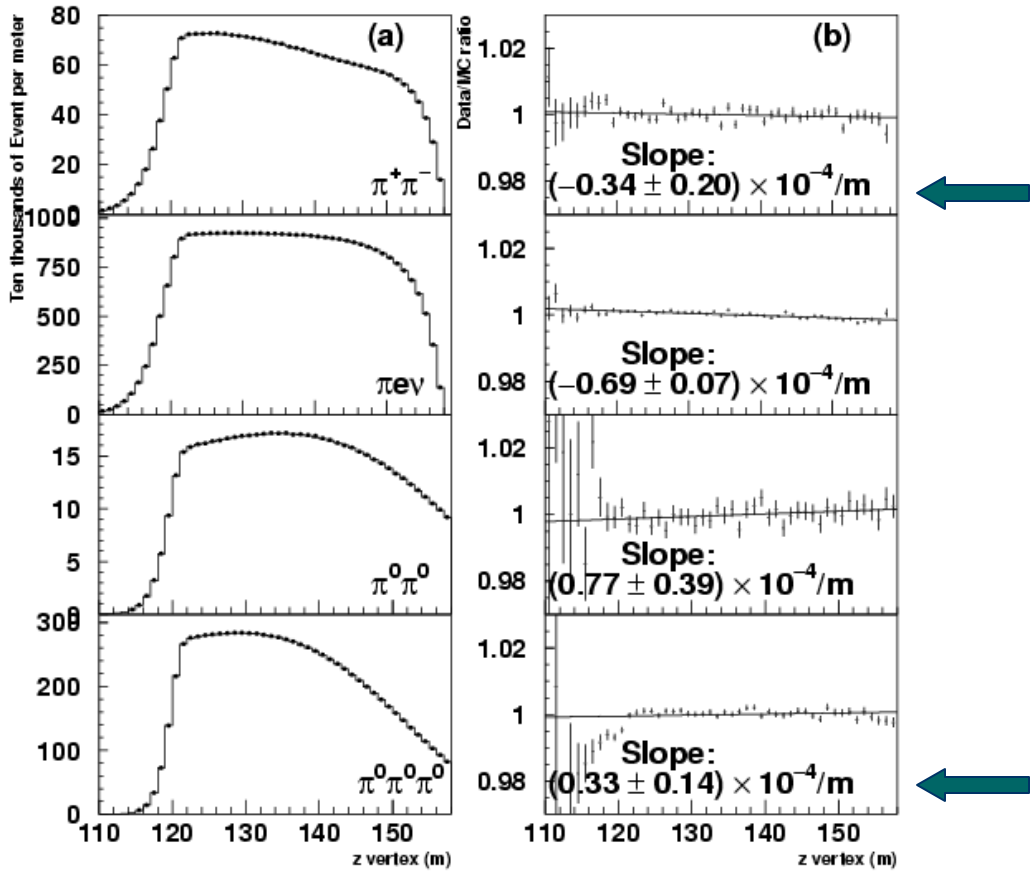
Systematic Uncertainties in Re(ε′/ ε)

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

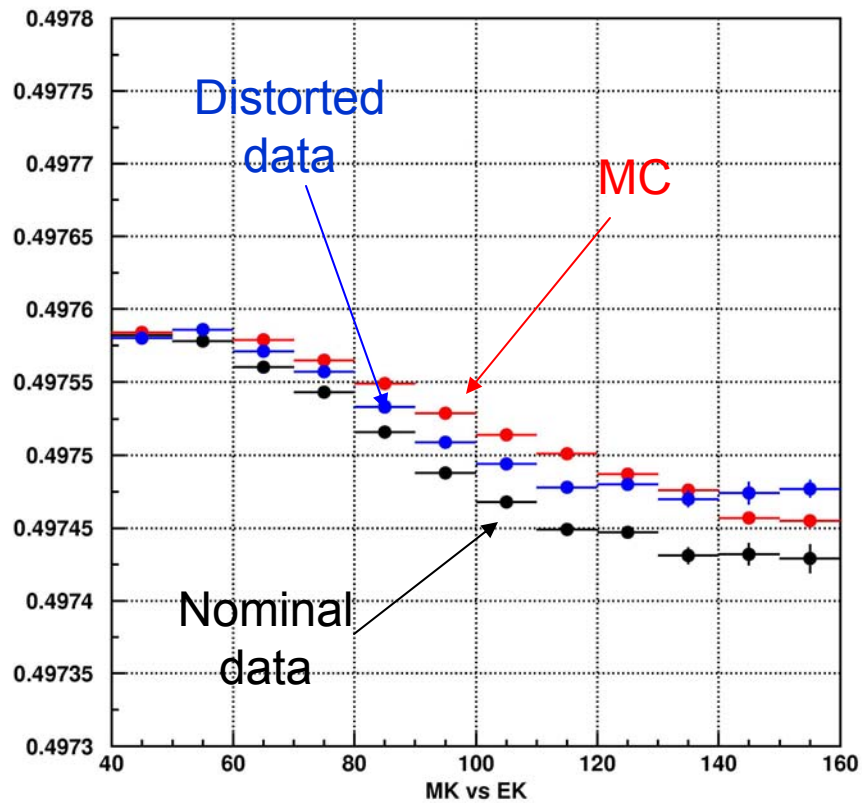
Uncertainty from Acceptance

- 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

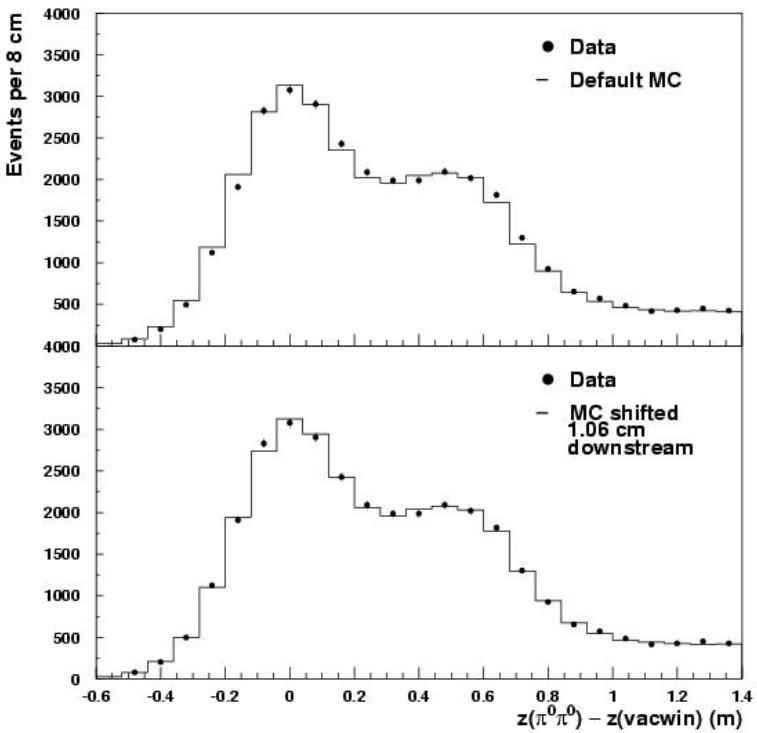


Uncertainty from Energy Non-linearity

- 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: $\pm 0.15 \times 10^{-4}$

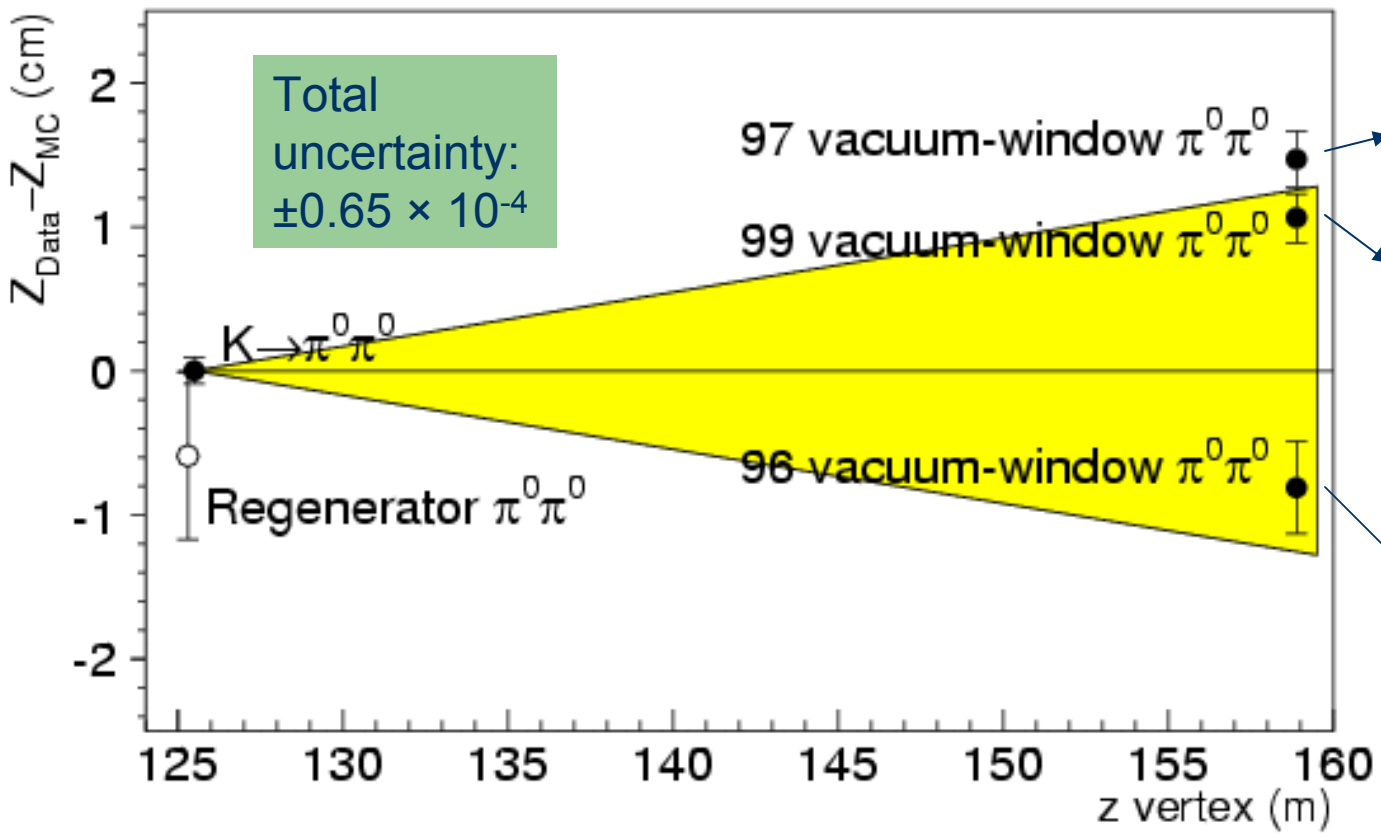


Uncertainty from Energy Scale



- Check energy scale by studying hadronic interaction events in regenerator and vacuum window
- Data and MC match within errors at regenerator
- Require shift to match data and MC at vacuum window
  - 1996: -0.81 ± 0.32 cm
  - 1997: 1.47 ± 0.19 cm
  - 1999: 1.06 ± 0.17 cm

Uncertainty from Energy Scale



±0.82 × 10-4

±0.59 × 10-4

±0.45 × 10-4

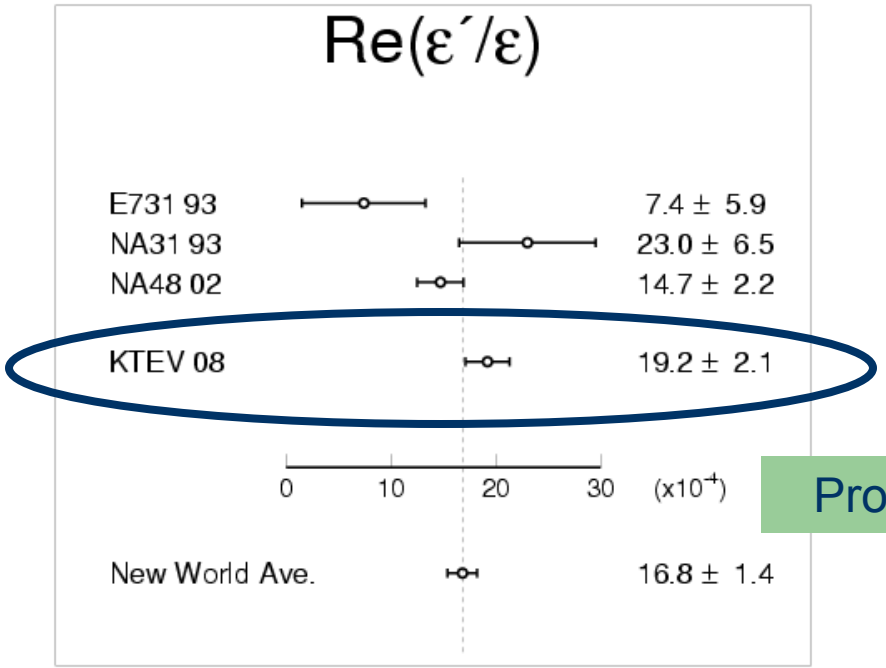
Results

The final KTeV measurement of Re(ε'/ε) . . .

Results: Re(ε′/ ε)

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

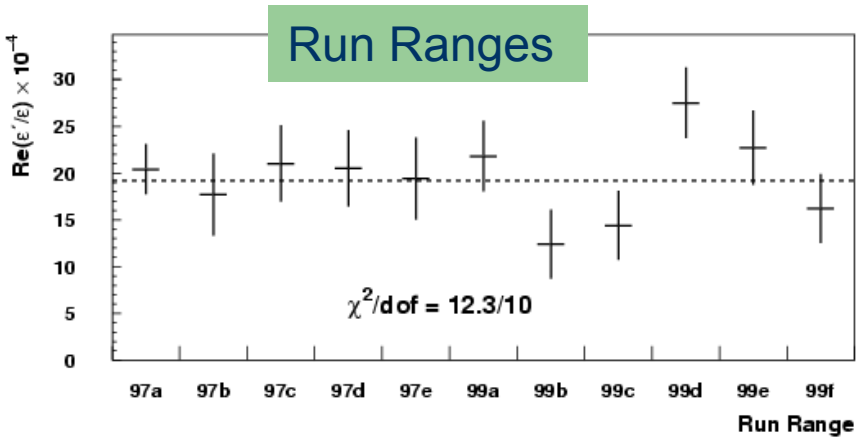
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$$

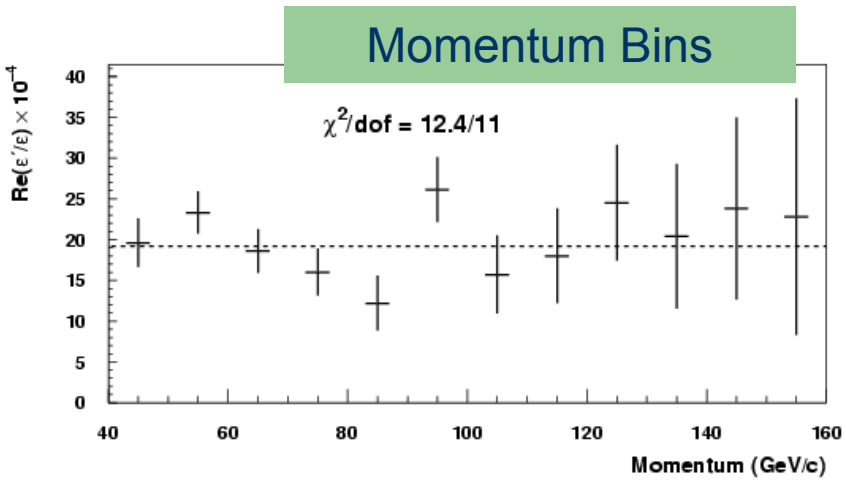


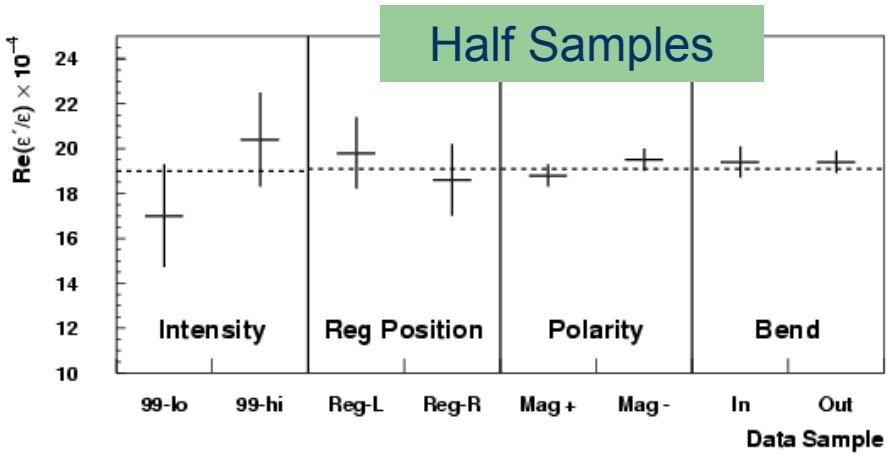
Probability = 13%

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

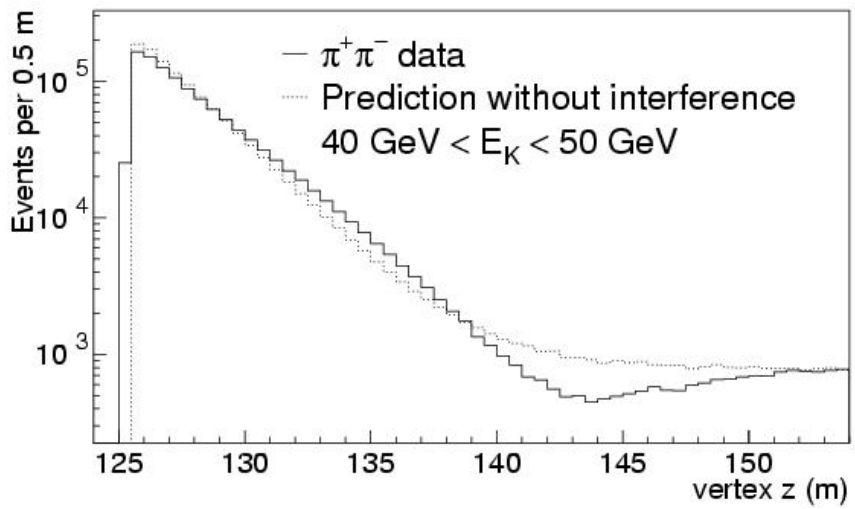
Results: Re(ε′/ ε) Crosschecks







Measuring Kaon Parameters



τ_S

$\cos(\Delta m + \Phi_\eta)$

$$\left|A_f(t)\right|^2 = \left|c_{S,0}A_{fS}\right|^2 \left\{ e^{\Gamma_S t} + 2\,\mathrm{Re}\left[\frac{c_{L,0}}{c_{S,0}}\frac{A_{fL}}{A_{fS}} e^{-i\Delta m t}\right] e^{-(\Gamma_S+\Gamma_L)t/2} + \left|\frac{c_{L,0}}{c_{S,0}}\right|^2 \left|\frac{A_{fL}}{A_{fS}}\right|^2 e^{-\Gamma_L t} \right\}$$

z-binned fit

- 10 GeV/c momentum bins
- 2 m z-bins in regenerator beam
- Single z-bin in vacuum beam
- Float 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*

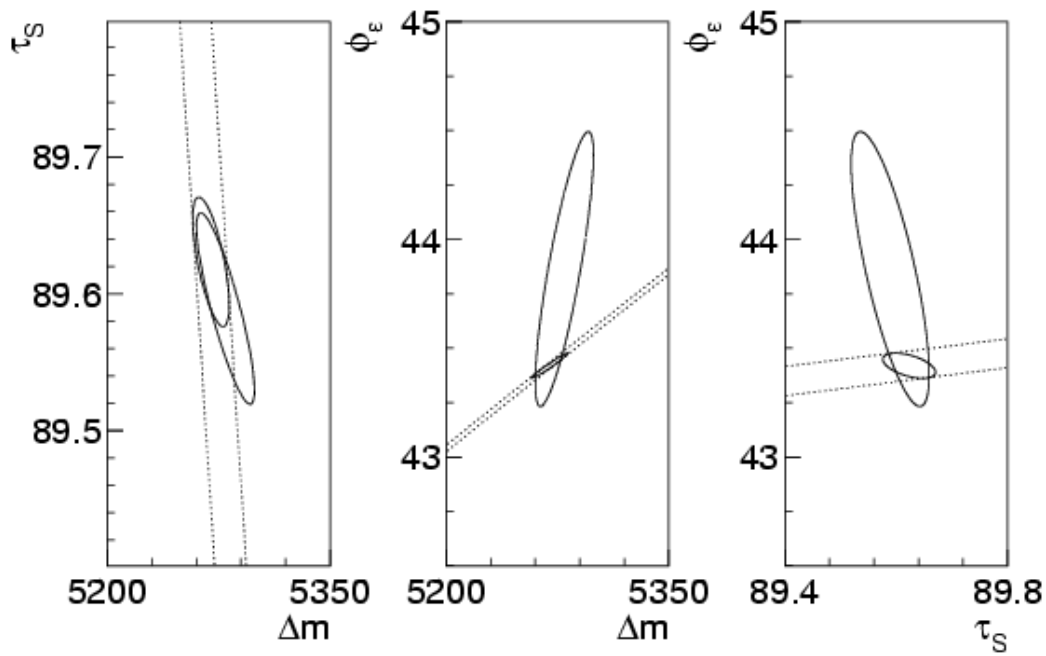
$$\Phi_{+-} \approx \Phi_\varepsilon + \mathrm{Im}(\varepsilon'/\varepsilon)$$

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

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

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

Results: z-binned Fit



No CPT assumption:

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

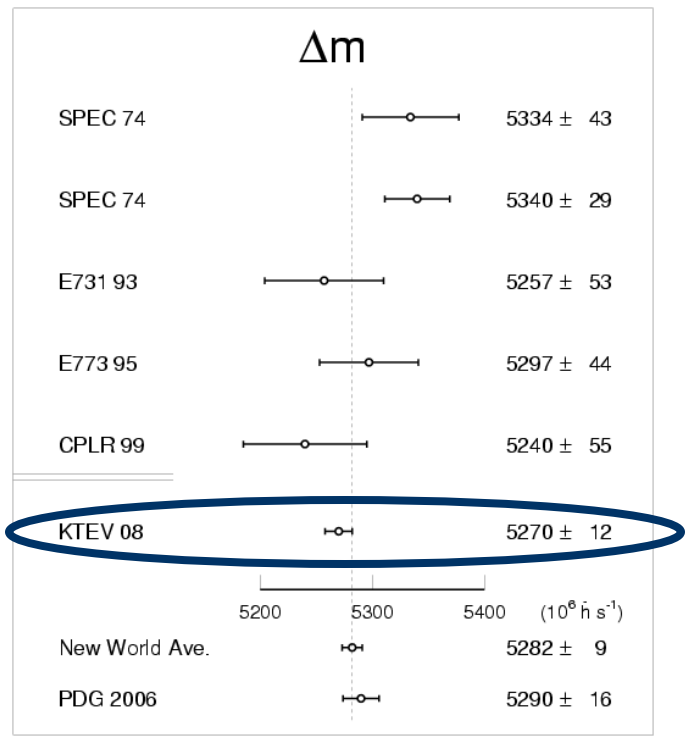
$\tau_S = (89.589 \pm 0.070) \times 10^{-12}$ s

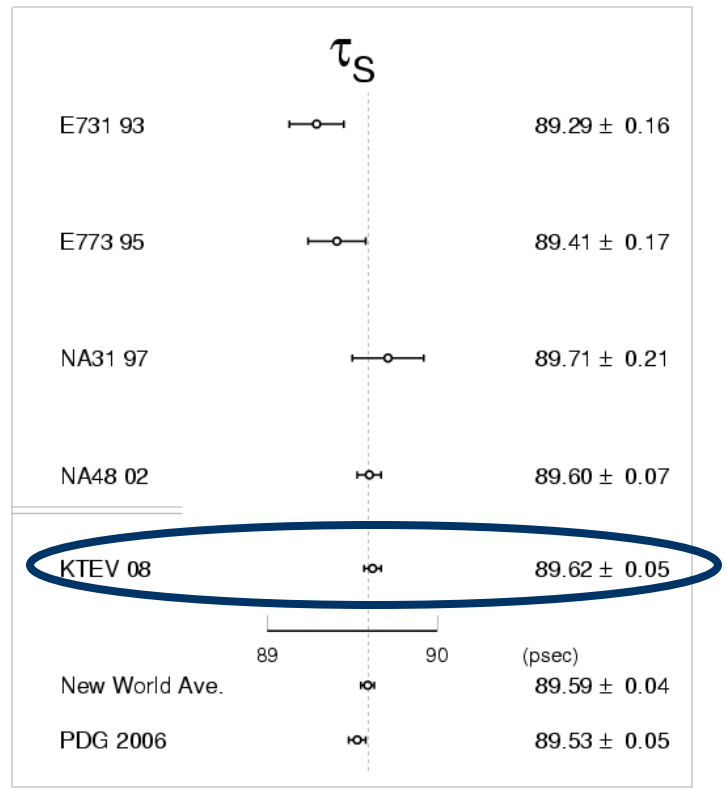
CPT assumption applied:

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

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

Results: Δm and τ_S



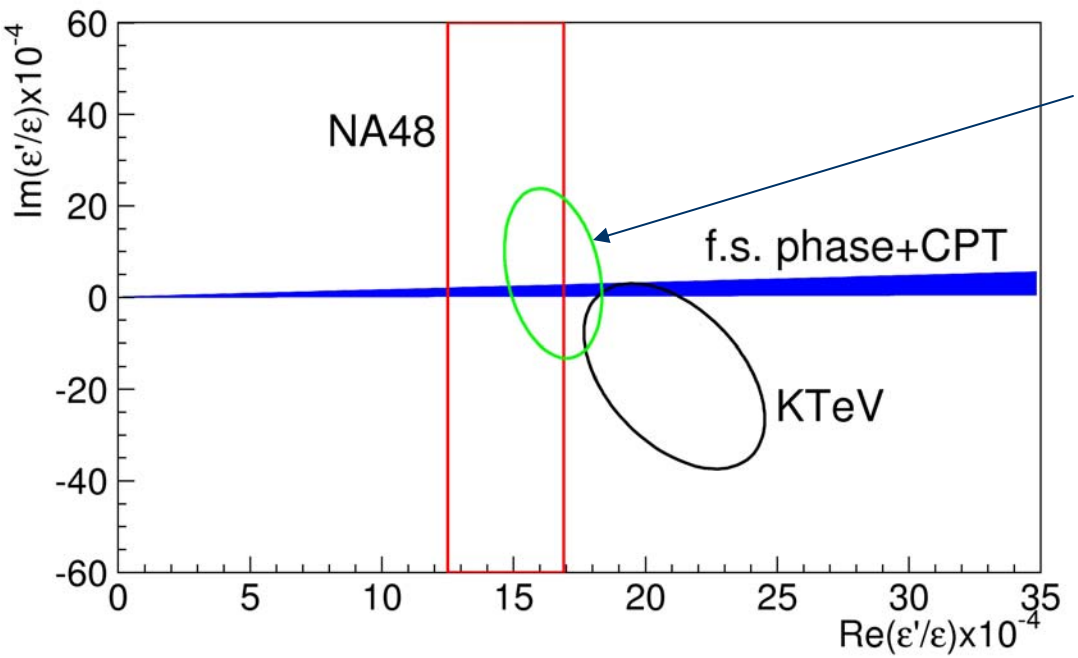


KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6\ \hbar s^{-1}$

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

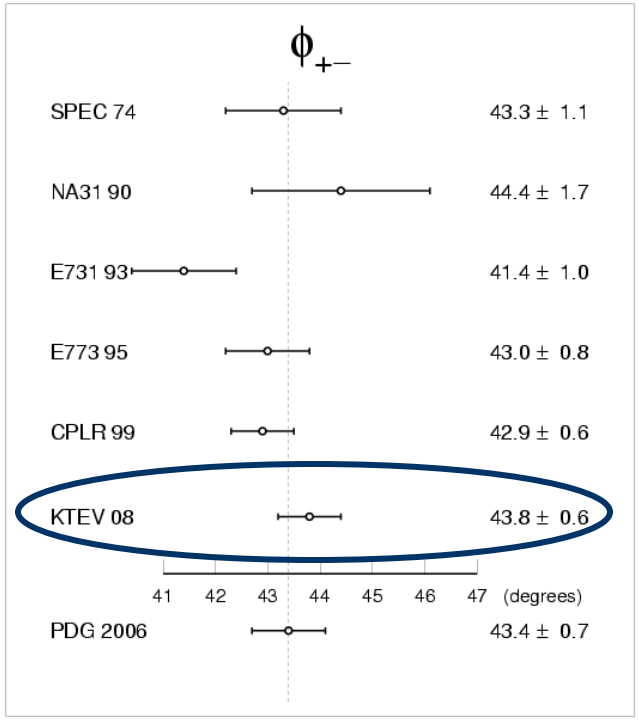
Results: z-binned fit

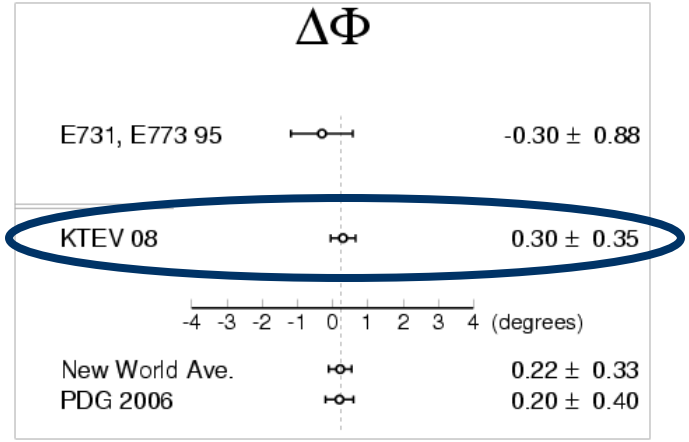
$\phi_\varepsilon = (43.86 \pm 0.63)°$
$\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$
$\Delta\phi = (0.30 \pm 0.35)°$



KTeV + NA48

Results: CPT Tests





Consistent with CPT symmetry

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

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

Conclusion

- $\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
  - Direct CP violation in neutral kaon decays established in 1999 and now measured precisely by KTeV and NA48
  - CP violation predicted by Standard Model but calculations of ε'/ε are difficult
  - Precise measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$ may be used as test of SM and beyond once lattice QCD calculations are under control
- Precise measurements made of kaon parameters
- CPT tests consistent with CPT symmetry

KTeV 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

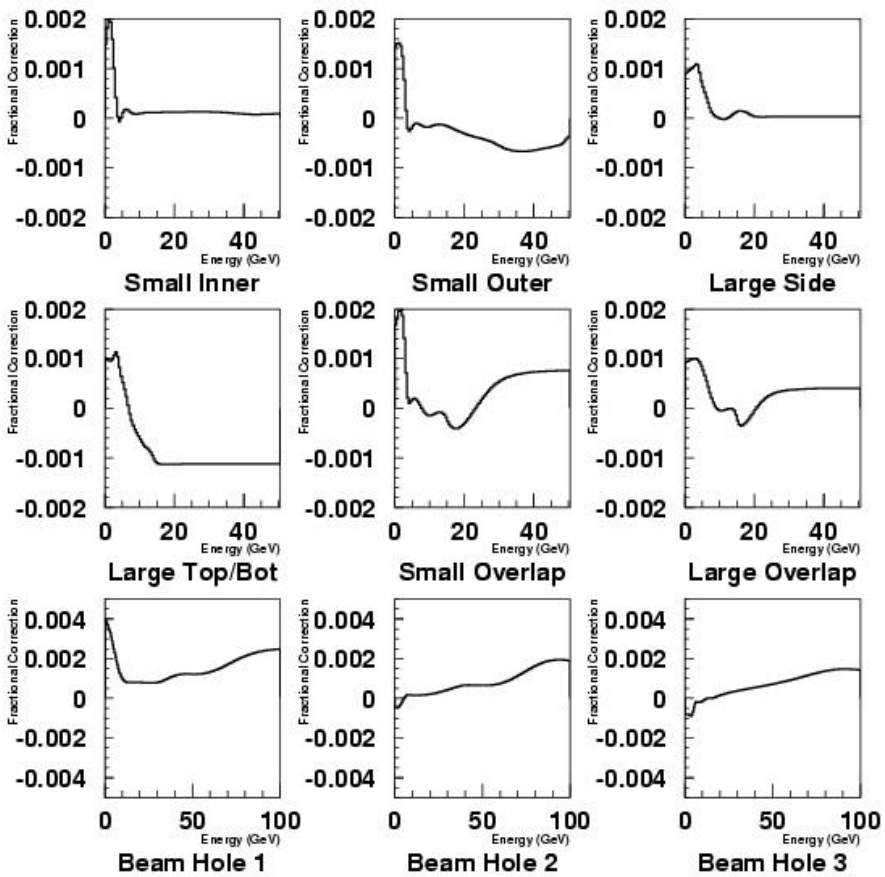
- $\phi_\varepsilon = (43.86 \pm 0.63)°$
- $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$
- $\Delta\phi = (0.30 \pm 0.35)°$

No CPT assumption

Extra Slides

Photon Correction

- Corrects for differences between electrons used for calibration and photons in signal mode
- Measured using kinematic constraints in $2\pi^0$ and $3\pi^0$ decays
- Measured in 9 different regions of calorimeter
- Applied to data only
- Correction less than 0.2%



Backgrounds

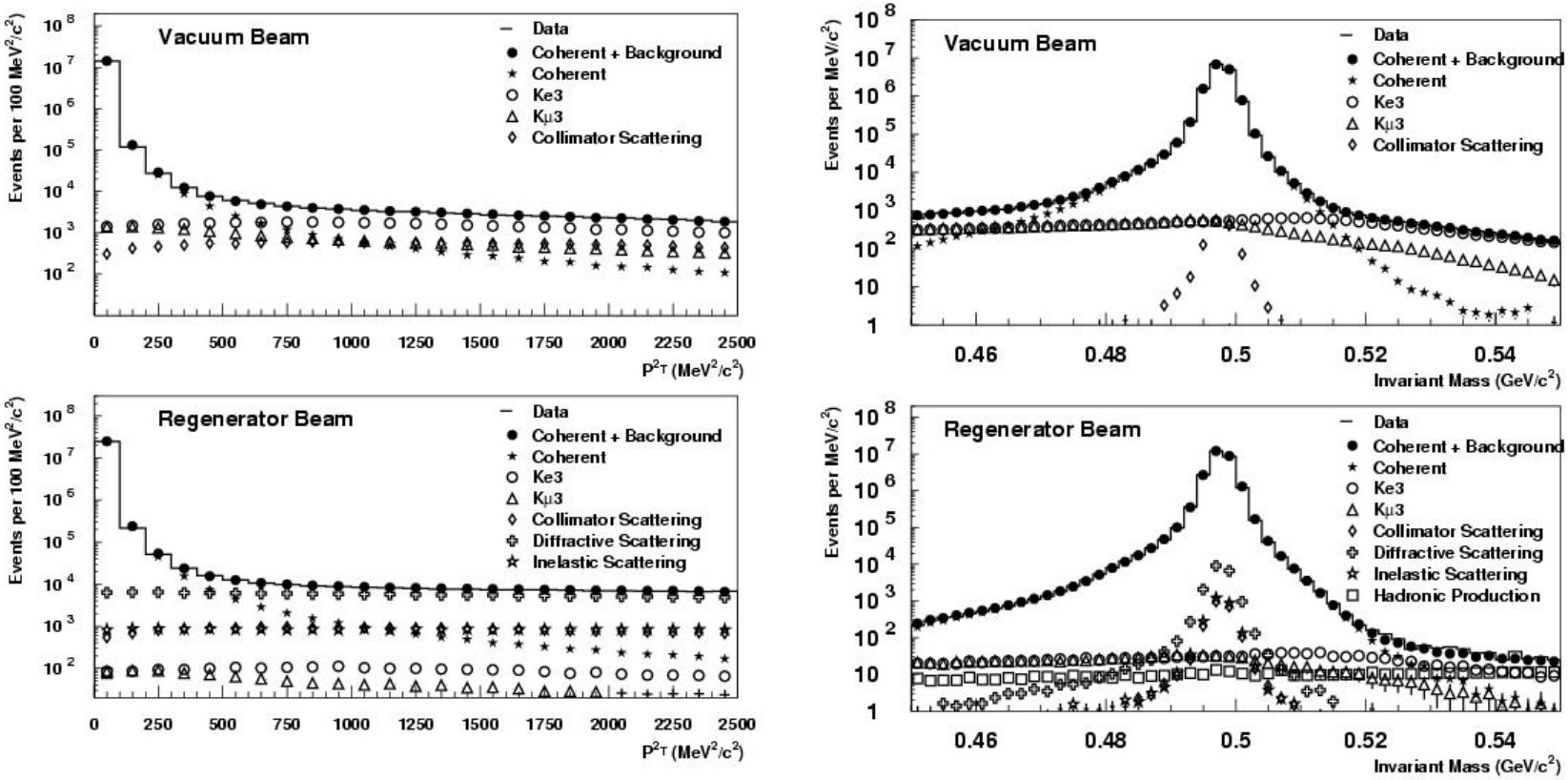
Source	Vacuum Beam 1997	Vacuum Beam 1999	Regenerator Beam 1997	Regenerator Beam 1999
Regenerator Scattering	—	—	0.073%	0.075%
Collimator Scattering	0.009%	0.008%	0.009%	0.008%
$K_L \to \pi^{\pm} e^{\mp} \nu$	0.032%	0.032%	0.001%	0.001%
$K_L \to \pi^{\pm} \mu^{\mp} \nu$	0.034%	0.030%	0.001%	0.001%
Total Background	0.074%	0.070%	0.083%	0.085%

Table 5.1: Summary of $K \to \pi^+\pi^-$ background levels

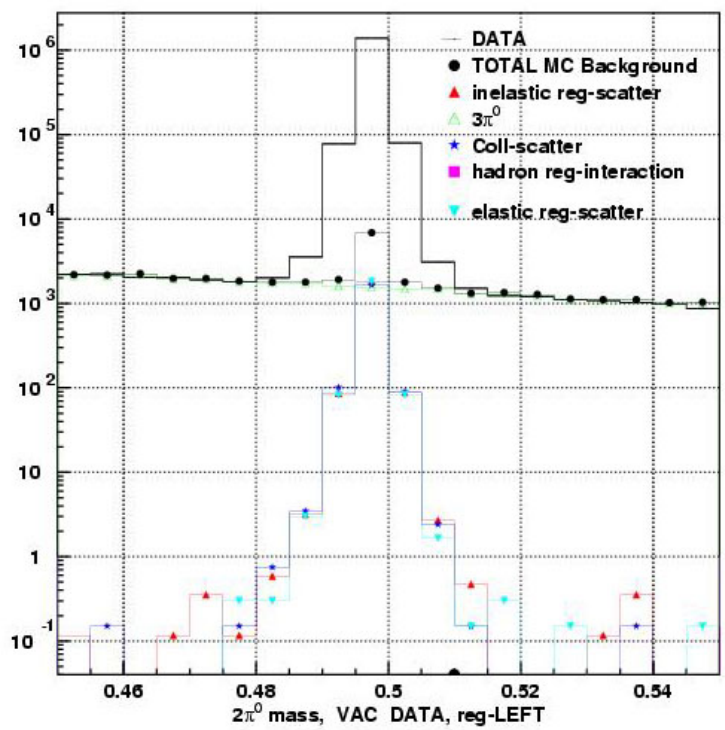
Source	Vacuum Beam 1996	Vacuum Beam 1997	Vacuum Beam 1999	Regenerator Beam 1996	Regenerator Beam 1997	Regenerator Beam 1999
Inelastic Scattering	0.153%	0.132%	0.128%	0.214%	0.186%	0.175%
Diffractive Scattering	0.135%	0.128%	0.130%	0.893%	0.906%	0.906%
Collimator Scattering	0.102%	0.122%	0.120%	0.081%	0.093%	0.091%
$K_L \to \pi^0\pi^0\pi^0$	0.444%	0.220%	0.301%	0.015%	0.006%	0.012%
Photon Mispairing	0.007%	0.007%	0.008%	0.007%	0.008%	0.007%
Hadronic Production	0.002%	0.001%	—	0.007%	0.007%	0.007%
Total Background	0.835%	0.603%	0.678%	1.209%	1.197%	1.190%

Table 5.3: Summary of $K \to \pi^0\pi^0$ background levels. Note that photon mispairing is not subtracted from the data and is not included in the total background sum.

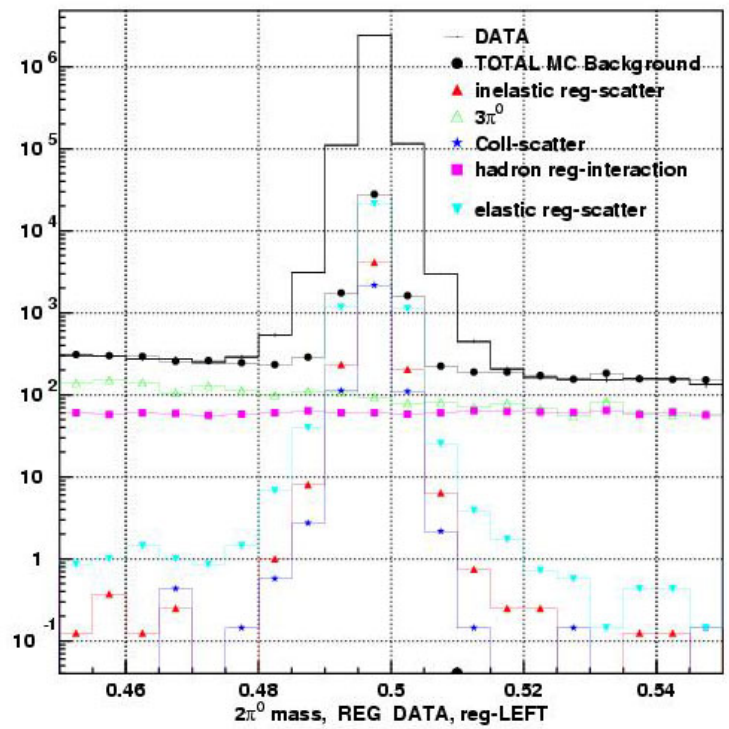
$K \rightarrow \pi^+\pi^-$ Backgrounds



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

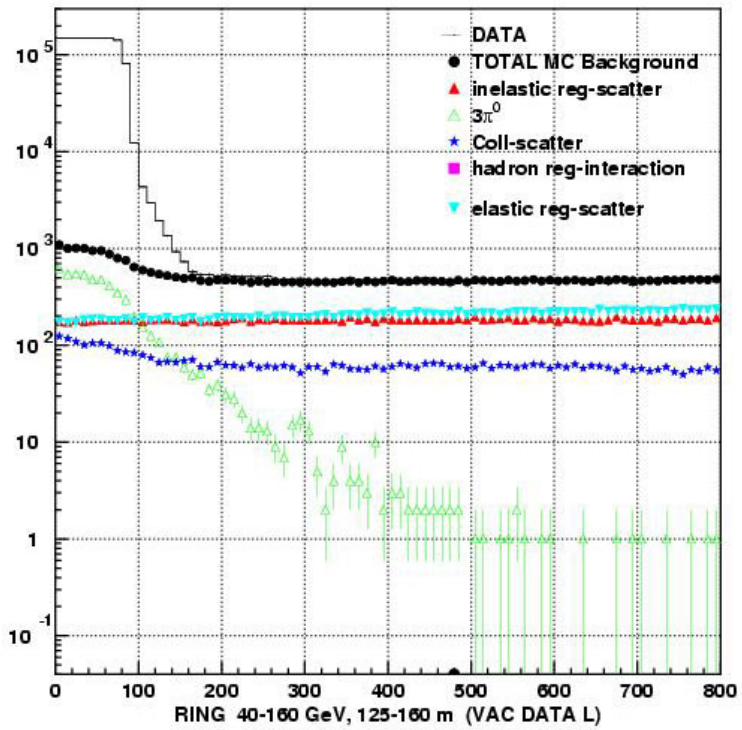


Vacuum Beam

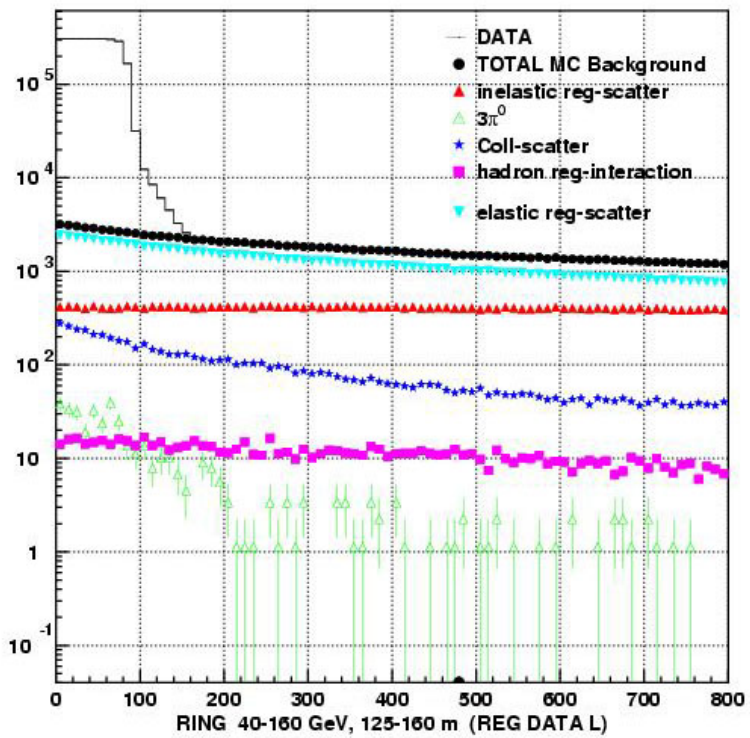


Regenerator Beam

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

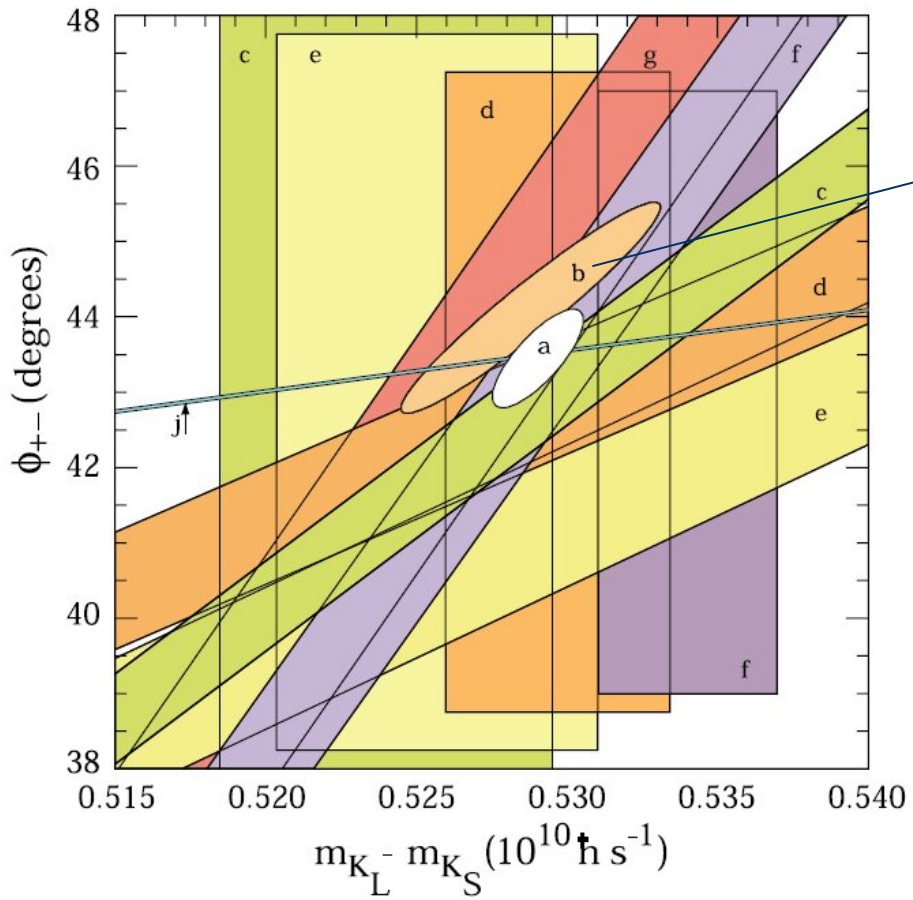


Vacuum Beam



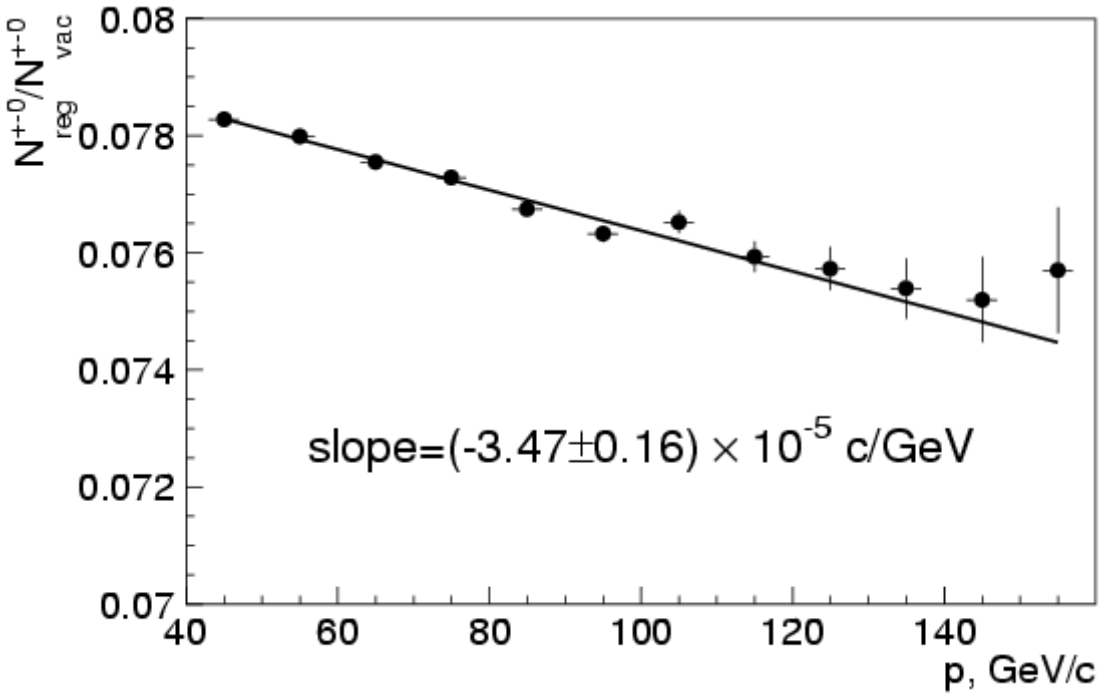
Regenerator Beam

PDG: ϕ_{+-}



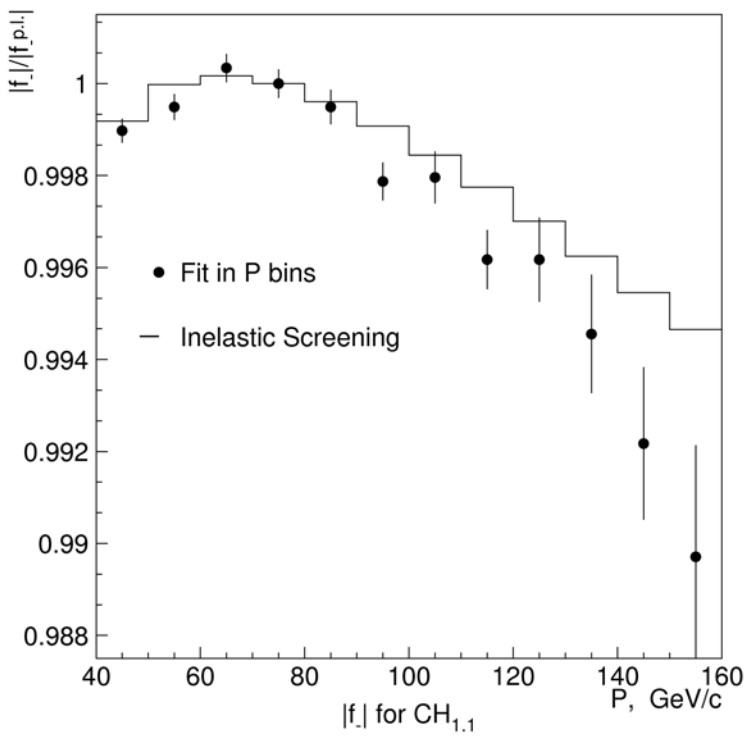
KTeV 2003

Regenerator Transmission



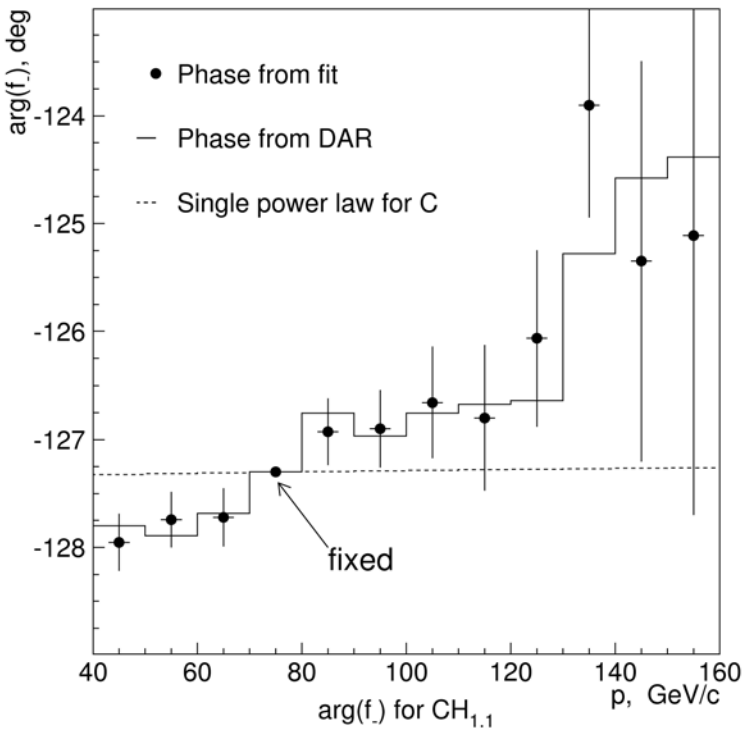
- Transmission measured from data using $K_L \rightarrow \pi^+\pi^-\pi^0$ decays
- Dedicated trigger in 1999 improved statistical precision of measurement

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