Final KTeV Measurements of CP Violation and CPT Symmetry

BNL Particle Physics Seminar

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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

- CP Violation and CPT Symmetry in Kaons
  - Introduction
  - Current status
- KTeV Experiment
  - Detector
  - Data analysis
  - Monte Carlo simulation
  - Fits
  - Systematic uncertainties
- KTeV Results
- Future of KTeV

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Focus on EM showers in CsI calorimeter

CP Violation and CPT Symmetry

CP Violation in Kaons

Strangeness Eigenstates:

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

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

CP Eigenstates:

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

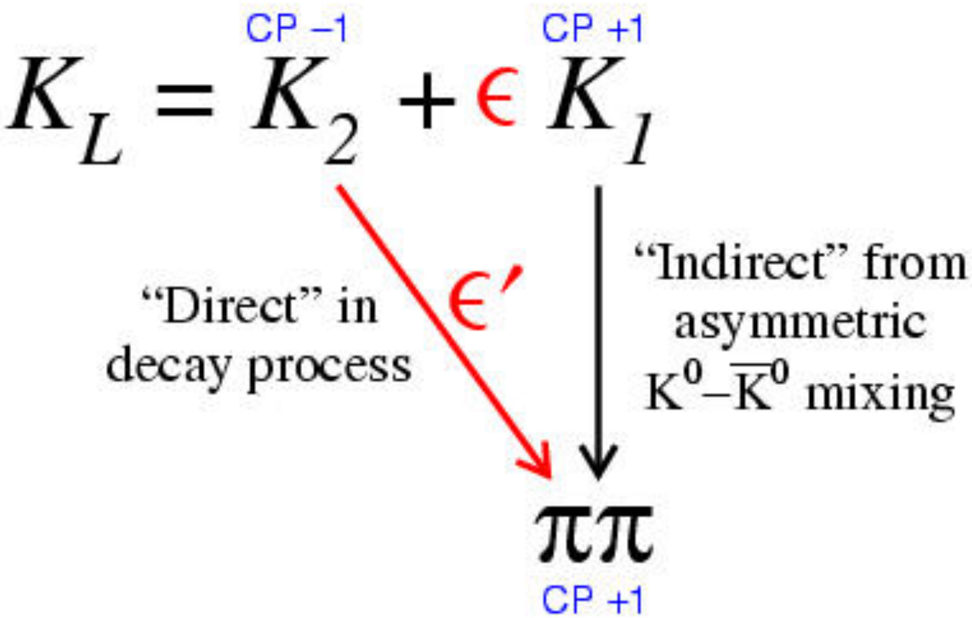
$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right) \quad (CP-1)$$

Weak Eigenstates:

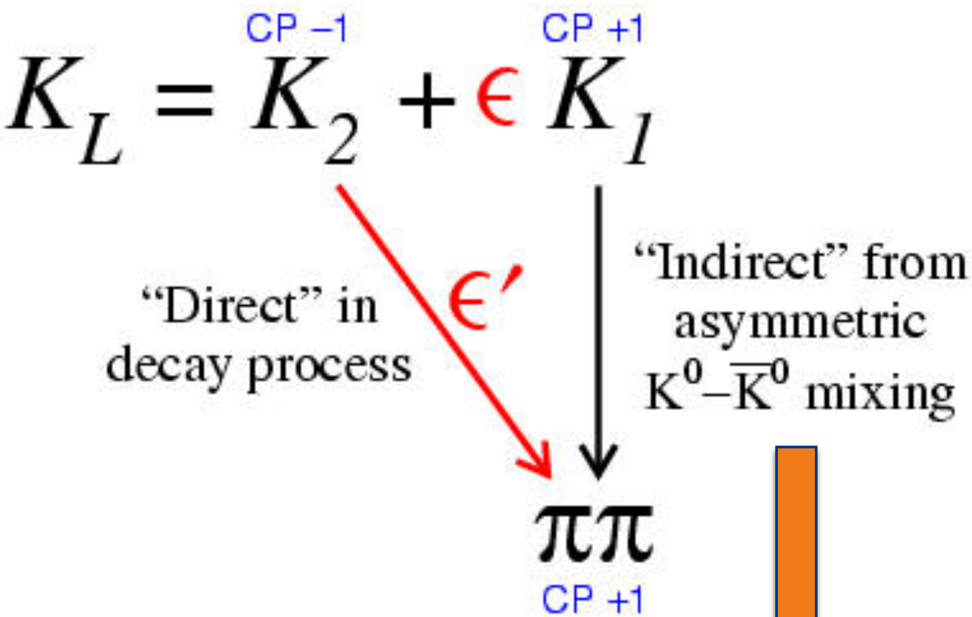
$$|K_L\rangle \approx |K_2\rangle + \varepsilon|K_1\rangle \quad (mostly\ CP-1)$$

$$|K_S\rangle \approx |K_1\rangle + \varepsilon|K_2\rangle \quad (mostly\ CP+1)$$

CP Violation in Kaons



CP Violation in Kaons

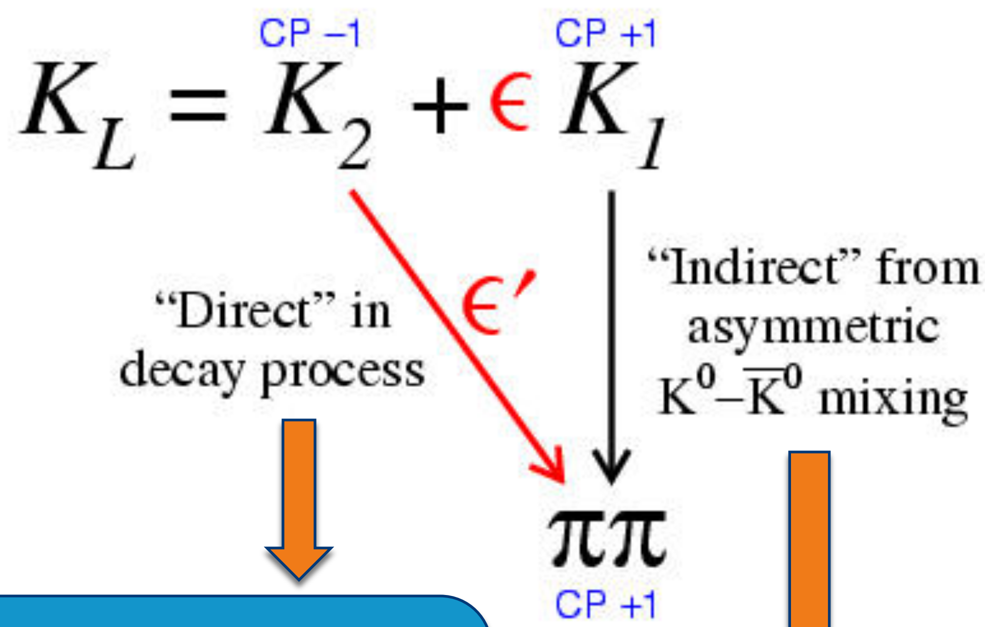


Indirect CP violation:

Discovered in 1964

$|\varepsilon| = 2.2 \times 10^{-3}$

CP Violation in Kaons



Direct CP violation:

Established in 1999

$$\mathrm{Re}\left(\varepsilon'/\varepsilon\right) = 1.7 \times 10^{-3}$$

Indirect CP violation:

Discovered in 1964

$$|\varepsilon| = 2.2 \times 10^{-3}$$

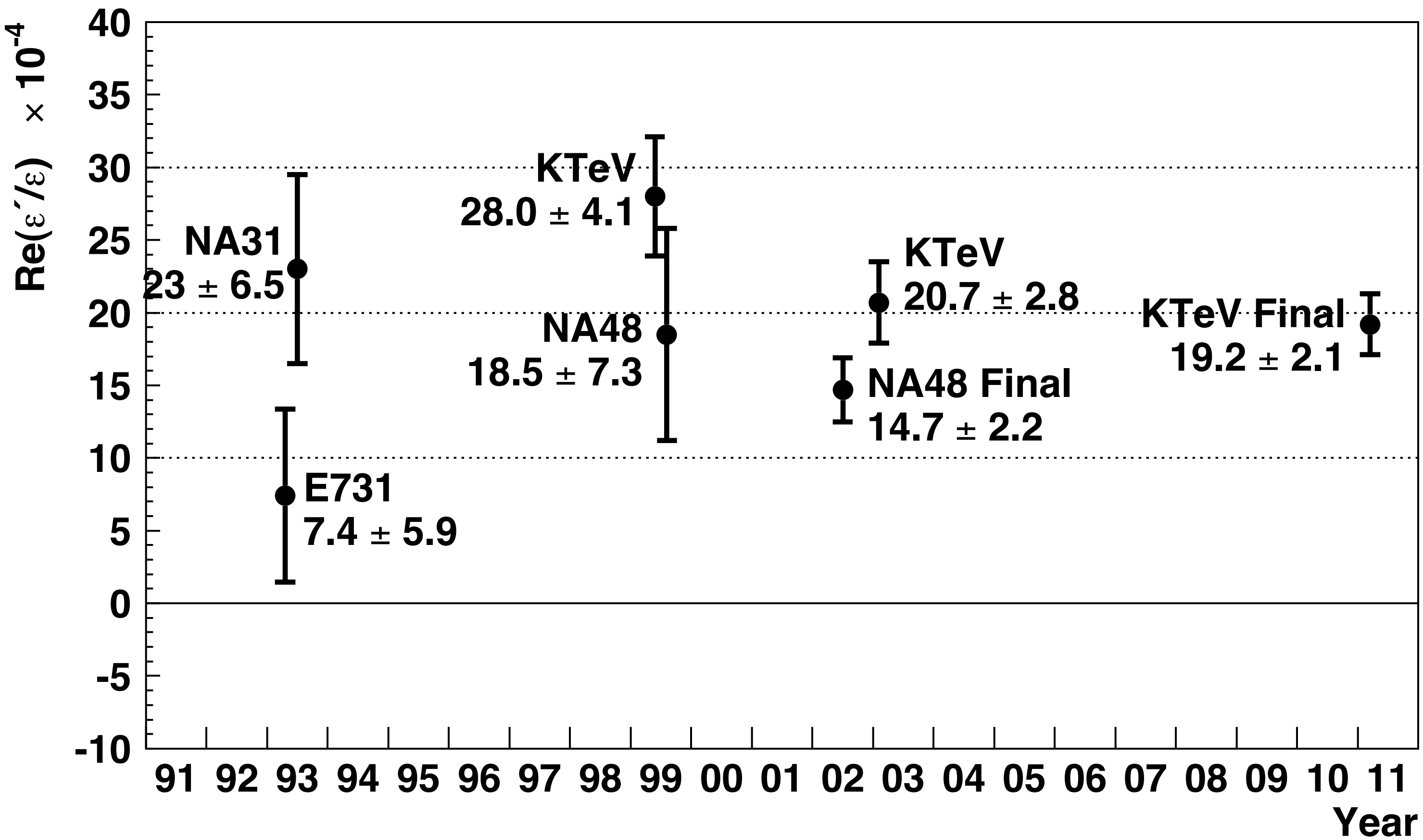
Measuring Re(ε′/ε)

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

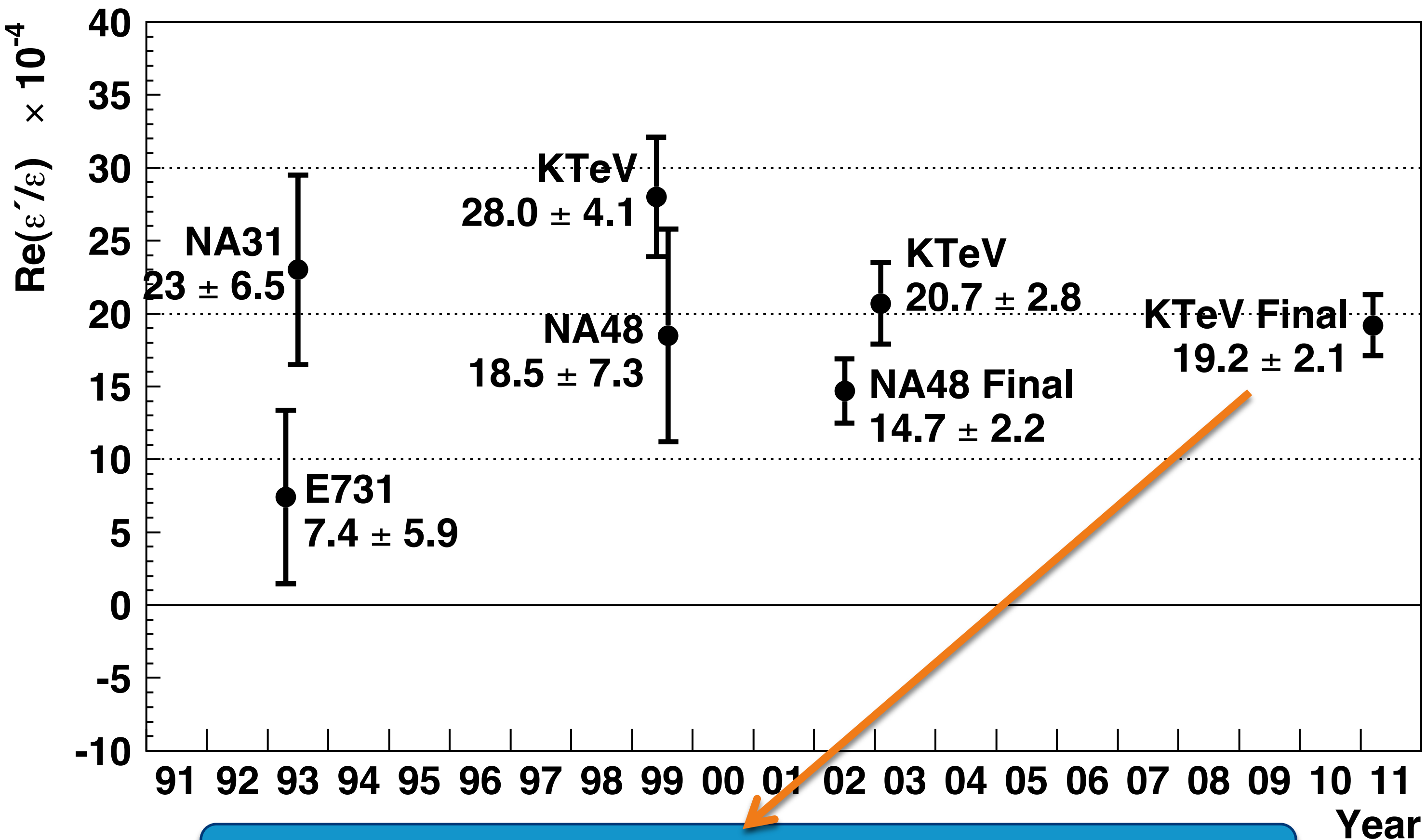
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

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

Measurements of Re(ε′/ε)



Measurements of Re(ε′/ε)



Phys.Rev.D83:092001,2011; arXiv:1011.0127

Calculating Re(ε′/ε)

- Standard model predicts CP violation through complex phase in 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$\times 10^{-4}$
- Precise lattice QCD calculations expected in the future (R. Mawhinney, Lattice 2011)

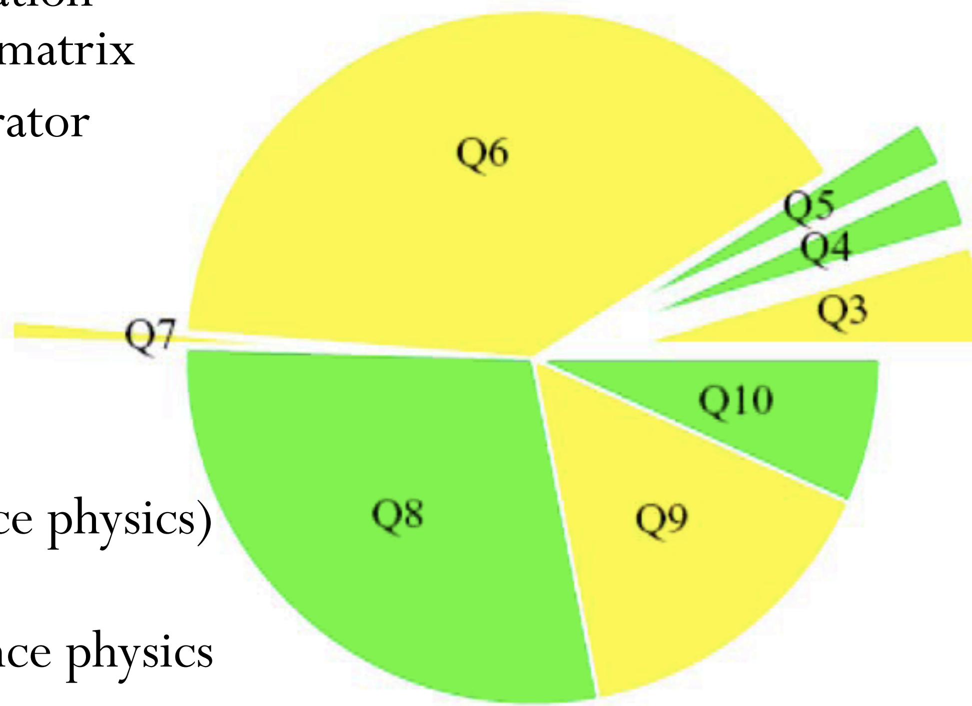


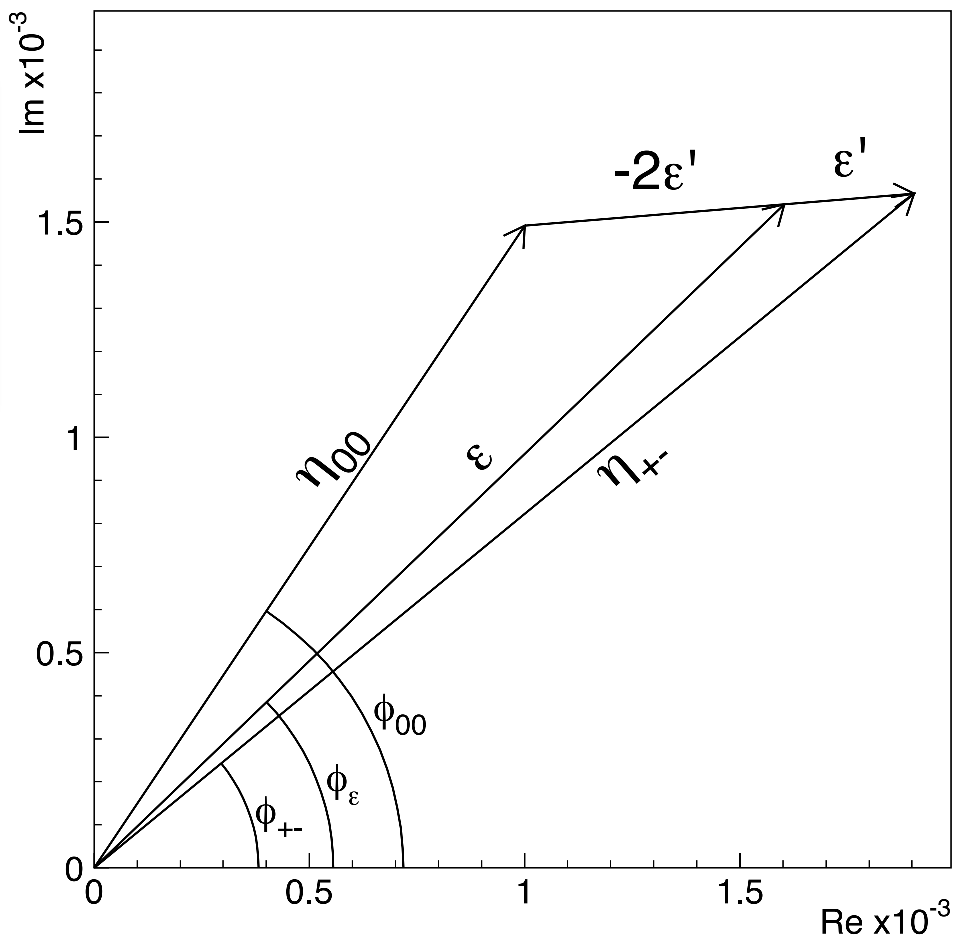
Figure courtesy of S. Bertolini.

CPT Symmetry in Kaons

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

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

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



CPT Symmetry in Kaons

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

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

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

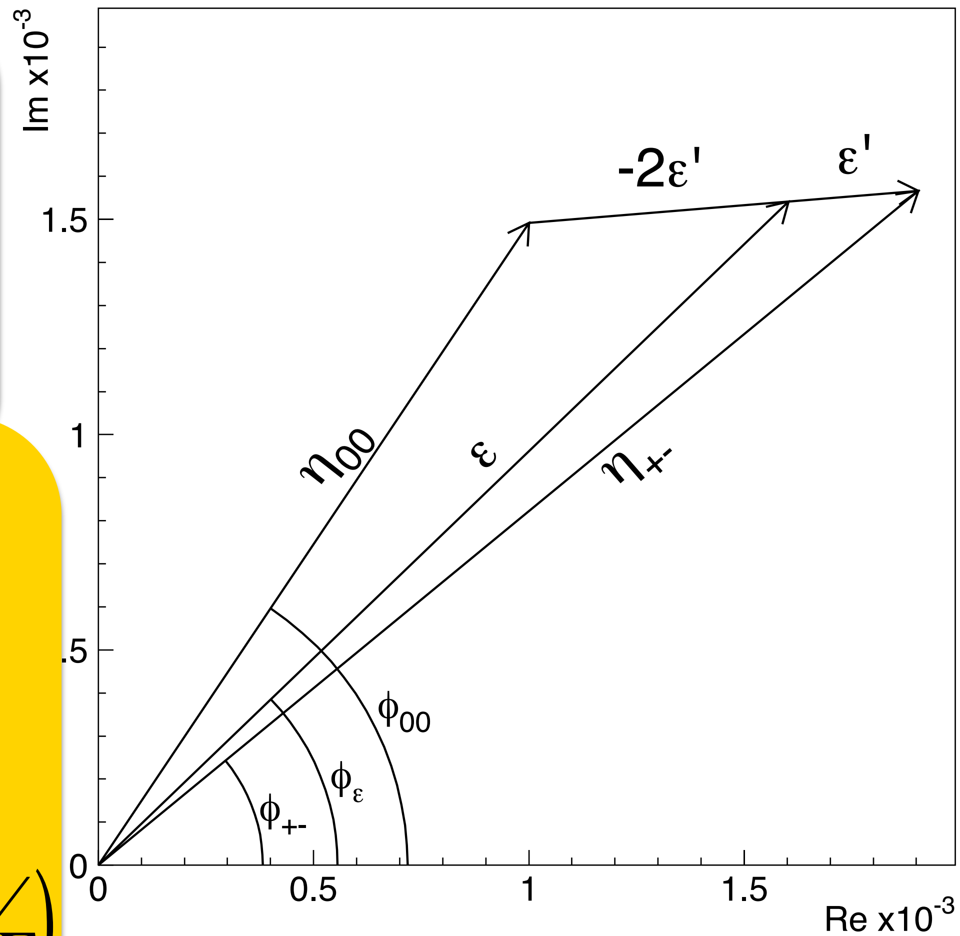
If CPT:

$$\phi_{\varepsilon} = \phi_{\varepsilon'}$$

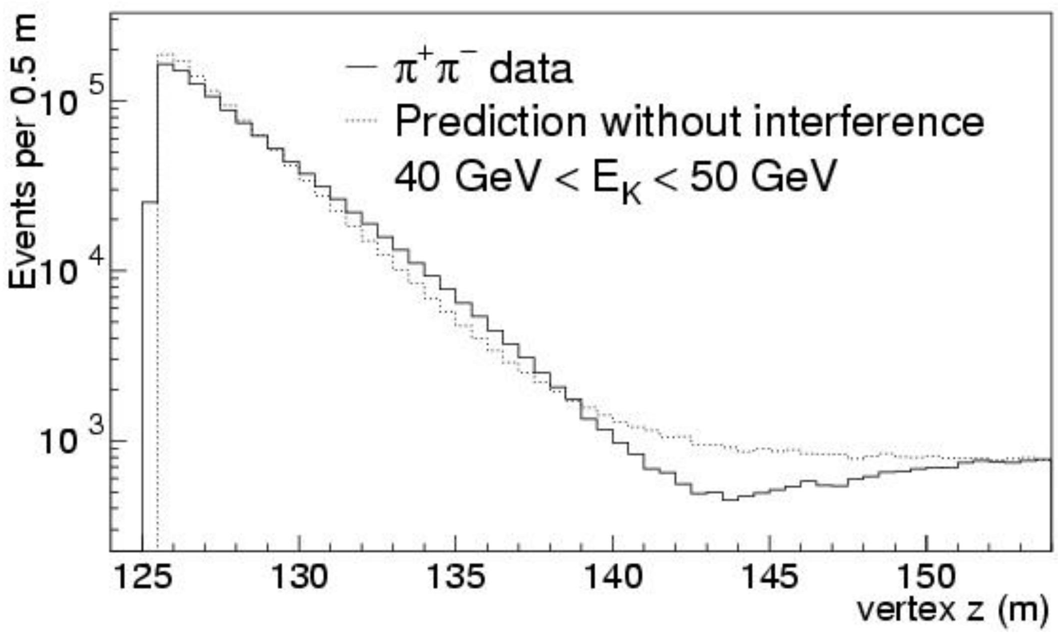
$$\mathrm{Im}(\varepsilon'/\varepsilon) = 0$$

$$\phi_{+-} = \phi_{00} = \phi_{SW}$$

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

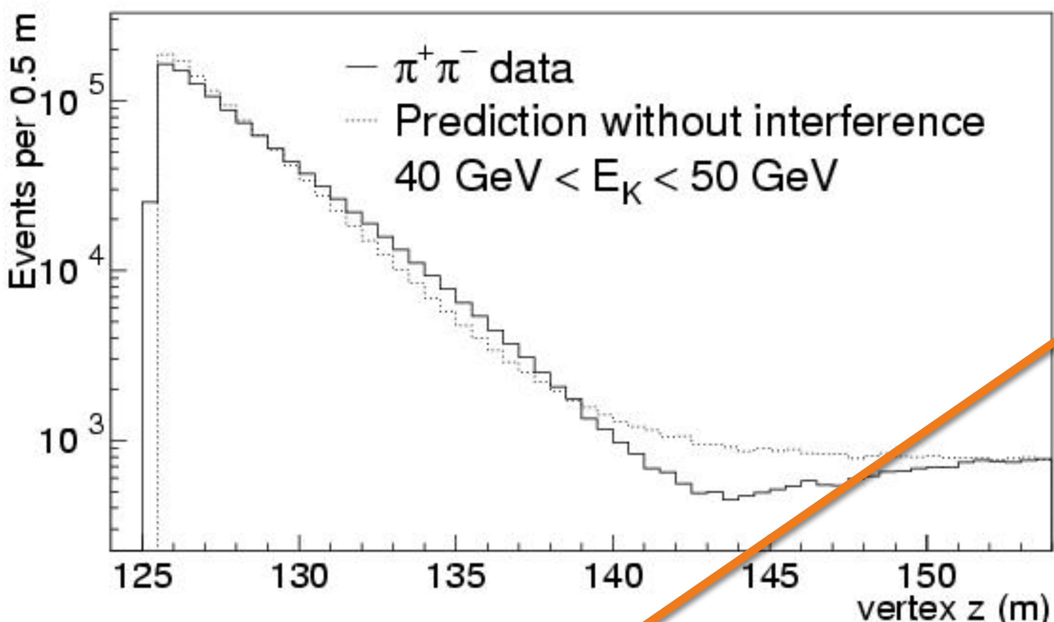


Measuring Kaon Parameters



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

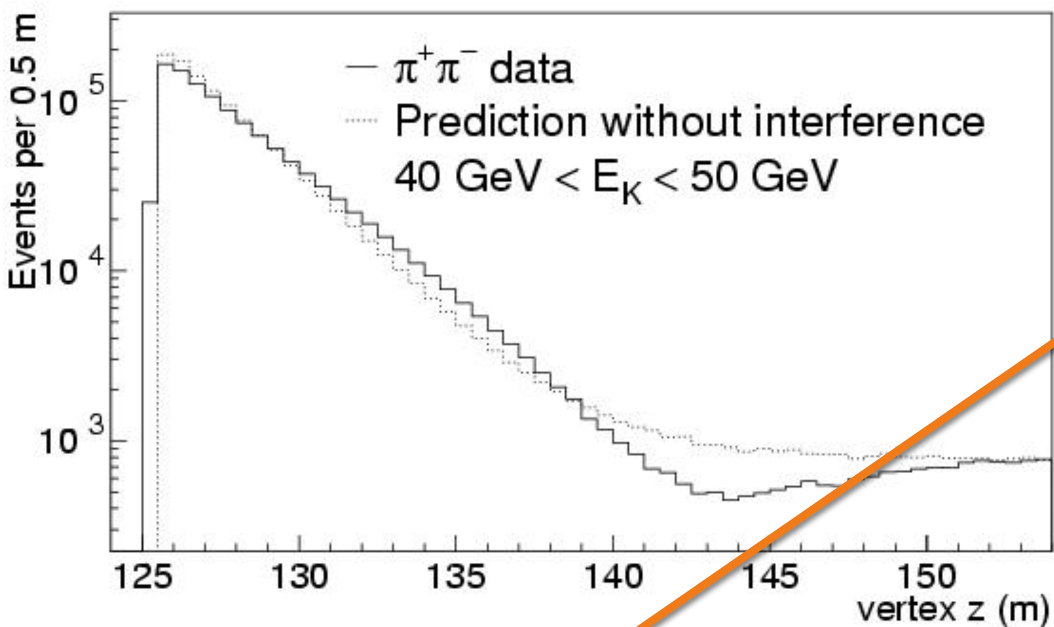
Measuring Kaon Parameters



τ_S

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

Measuring Kaon Parameters



τ_S

$\cos(\Delta mt + \phi_\eta)$

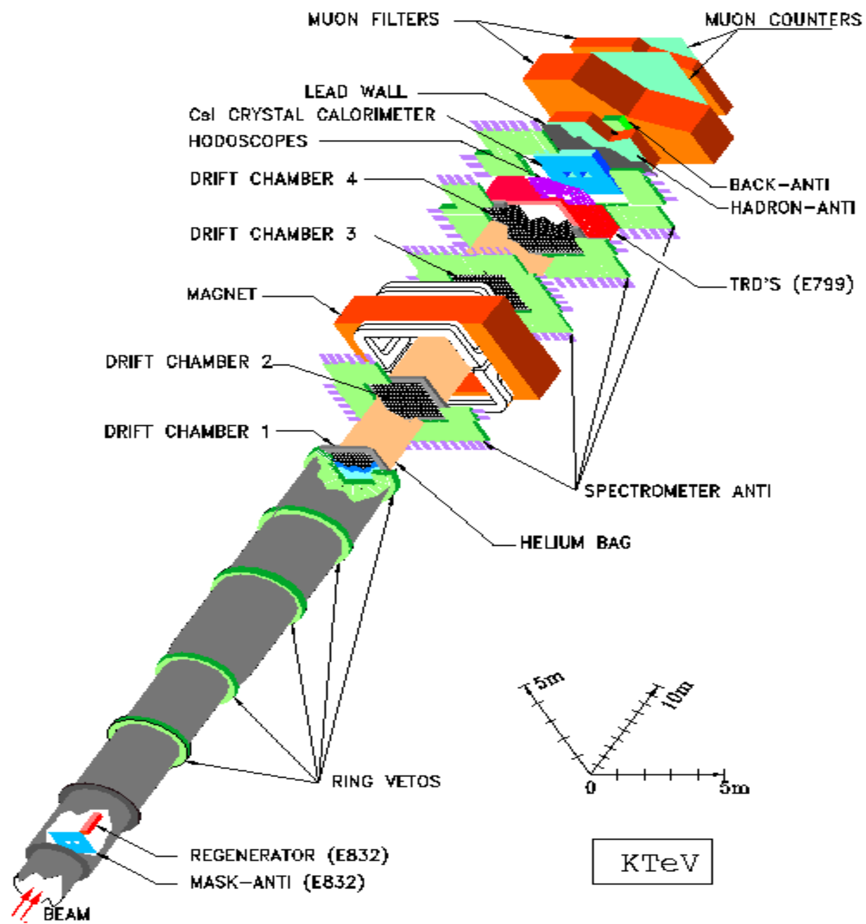
$$\left|A_f(t)\right|^2 \propto \left\{ e^{\Gamma_S t} + 2\mathrm{Re}\left[\frac{c_{L,0}}{c_{S,0}} \frac{A_{fL}}{A_{fS}} e^{-i\Delta mt}\right] e^{-(\Gamma_S + \Gamma_L)t/2} + \left|\frac{c_{L,0}}{c_{S,0}}\right|^2 \left|\frac{A_{fL}}{A_{fS}}\right|^2 e^{-\Gamma_L t} \right\}$$

The KTeV Experiment

Bruce Winstein (1943-2011)

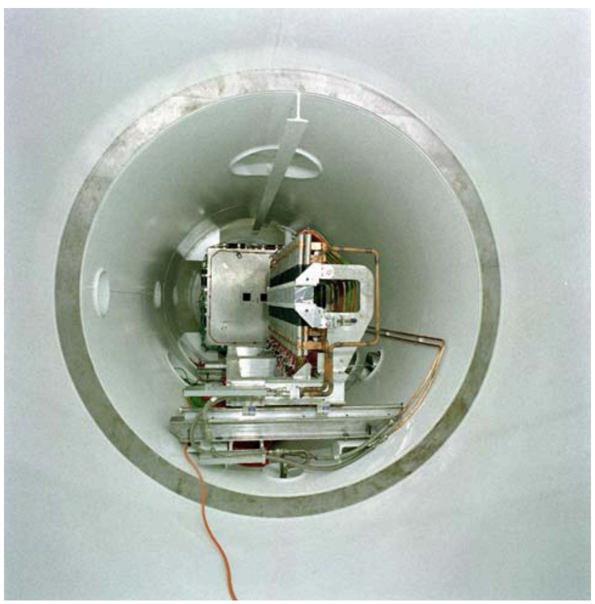
The KTeV Experiment

- Collect K_L and K_S decays to charged and neutral final states simultaneously
- Movable active regenerator to provide a coherent mixture of K_L and K_S and to veto scattered kaons
- Charged spectrometer to reconstruct $K \to \pi^+\pi^-$ decays
- CsI calorimeter to reconstruct $K \to \pi^0\pi^0$ decays
- Detailed MC simulation to correct acceptance
- Collected data in 1996, 1997, and 1999



Regenerator

$|K_L\rangle$ → **Regenerator (ρ)** $\sigma_{\bar{K}^0} > \sigma_{K^0}$ → $|K_L\rangle + \rho|K_S\rangle$



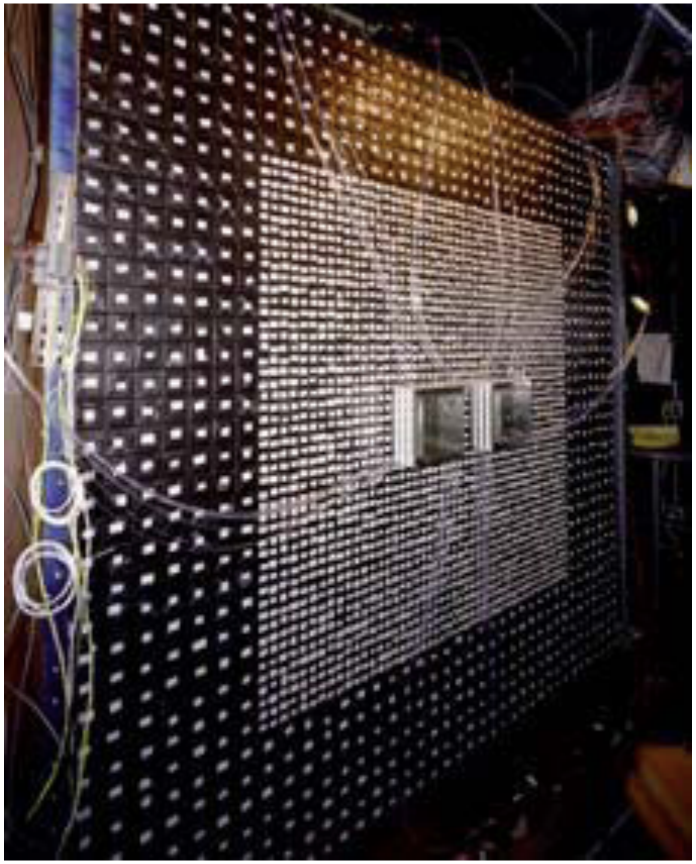
- Coherent regeneration: forward direction
- Diffractive regeneration: kaon scatters at finite angle
- Inelastic regeneration: target nucleus destroyed, secondary particles may be produced

Charged Spectrometer

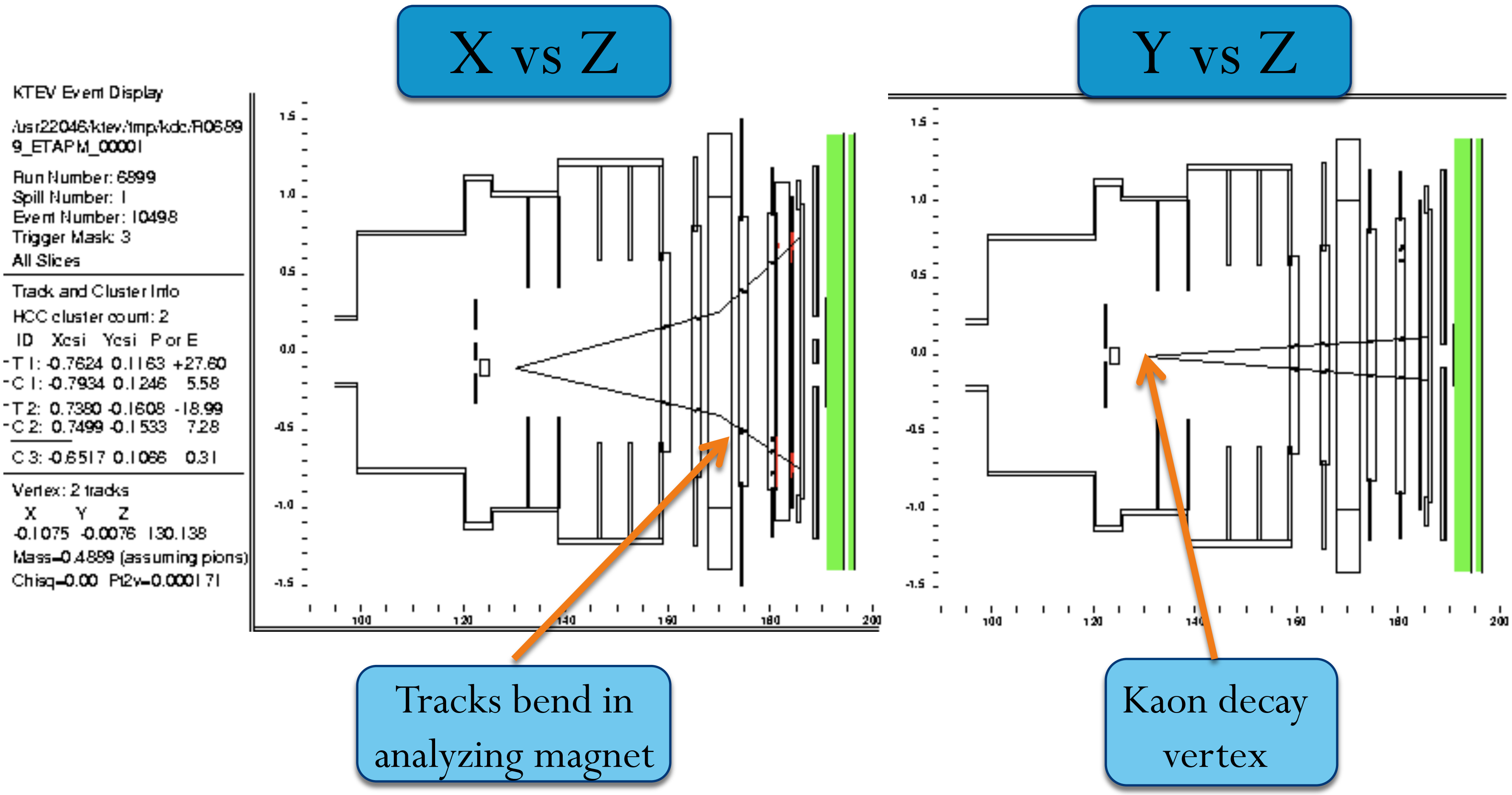
- 4 drift chambers
  - Hexagonal cell geometry
  - 2 planes each in x and y
- Dipole magnet
  - ~412 MeV/c kick in x
- Calibrated using data and the known kaon mass
  - Position resolution ~80 μm
  - Momentum resolution ~0.3%
  - Absolute momentum scale ~0.01%

CsI Calorimeter

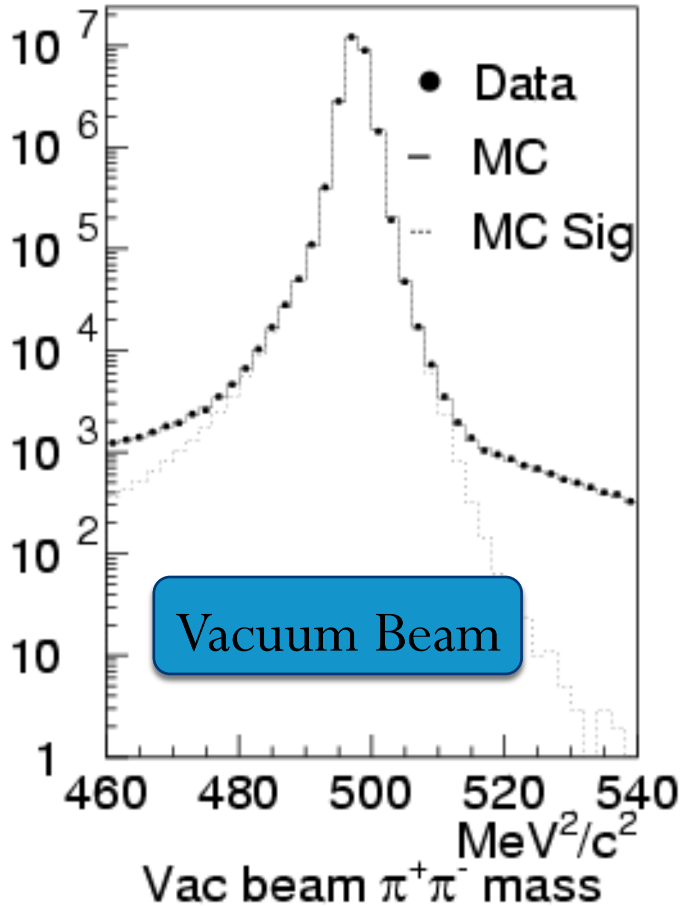
- 3100 CsI crystals viewed by PMTs
  - Small crystals $2.5\times2.5\times50\ \mathrm{cm}^3$
  - Large crystals $5.0\times5.0\times50\ \mathrm{cm}^3$
- Calibrated by in-situ laser system and momentum analyzed electrons from Ke3 decays
  - Position resolution
    - ~1.2 mm (small crystals)
    - ~2.4 mm (large crystals)
  - Energy resolution ~0.6%
  - Absolute energy scale ~0.04%

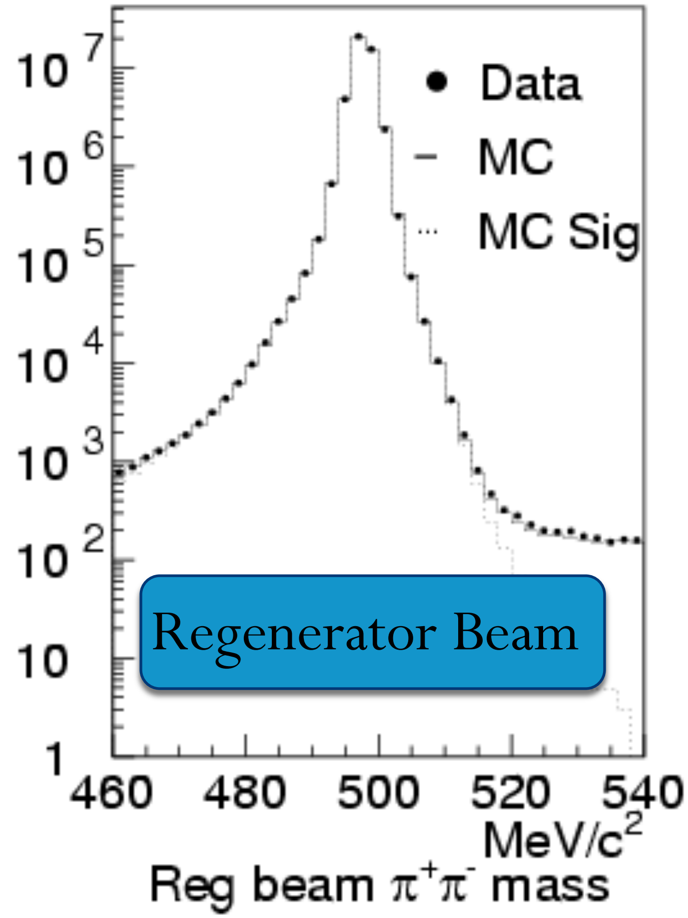


$K \rightarrow \pi^{+}\pi^{-}$ Analysis: Reconstruction

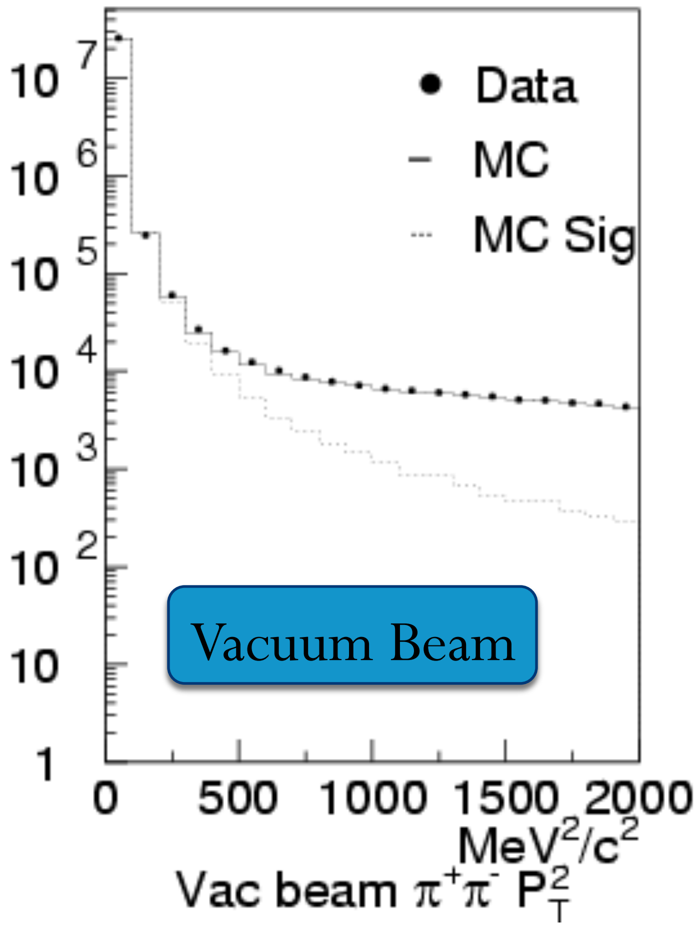


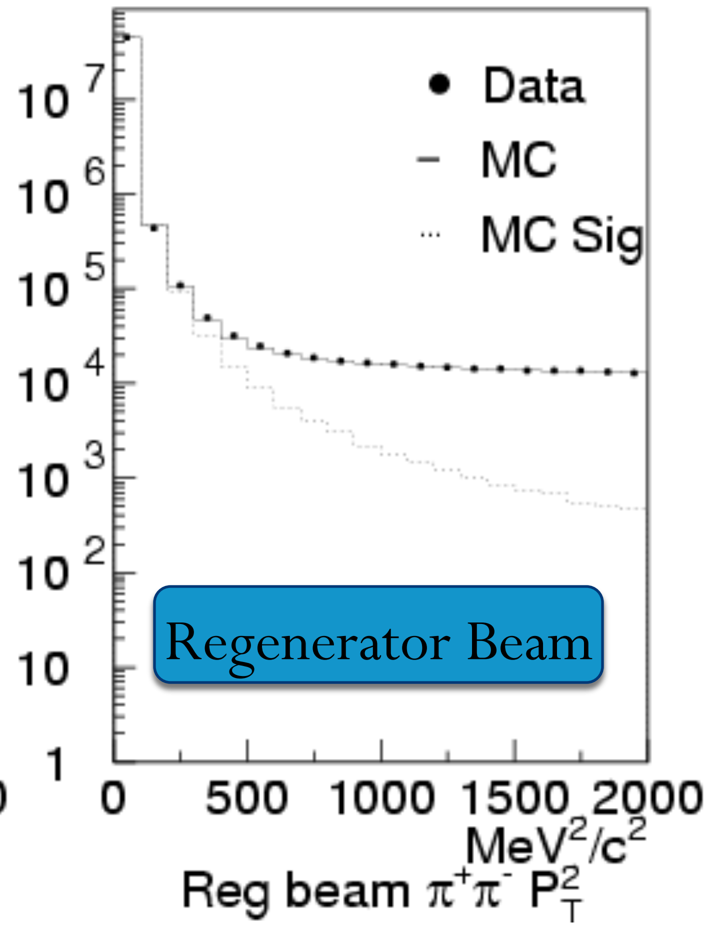
$K \rightarrow \pi^+\pi^-$ Analysis: Invariant Mass



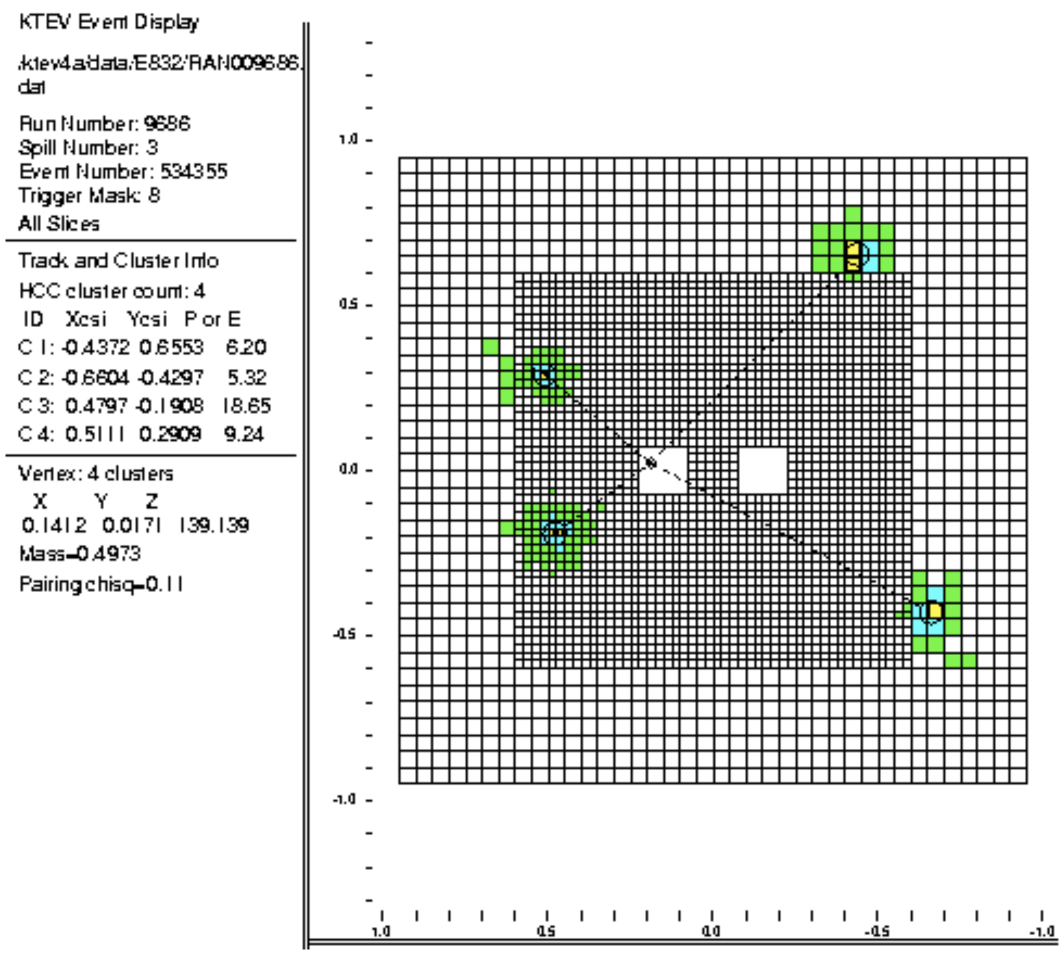


$K \rightarrow \pi^+\pi^-$ Analysis: P_T^2





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



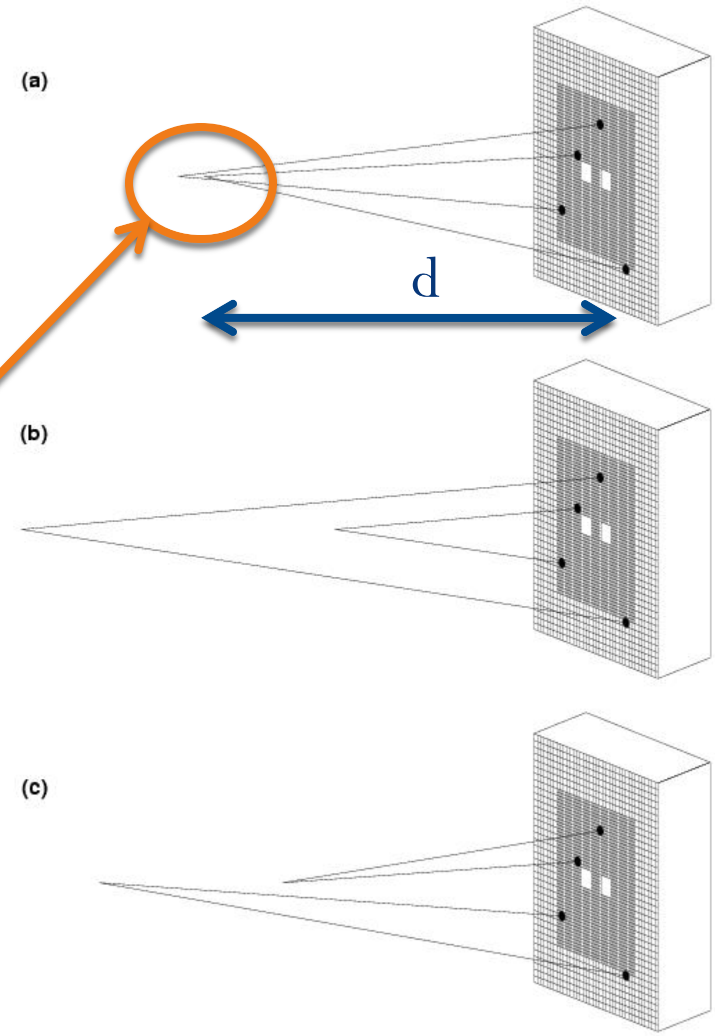
Only signal is 4 photon showers in CsI calorimeter

$K \to \pi^0\pi^0$ Analysis: Photon Pairing

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

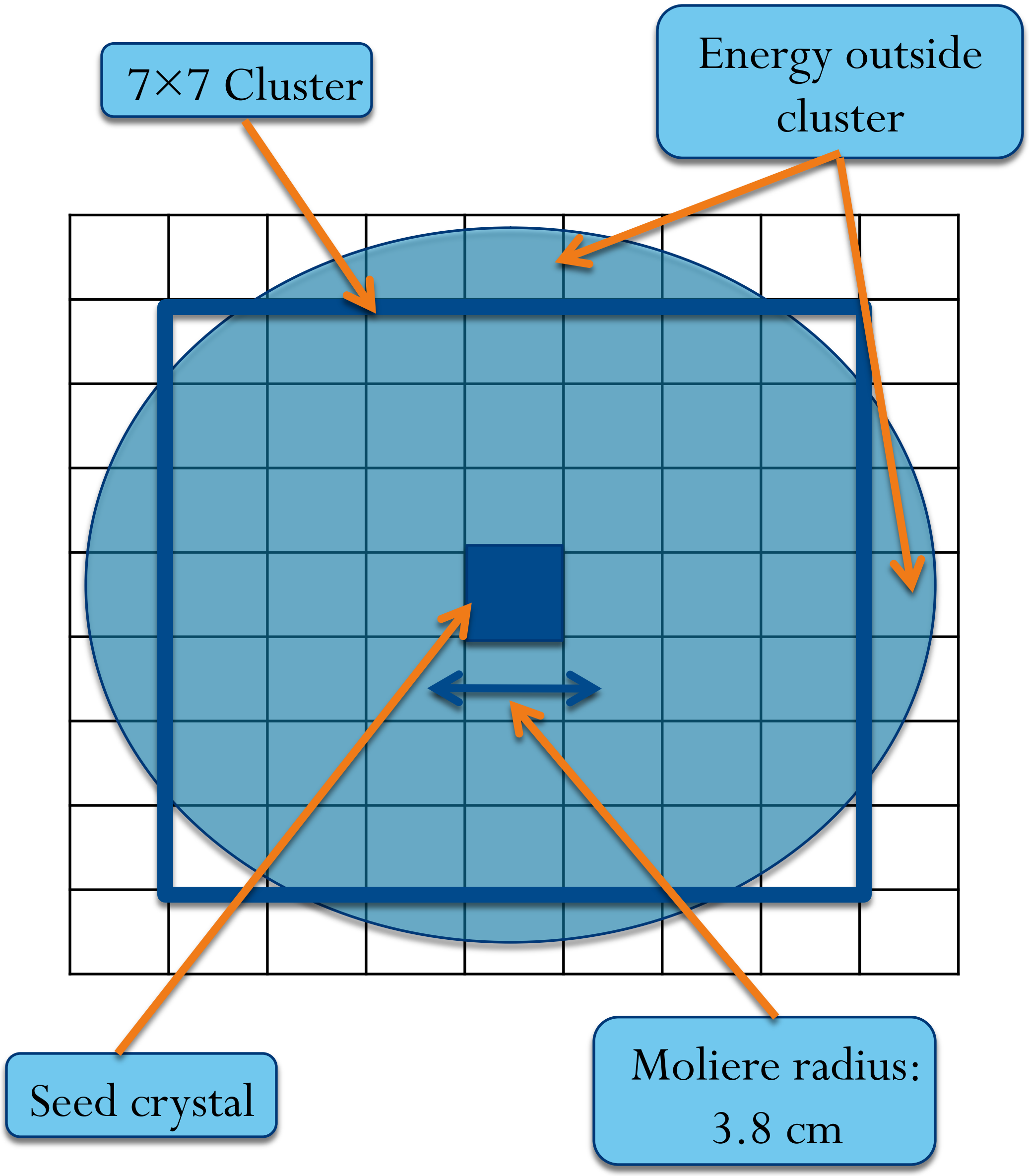
$$d_{12} \approx \frac{\sqrt{E_1 E_2}}{m_{\pi^0}} r_{12}$$

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



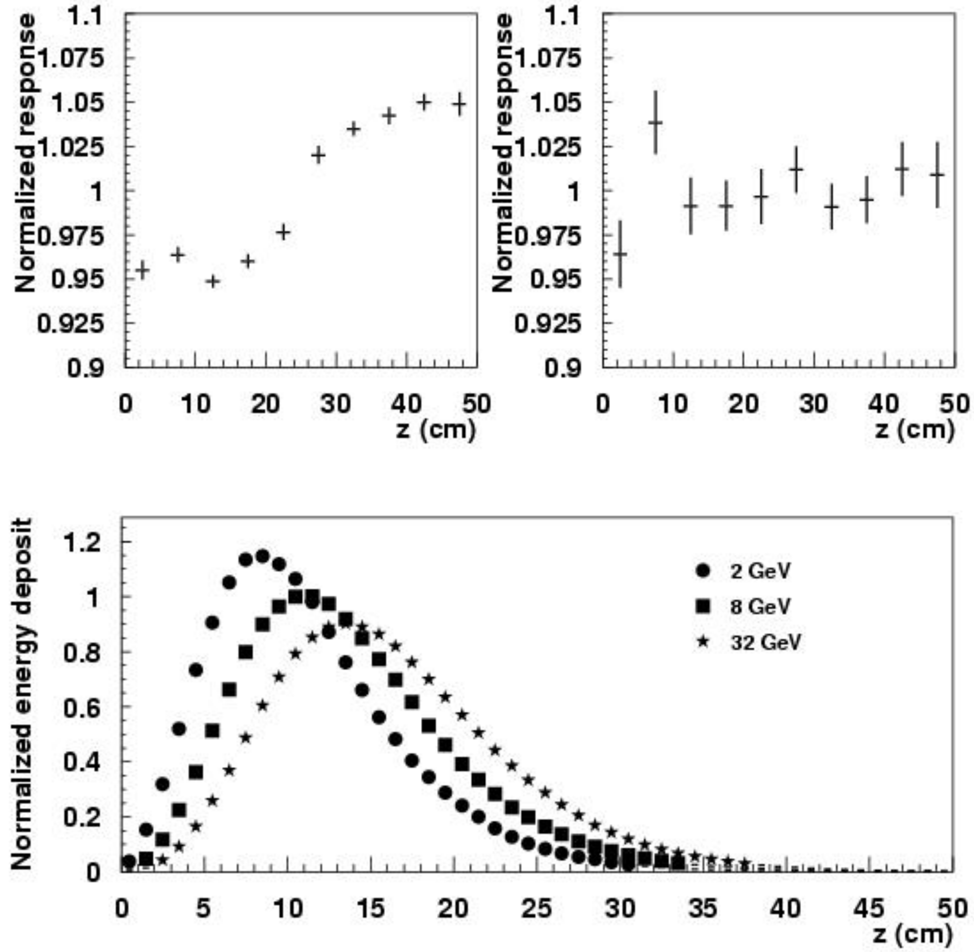
CsI Clustering

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



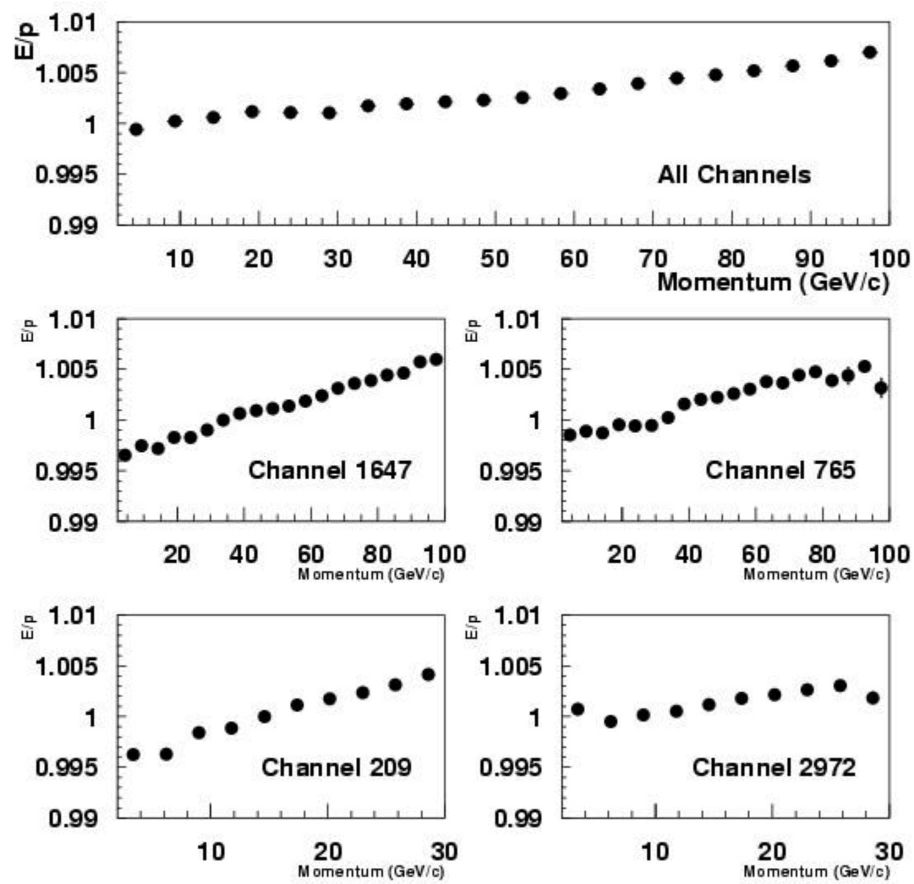
Longitudinal Uniformity Correction

- 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 convolved with predicted shower profile for each crystal
- Individual crystal energies corrected

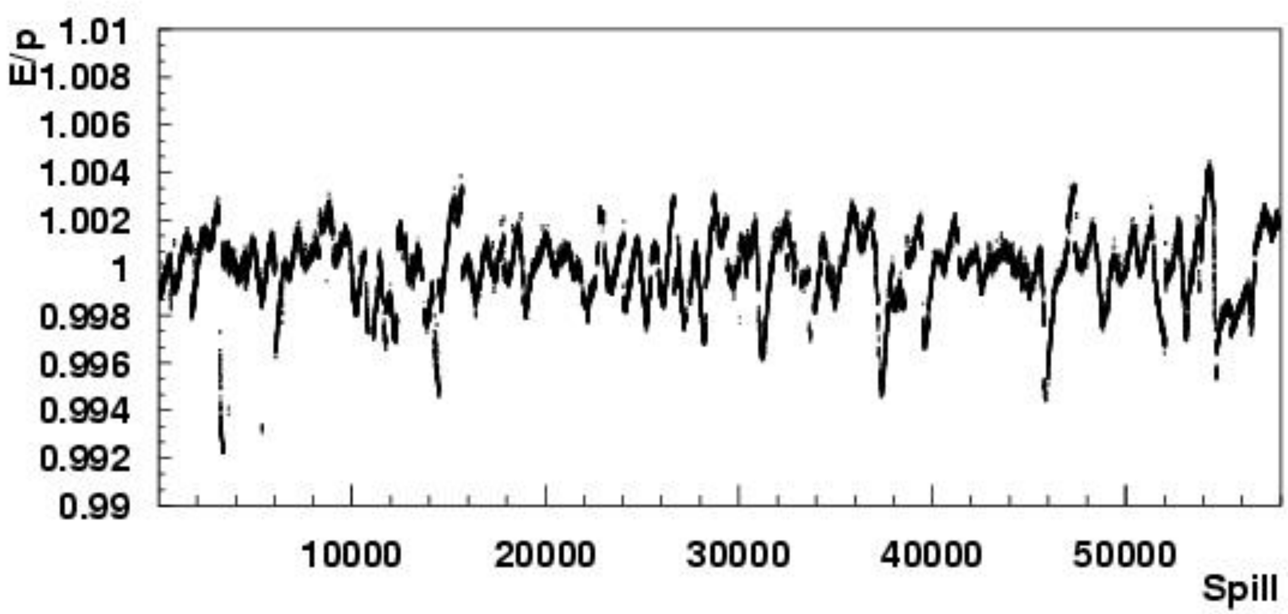


Energy Linearity Correction

- 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 crystal
  - Applied as a function of cluster energy
- Correction generally < 1%

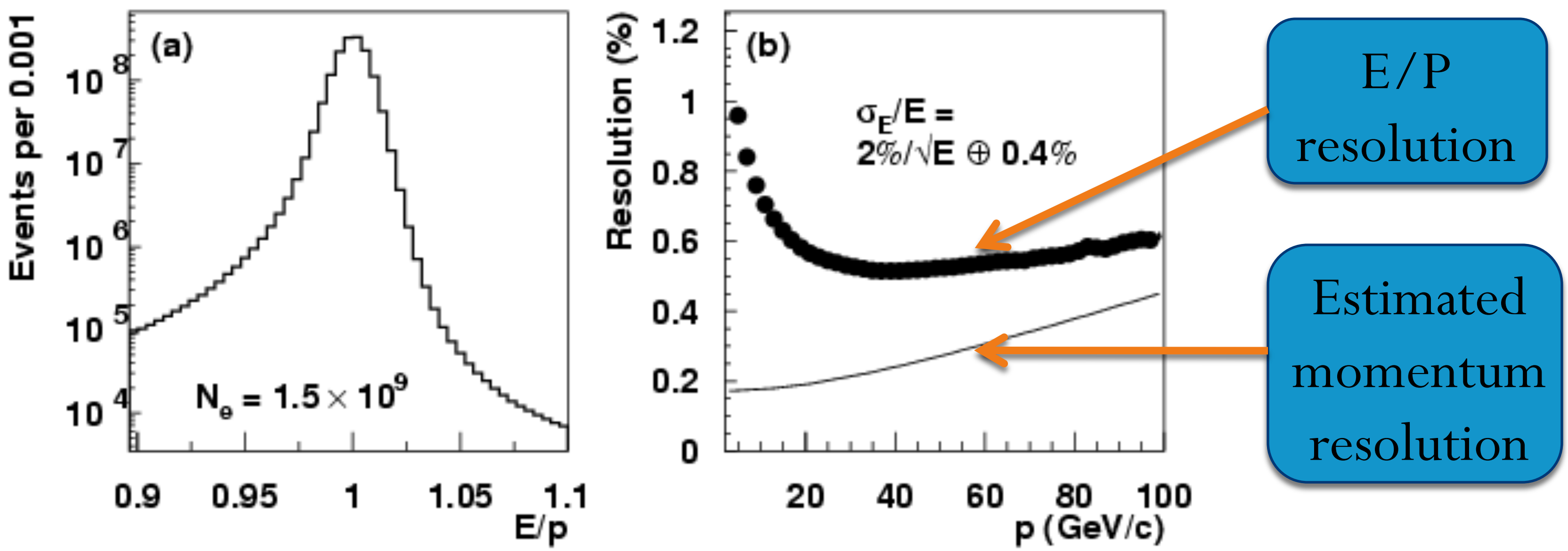


Spill-by-Spill Correction



- 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 < ~0.5%

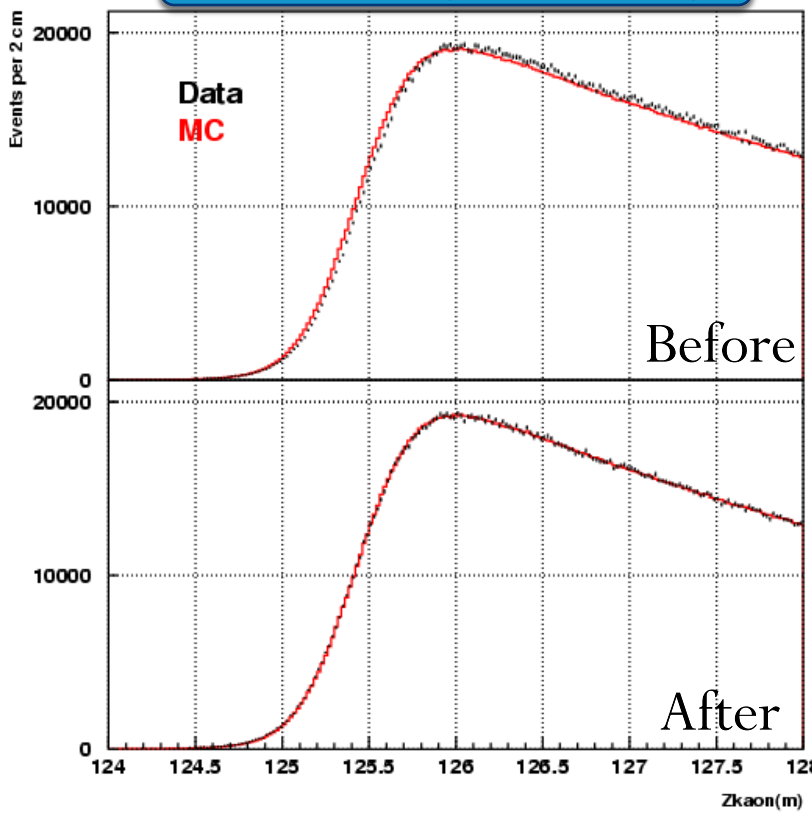
CsI Performance



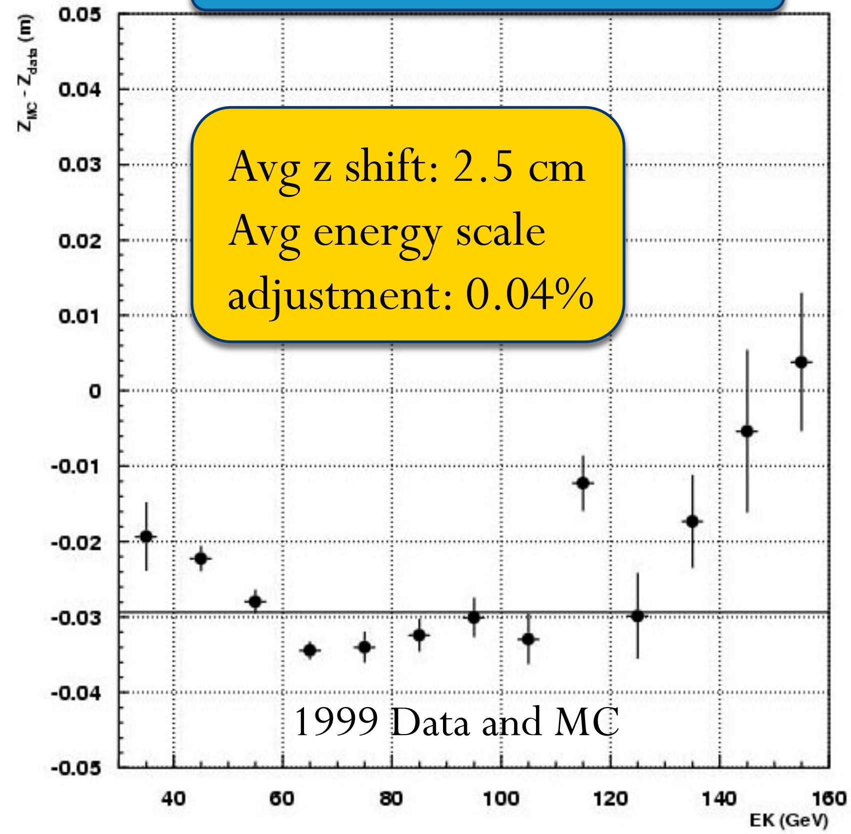
- Calibration based on 1.5 billion electrons from $K_L \rightarrow \pi^{\pm} e^{\mp} \nu$ decays
- Final E/p resolution after all corrections ~0.6%

Final Energy Scale

z vertex at regenerator edge



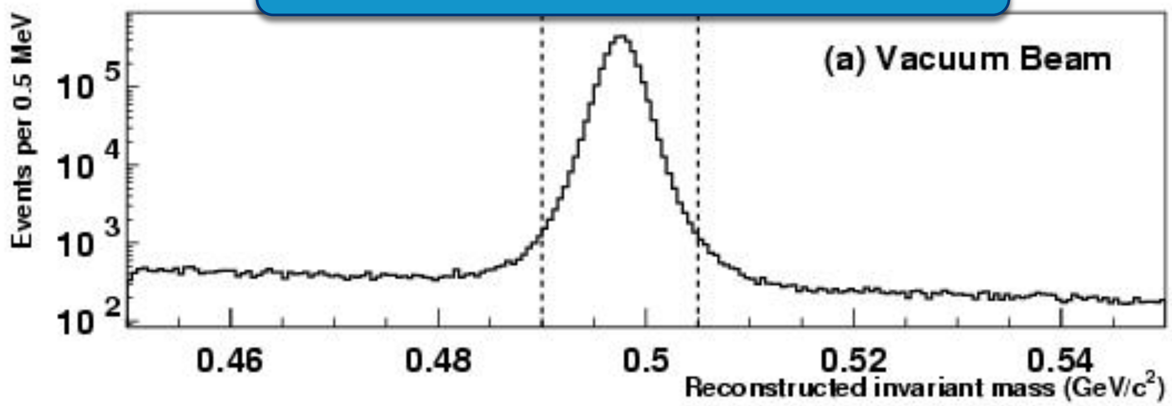
z shift to match data to MC

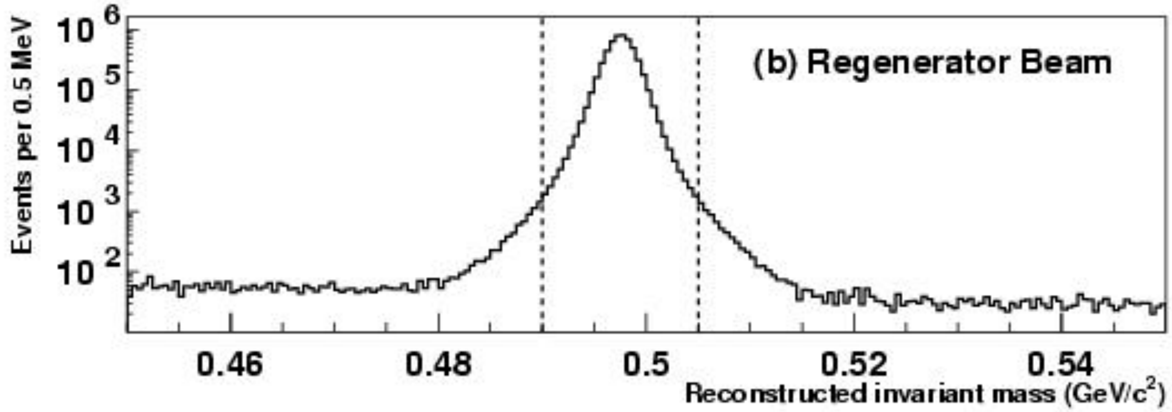


Avg z shift: 2.5 cm
Avg energy scale adjustment: 0.04%

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

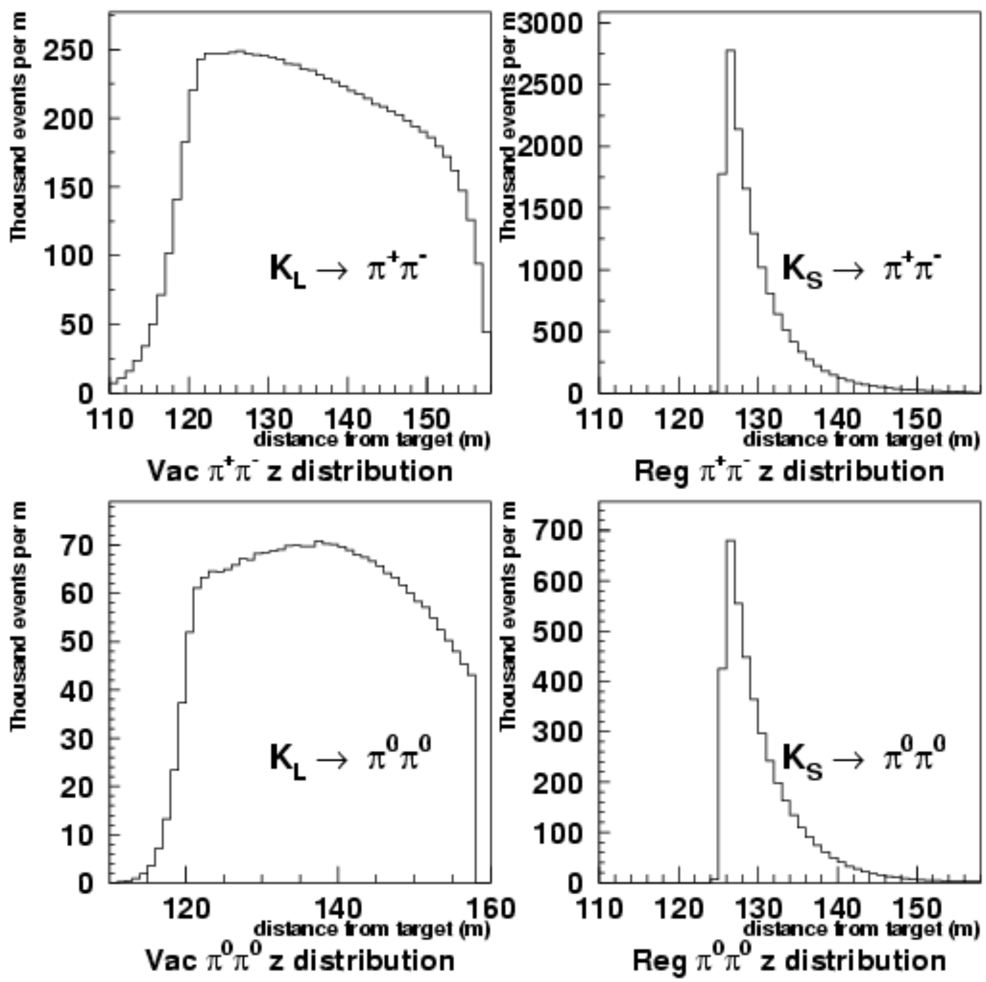
Reconstructed Invariant Mass





Mass resolution $\sim$1.5 MeV/c^2

Monte Carlo Simulation



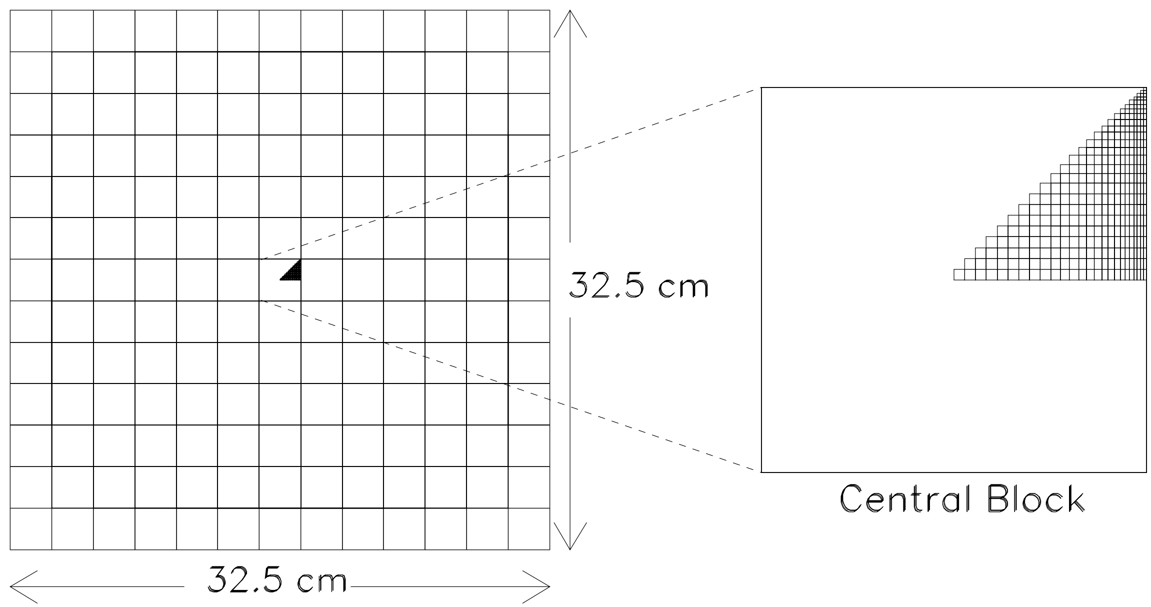
- Monte Carlo used to make acceptance correction and to simulate background to signal modes
  - Simulates kaon generation, propagation, and decay
  - Simulates detector geometry and response
  - Much of tracing and detector response based on GEANT libraries
  - Includes beam intensity effects by overlaying data events selected by an "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
  - Effects of dead material (wrapping and shims) in CsI calorimeter

EM Shower Simulation

- GEANT shower library
  - 6 energy bins: (2, 4, 8, 16, 32, 64) GeV
    - Smear energy to match data resolution
    - Select bin using logarithmic interpolation
    - Scale energy in each crystal to desired energy
  - 325 position bins distributed over one octant of central crystal
    - Rotate showers using octant symmetry to cover other 7 octants



EM Shower Simulation (cont.)

- GEANT shower library
  - Angle bins
    - Photons: 9 bins (0, ±5, ±15, ±25, ±35) mrad
    - Electrons: 15 bins (0, ±5, ±15, ±25, ±35, ±45, ±65, ±85) mrad
    - Select bin using linear interpolation
    - Correct for difference between desired angle and library angle by shifting transverse position
  - Library Storage
    - Shower libraries read into memory during MC generation
    - Packing scheme saves shower info with no more precision than necessary
    - One photon library: 150,000+ showers, 33 Mb
    - One electron library: 400,000+ showers, 93 Mb
    - 16 different libraries generated for use in distributed computing

EM Shower Simulation (cont.)

New since 2003

- GEANT shower library
  - Angle bins
    - Photons: 9 bins (0, ±5, ±15, ±25, ±35) mrad
    - Electrons: 15 bins (0, ±5, ±15, ±25, ±35, ±45, ±65, ±85) mrad
    - Select bin using linear interpolation
    - Correct for difference between desired angle and library angle by shifting transverse position
  - Library Storage
    - Shower libraries read into memory during MC generation
    - Packing scheme saves shower info with no more precision than necessary
    - One photon library: 150,000+ showers, 33 Mb
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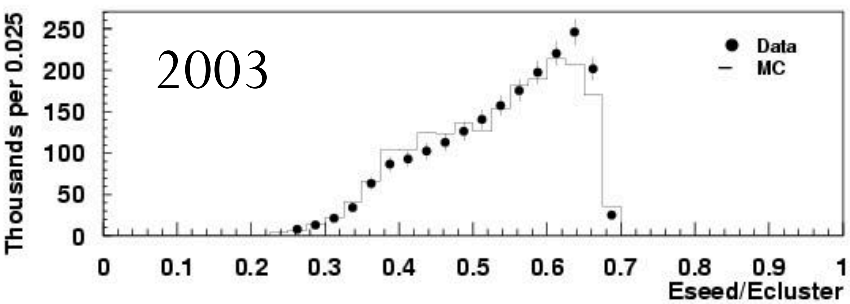
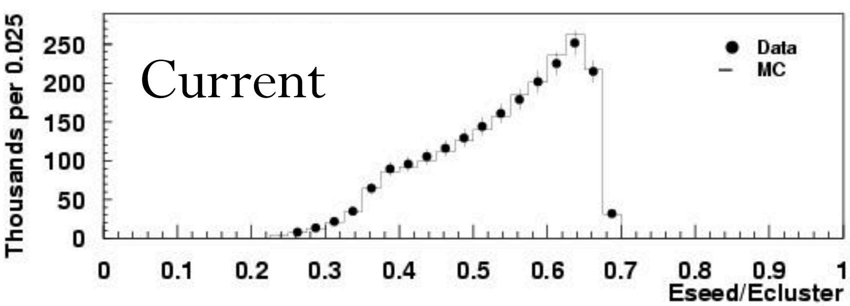
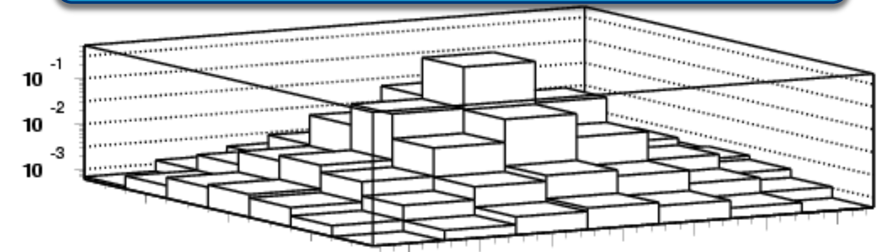
Improvements: Shower Shape

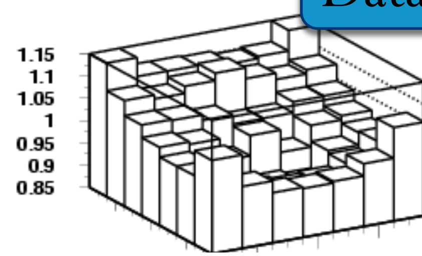




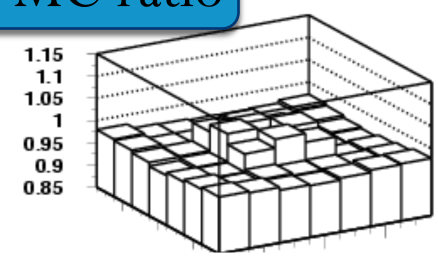
Fraction of energy per CsI crystal



Data/MC ratio



2003

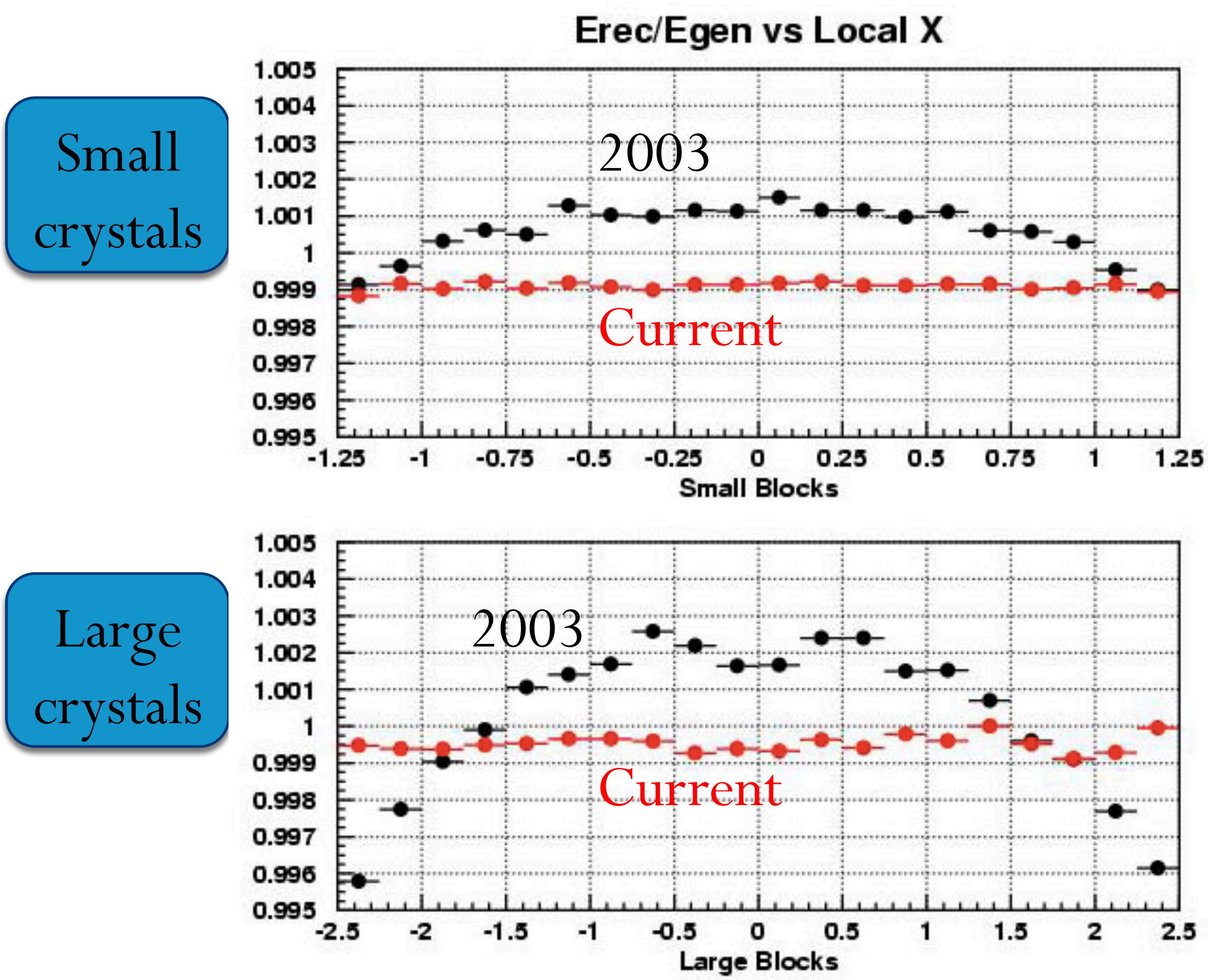


Current

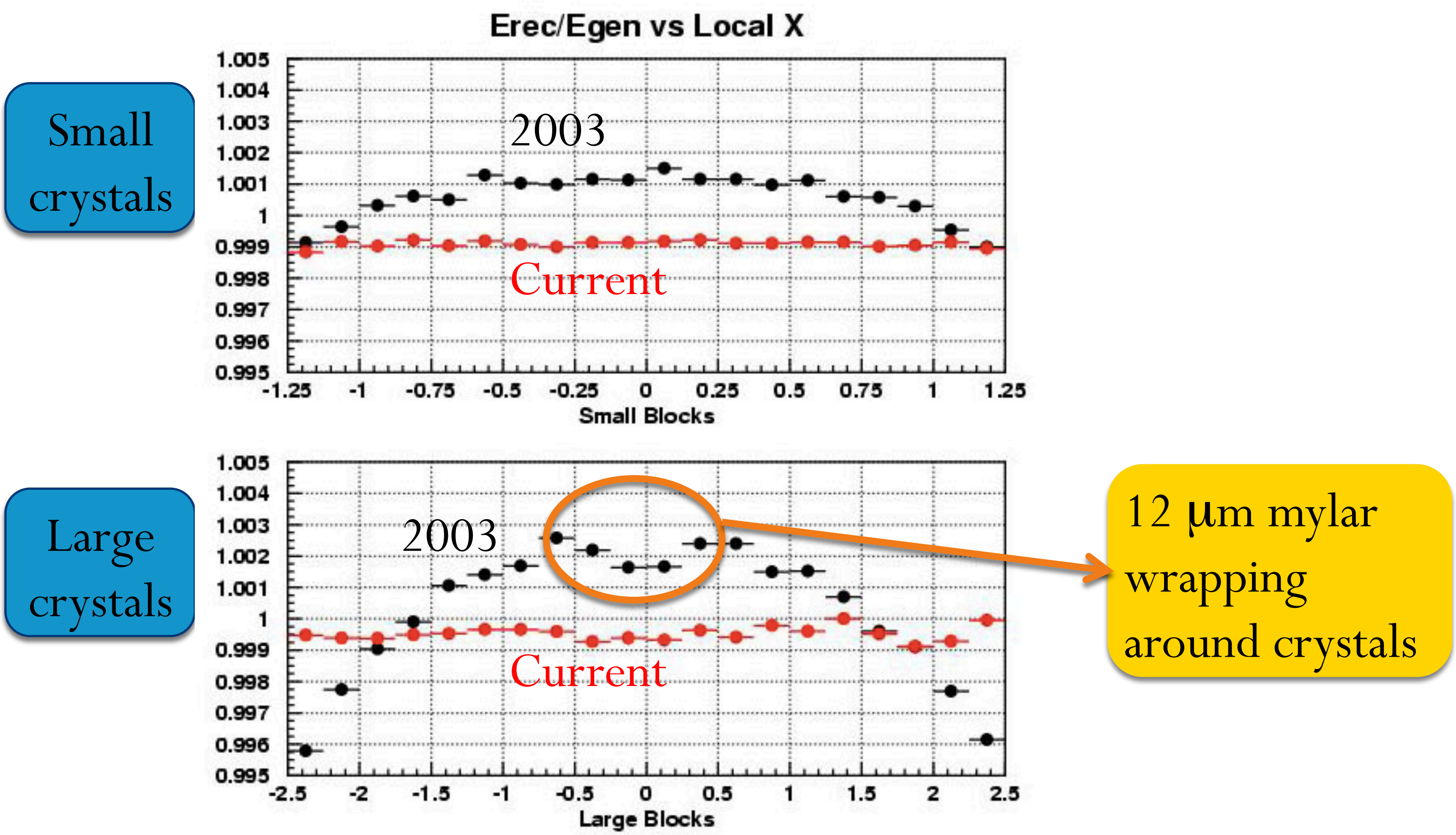
2003: Includes transverse energy correction to match data and MC

Current: No correction required

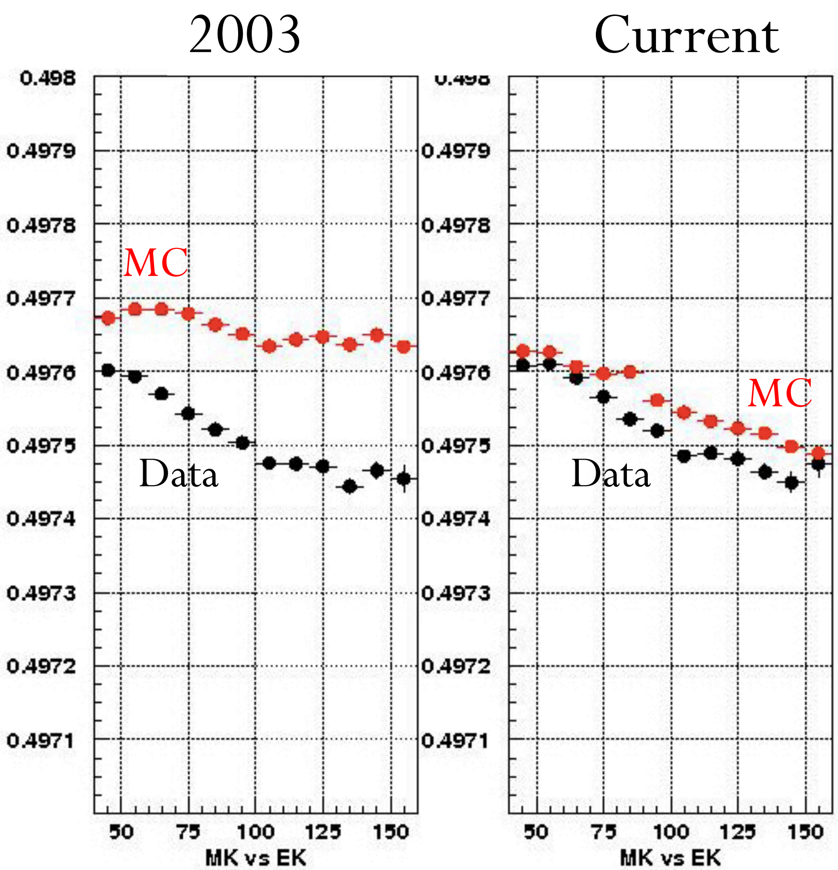
Improvements: Reconstructed Energy



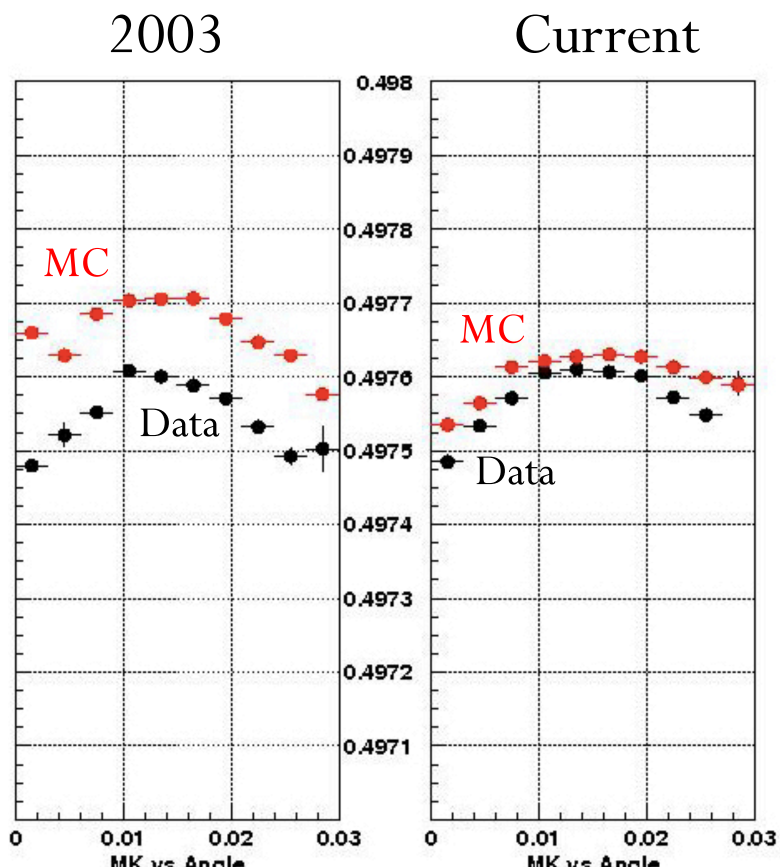
Improvements: Reconstructed Energy



Improvements: Energy Linearity



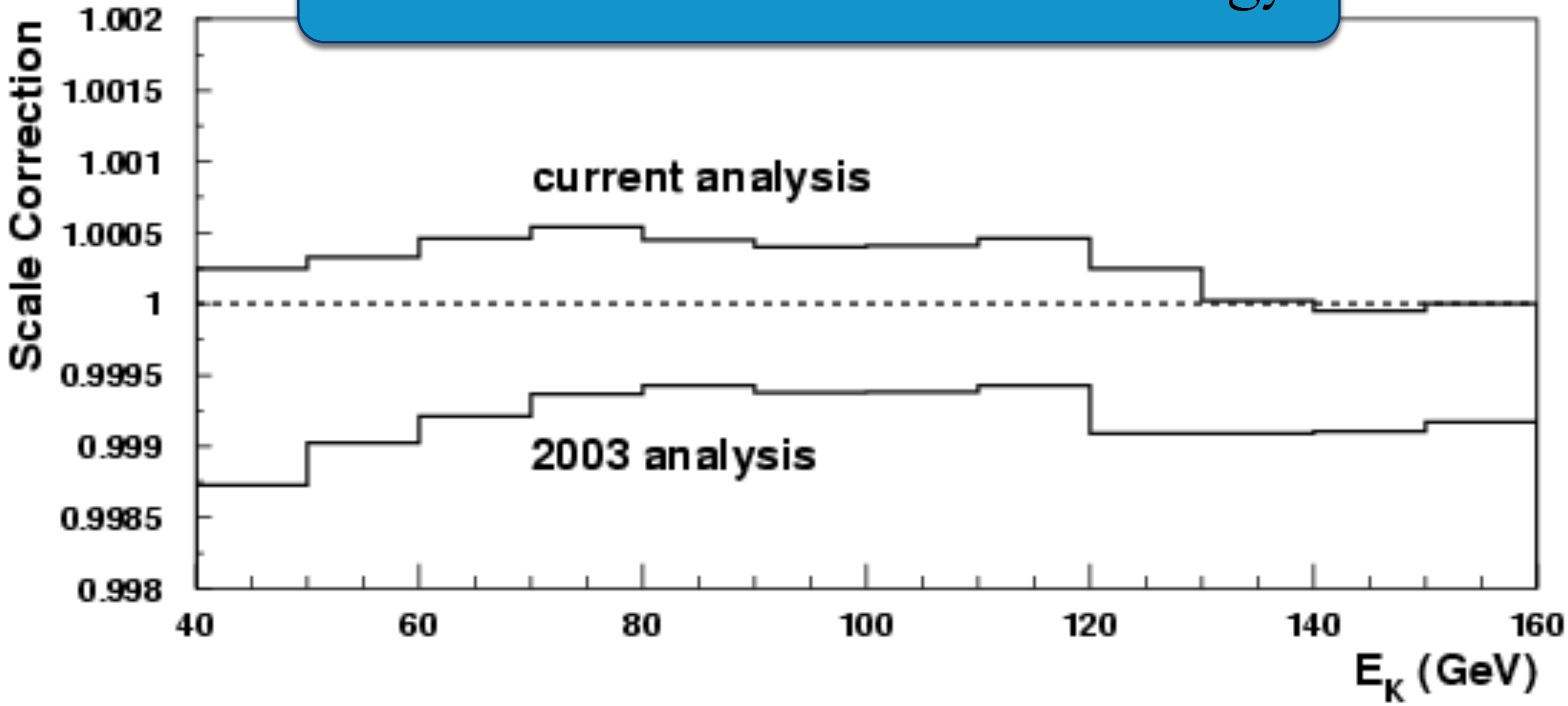
Mass vs. Energy



Mass vs. Photon Angle

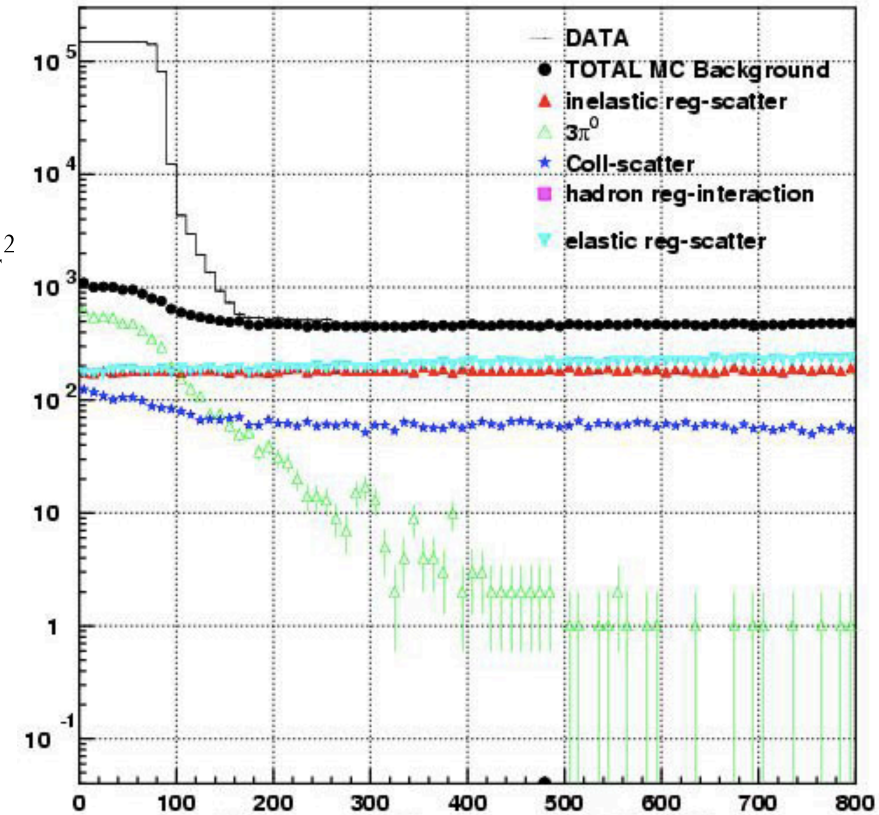
Improvements: Energy Scale

Scale Correction vs. Kaon Energy



Background

- Scattering background
  - Scattering in defining collimator
  - Diffractive and inelastic scattering in regenerator
  - Common to charged and neutral modes
  - Characterized using $\pi^+\pi^-$ events with large p_T^2
  - Level higher in neutral mode: no cut on p_T^2
    - Use RING variable instead (C.O.E. to beam center)
- Non $\pi\pi$ background
  - Semileptonic kaon decays in charged mode
  - $K \rightarrow 3\pi^0$ decays and hadronic production in neutral mode
- Background simulated by MC, normalized to data sidebands, and subtracted
- Total background levels
  - Charged mode: ~0.1%
  - Neutral mode: ~1%



$K \rightarrow \pi^0\pi^0$ RING, vacuum beam

Extracting physics parameters

- Fitter used to apply MC acceptance correction and treat K_L-K_S interference
- 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
- $Re(\varepsilon'/\varepsilon)$
  - 12 p bins
  - CPT symmetry assumed: $\phi_{+-} = \phi_{00} = \phi_{SW}$
- Kaon parameters and phases
  - 12 p bins, 12 z bins (reg. beam)
  - τ_S, Δm, ϕ_ε, $Re(\varepsilon'/\varepsilon)$, $Im(\varepsilon'/\varepsilon)$ are fit simultaneously
  - CPT assumption applied *a posteriori*

Systematic Uncertainties

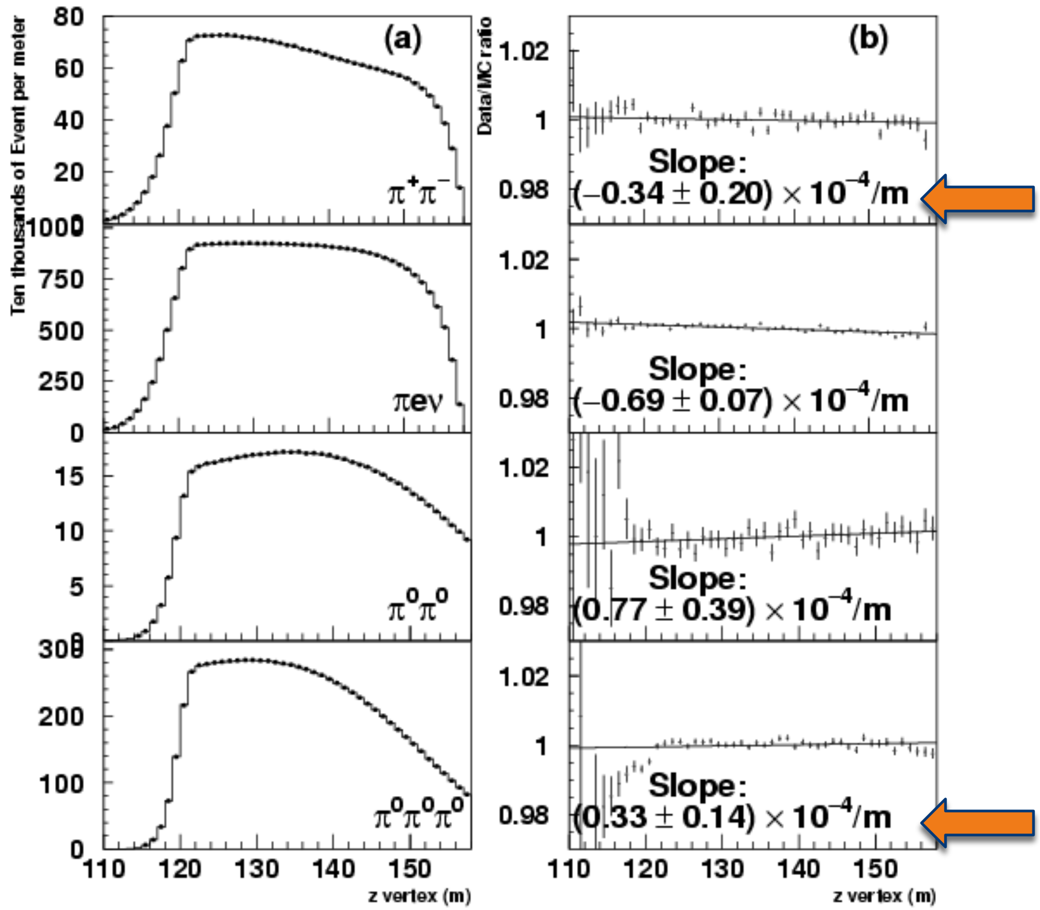
Source	Error on $Re(\epsilon'/\epsilon)$ $(\times 10^{-4})$	
	$K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.23	0.20
CsI cluster reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Backgrounds	0.20	1.07
MC statistics	0.20	0.25
Total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

Uncertainty from Background

Background Source	Systematic Uncertainty in Re(ε′/ε) (×10^{-4})
Regenerator Scattering:	
High p_T^2 Acceptance	0.40
$K \to \pi^+\pi^-$ Background	0.20
$K \to \pi^+\pi^-$ Analysis	0.75
p_T^2 Fit Procedure	0.30
p_T^2 Fit Quality	0.40
Charged-Neutral Veto Differences	0.30
Collimator Scattering	0.10
$K_L \to \pi^0\pi^0\pi^0$	0.06
Other	0.11
Total	1.06

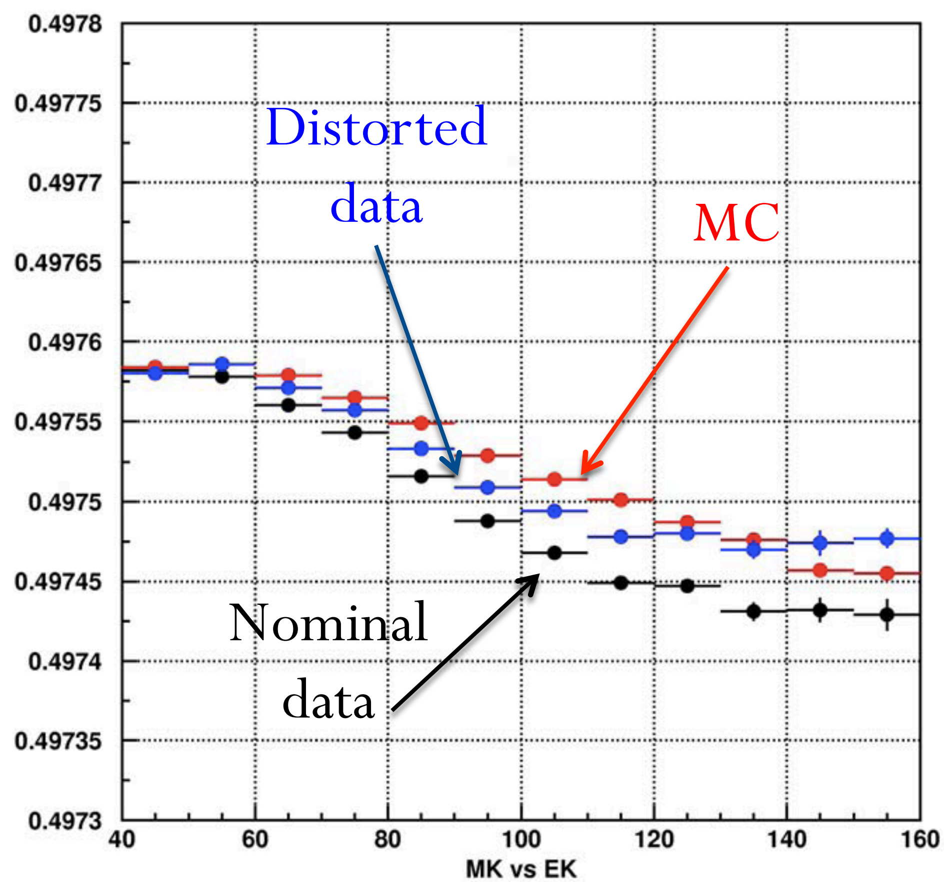
Uncertainty from Acceptance

- Quality of MC simulation evaluated by comparing vacuum beam z vertex distributions between data and MC
- Bias in Re(ε′/ε) given by sΔz/6
  - s: slope of data-MC ratio
  - Δz: 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 that provides best data-MC match
- Non-linearities:
  - 1996: 0.3%/100 GeV
  - 1997: 0.1%/100 GeV
  - 1999: 0.1%/100 GeV
- Change in $Re(\varepsilon'/\varepsilon)$
  - 1996: -0.1×10^{-4}
  - 1997: -0.1×10^{-4}
  - 1999: $+0.2 \times 10^{-4}$
- Systematic uncertainty: $\pm 0.15 \times 10^{-4}$



Uncertainty from Energy Non-linearity

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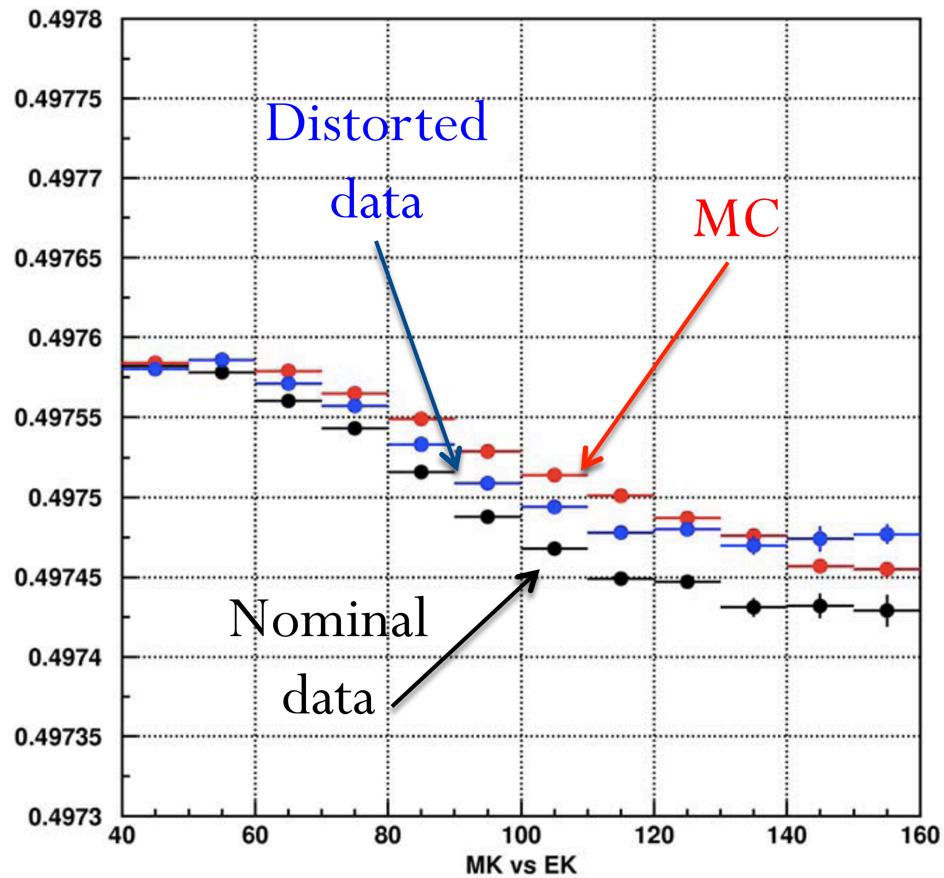
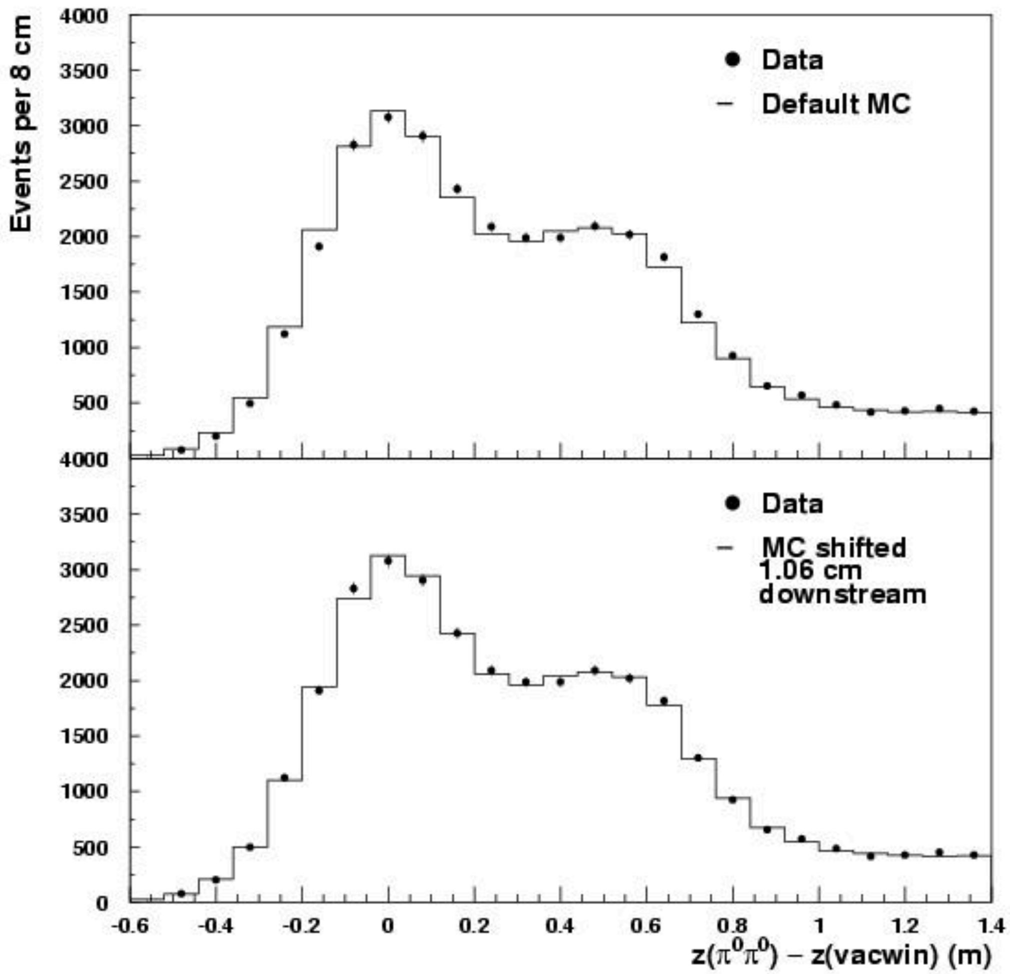


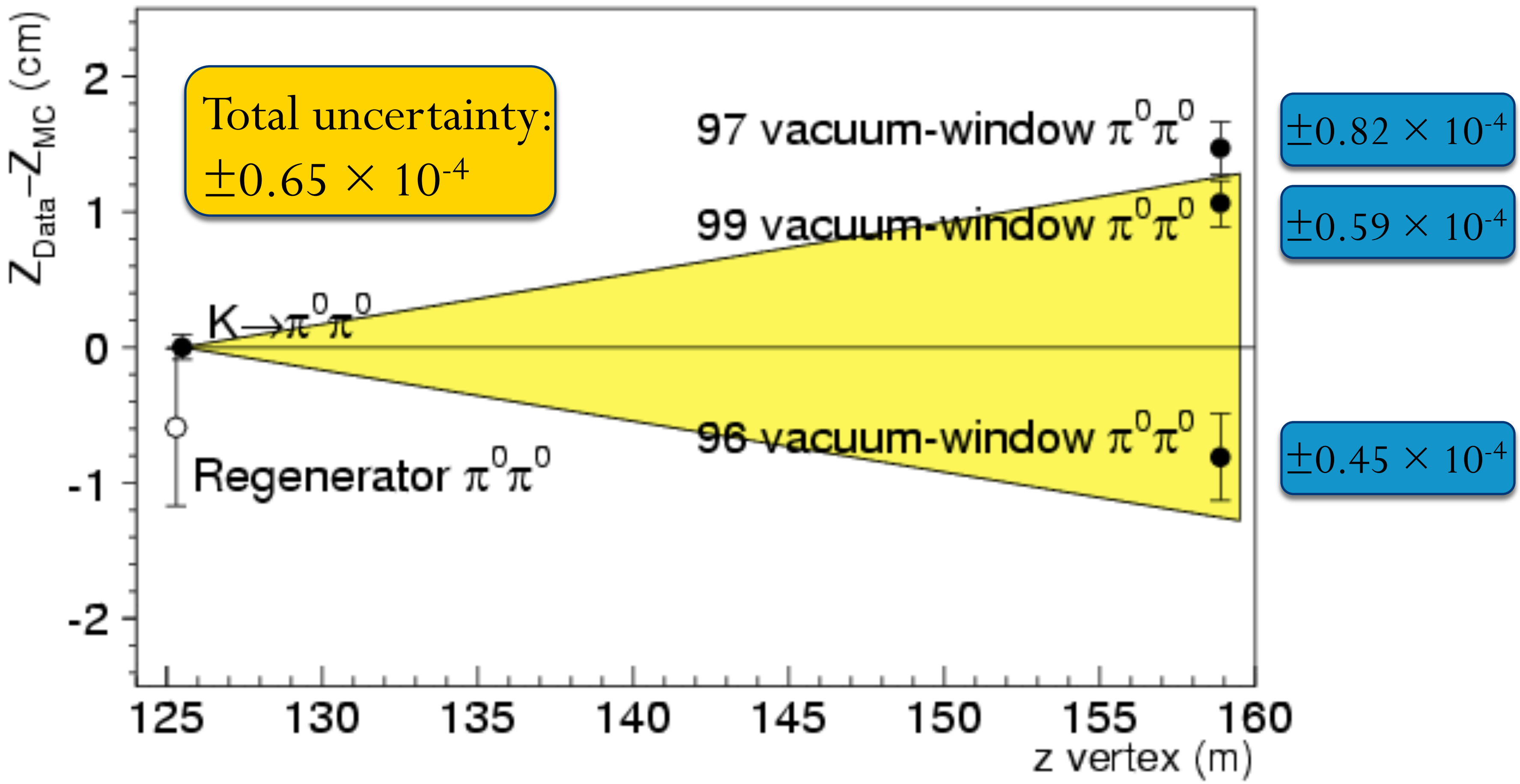
Reduced from $\pm 0.66 \times 10^{-4}$ in 2003

Uncertainty from Energy Scale

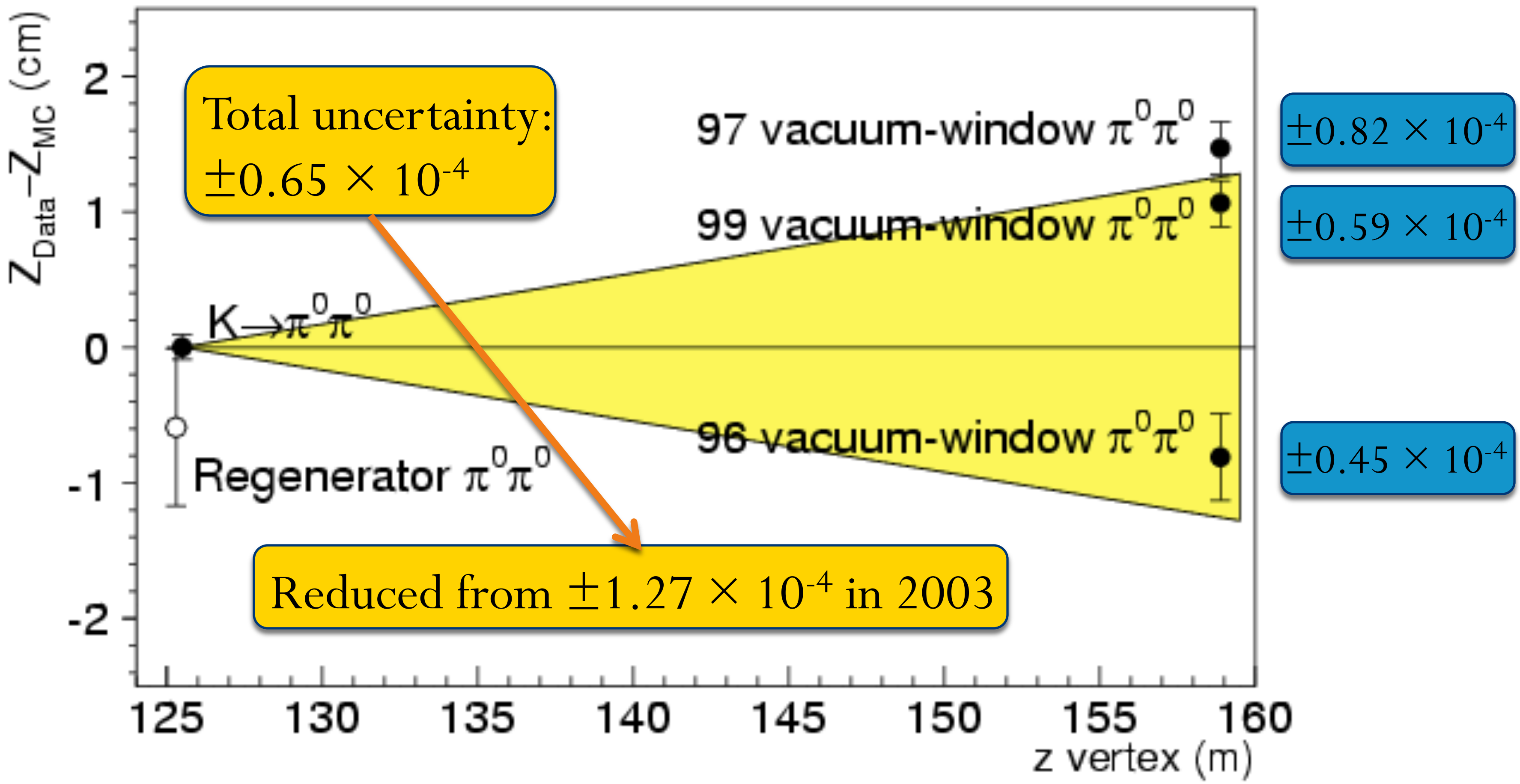


- Check energy scale by studying hadronic interaction events in regenerator and vacuum window
- Data and MC match within errors at regenerator
- Shifts required to match data and MC at vacuum window
  - 1996: -0.81 $\pm$ 0.32 cm
  - 1997: 1.47 $\pm$ 0.19 cm
  - 1999: 1.06 $\pm$ 0.17 cm

Uncertainty from Energy Scale

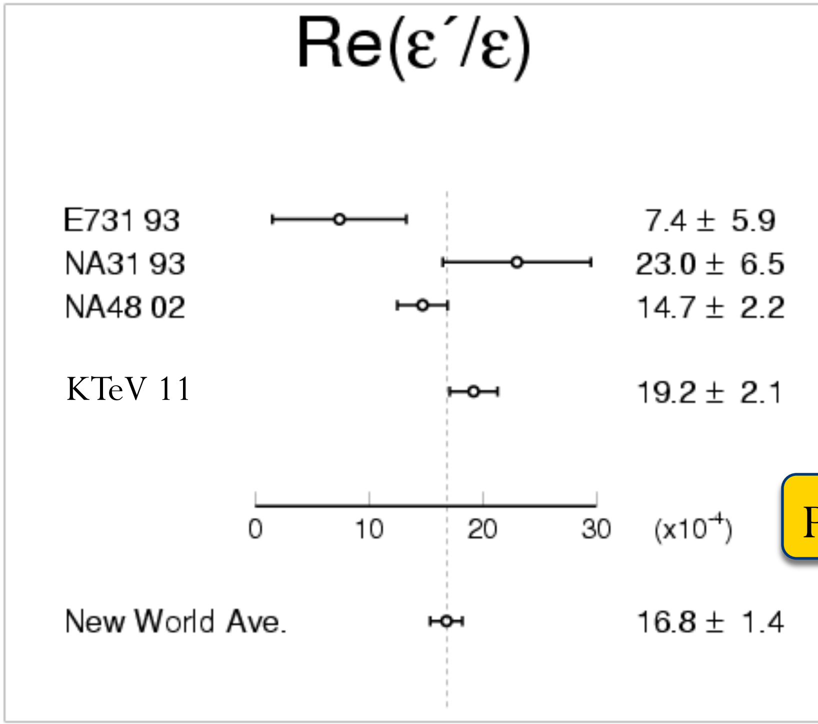


Uncertainty from Energy Scale



KTeV Results

Re(ε′/ε) Result

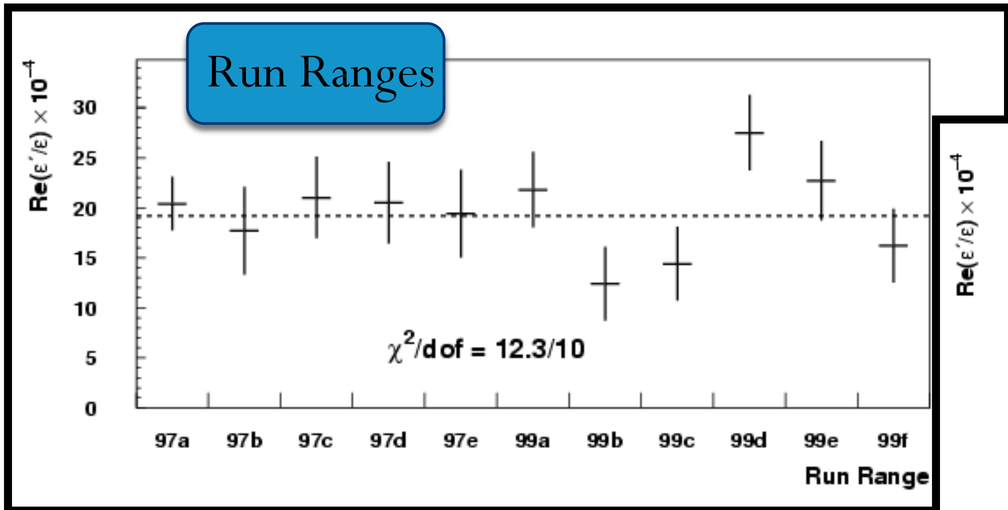


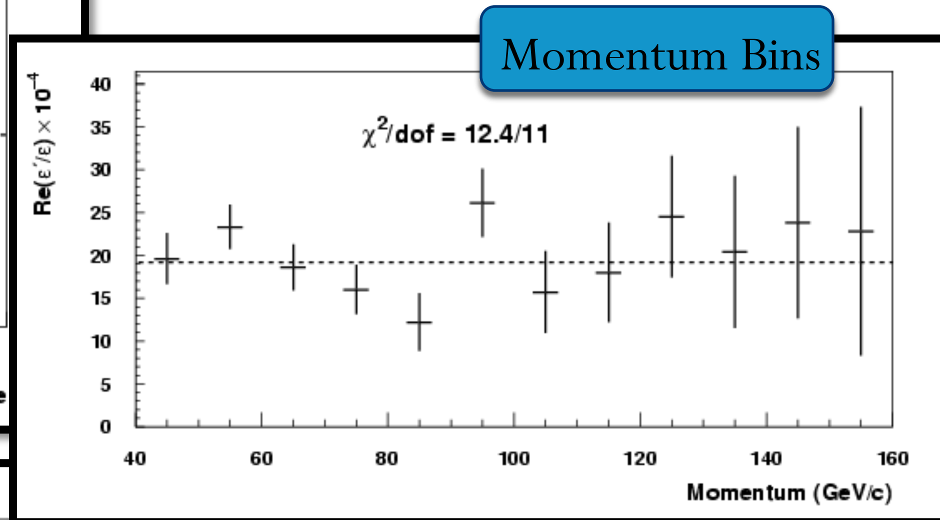
Probability: 13%

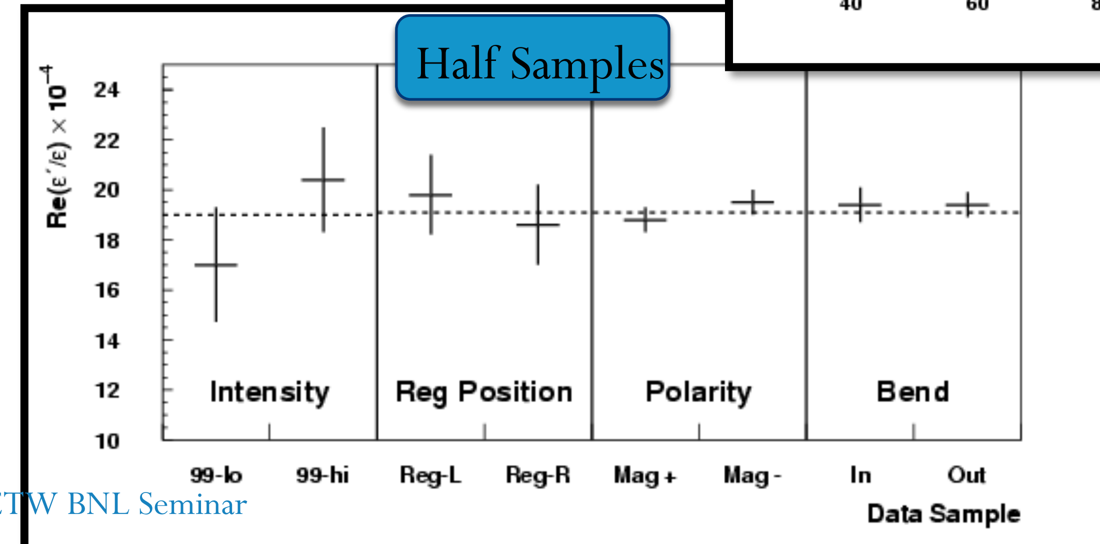
$$\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(stat) \pm 1.8(syst)] \times 10^{-4}$$

$$= (19.2 \pm 2.1) \times 10^{-4}$$

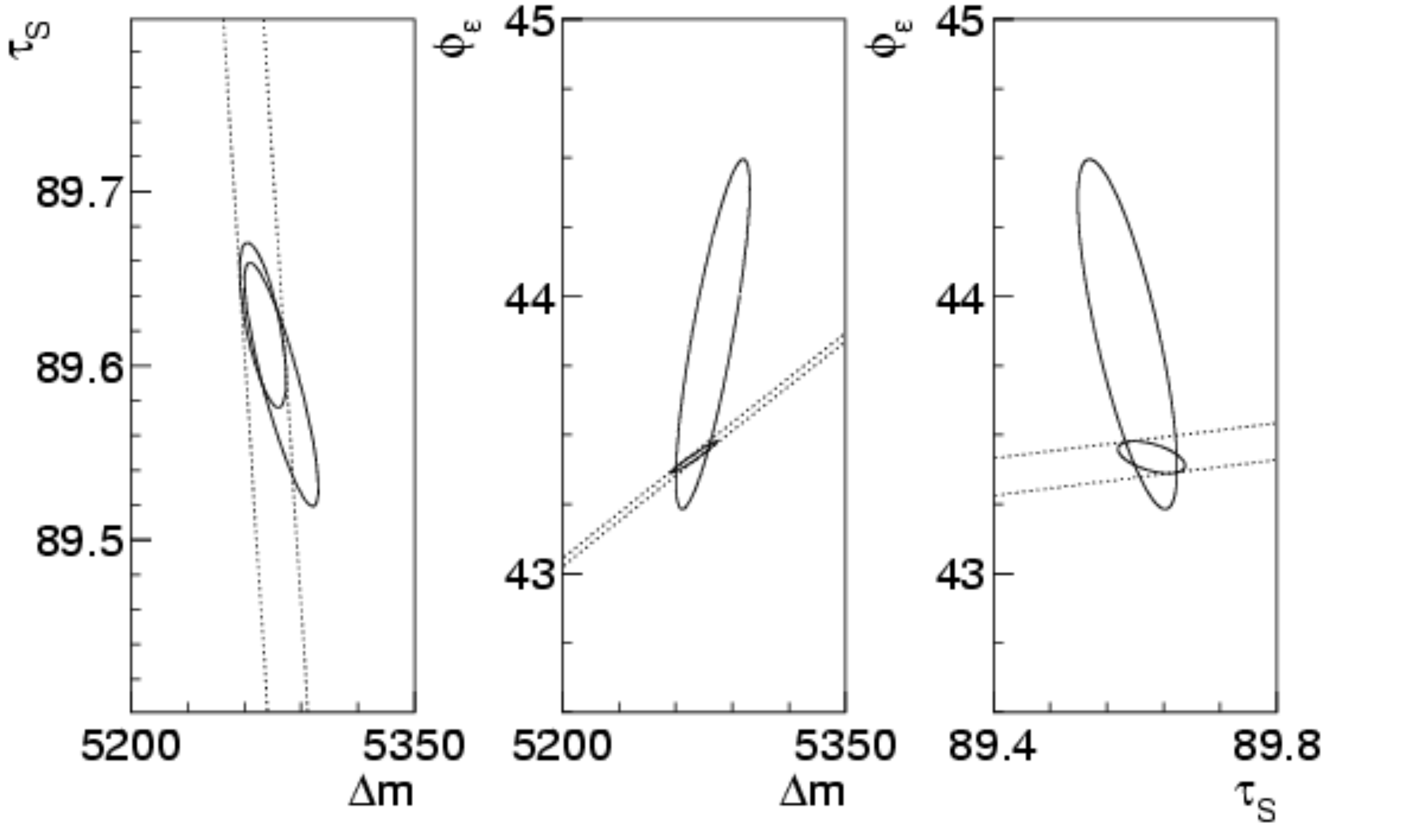
Re(ε′/ε) Result: Crosschecks







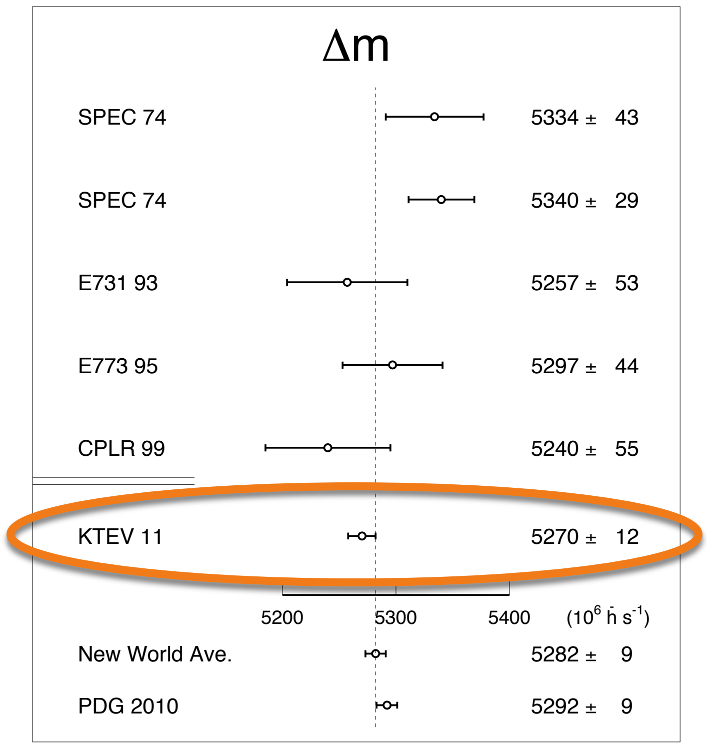
Kaon Parameter Results

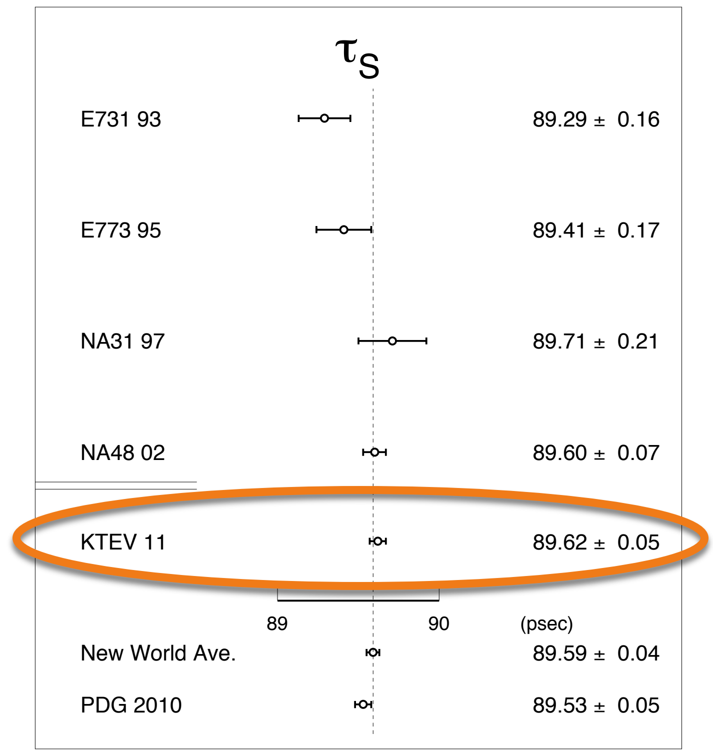


No CPT assumption:
$\Delta m = (5279.7 \pm 19.5) \times 10^6\ \hbar s^{-1}$
$\tau_S = (89.589 \pm 0.070) \times 10^{-12}$ s

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

Kaon Parameter Results: Δm and τ_S



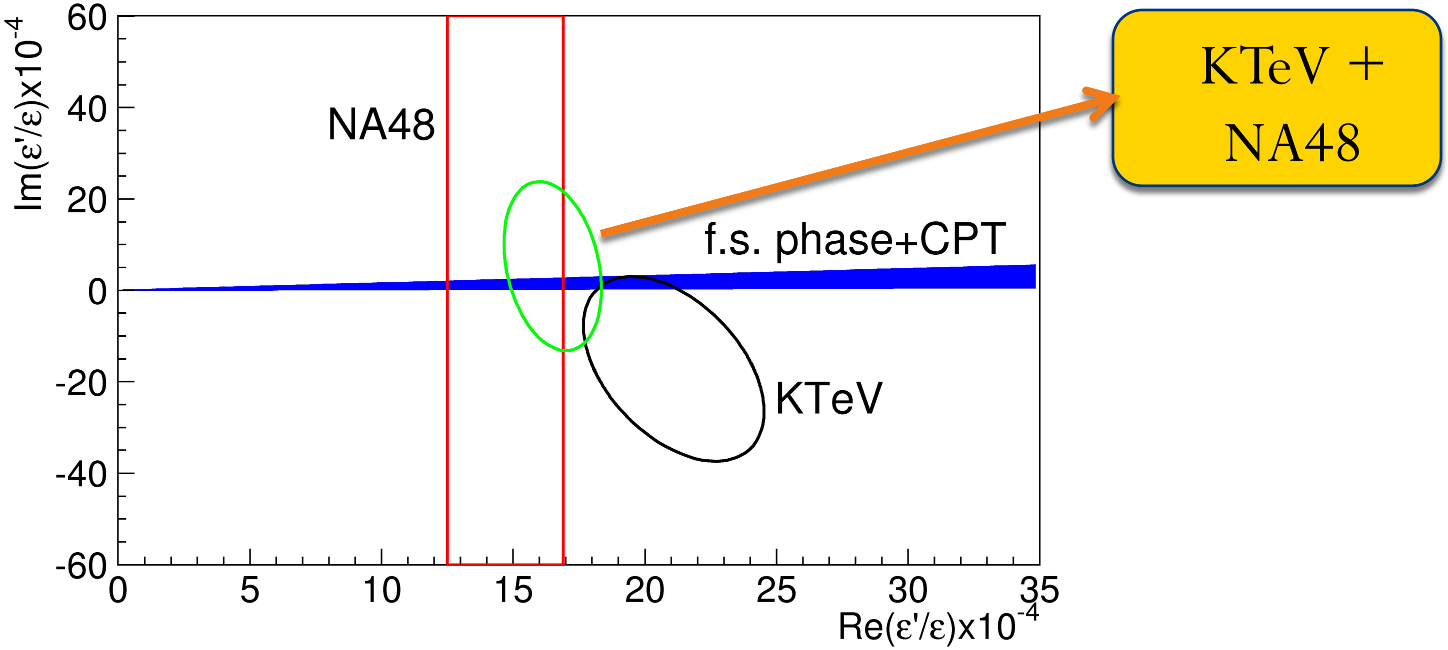


KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6\ \hbar s^{-1}$

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

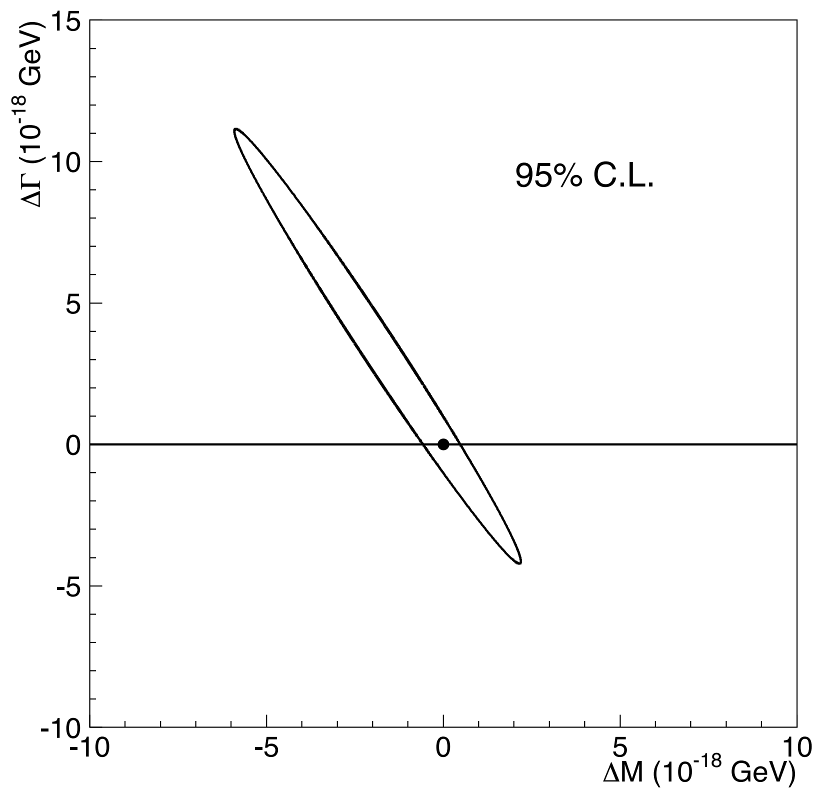
Kaon Parameter Results: CPT Tests

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



K^0-$\overline{K^0}$ Mass Difference

- Use Bell-Steinberger and KTeV measurements to place limit on K^0-$\overline{K^0}$ mass difference (ΔM)
- Non-zero $\Delta M \rightarrow$ CPT violation
- Largest contribution comes from $K_{L,S} \rightarrow \pi^+\pi^-$ and $K_{L,S} \rightarrow \pi^0\pi^0$
- $\Delta M < 4.8 \times 10^{-19}$ GeV/c^2 (95% C.L., $\Delta\Gamma = 0$)



KTeV Results: Summary

- $\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
- $\Delta m = (5269.9 \pm 12.3) \times 10^{6}\ \hbar s^{-1}$
- $\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s
- $\phi_\varepsilon = (43.86 \pm 0.63)°$
- $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$
- $\Delta\phi = (0.30 \pm 0.35)°$
- $\left|M_{K^0} - M_{\overline{K}^0}\right| < 4.8 \times 10^{-19}$ GeV/c^2 at 95% C.L.

Assuming CPT

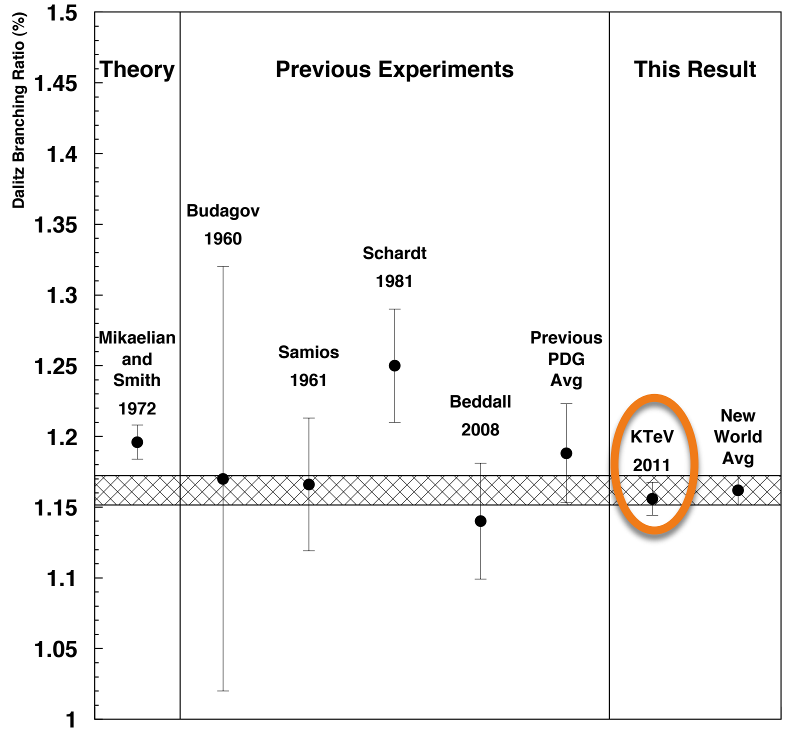
No CPT assumption

Consistent with CPT symmetry

The Future of KTeV

Dalitz Branching Ratio Measurement

$$K_L \to \pi^0 \pi^0 \pi^0$$
$$\quad \hookrightarrow e^+ e^- \gamma$$



- E. Abouzaid thesis (U.Chicago)
- ~60k Dalitz decays
- PRD to be submitted this year

$$\frac{B\left(\pi^0 \to e^+ e^- \gamma\right)}{B\left(\pi^0 \to \gamma\gamma\right)} = (1.1559 \pm 0.0116)\%$$

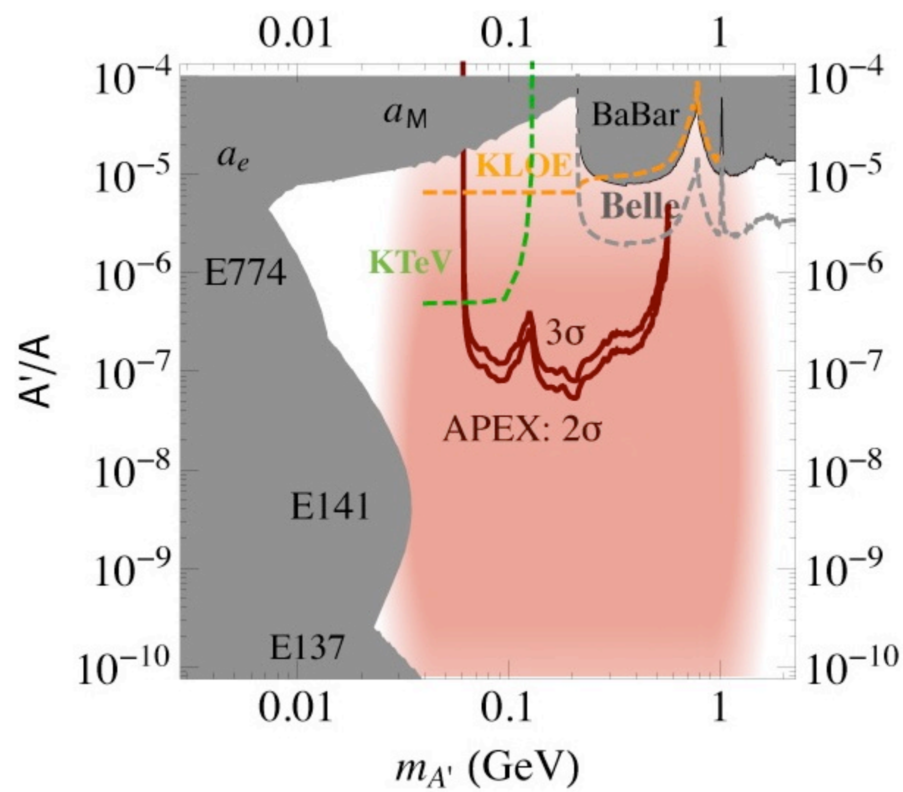
Continuing access to KTeV data

- Aging computers difficult/impossible to maintain
- Analysis software/computing infrastructure designed for older machines
- Data still valuable
  - Stored in dCache/Enstore at FNAL
- Use VirtualBox to create 'kopy' – a virtual Linux machine capable of running KTeV software
  - M. Ronquest (LANL)
  - It works!

http://www.virtualbox.org/

Dark Photons

- A': same interactions as SM photon with reduced coupling
- APEX: JLab experiment to search for A'
- KTeV search:
  - $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-$
  - Signal would appear as resonance above continuum in e^+e^- invariant mass distribution
  - Expected sensitivity based on $K_L \rightarrow 3\pi^0_D$ decays used in measurement of $\pi^0 \rightarrow e^+e^-$ branching ratio
    - R. Niclasen thesis (U. Colorado)



R. Essig, JLab 2010

Conclusion

- Re(ε'/ε) measured to 10%
  - Re(ε'/ε) $= (19.2 \pm 2.1) \times 10^{-4}$
- Precise measurements of kaon parameters Δm and τ_S
  - $\Delta m = (5269.9 \pm 12.3) \times 10^{6}\, \hbar s^{-1}$
  - $\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s
- Phase measurements consistent with CPT symmetry
- Precise π^0 Dalitz branching ratio
  - $B(\pi^0 \to e^+e^-\gamma)/B(\pi^0 \to \gamma\gamma) = (1.1559 \pm 0.0116)\%$
- Dark photons to come?

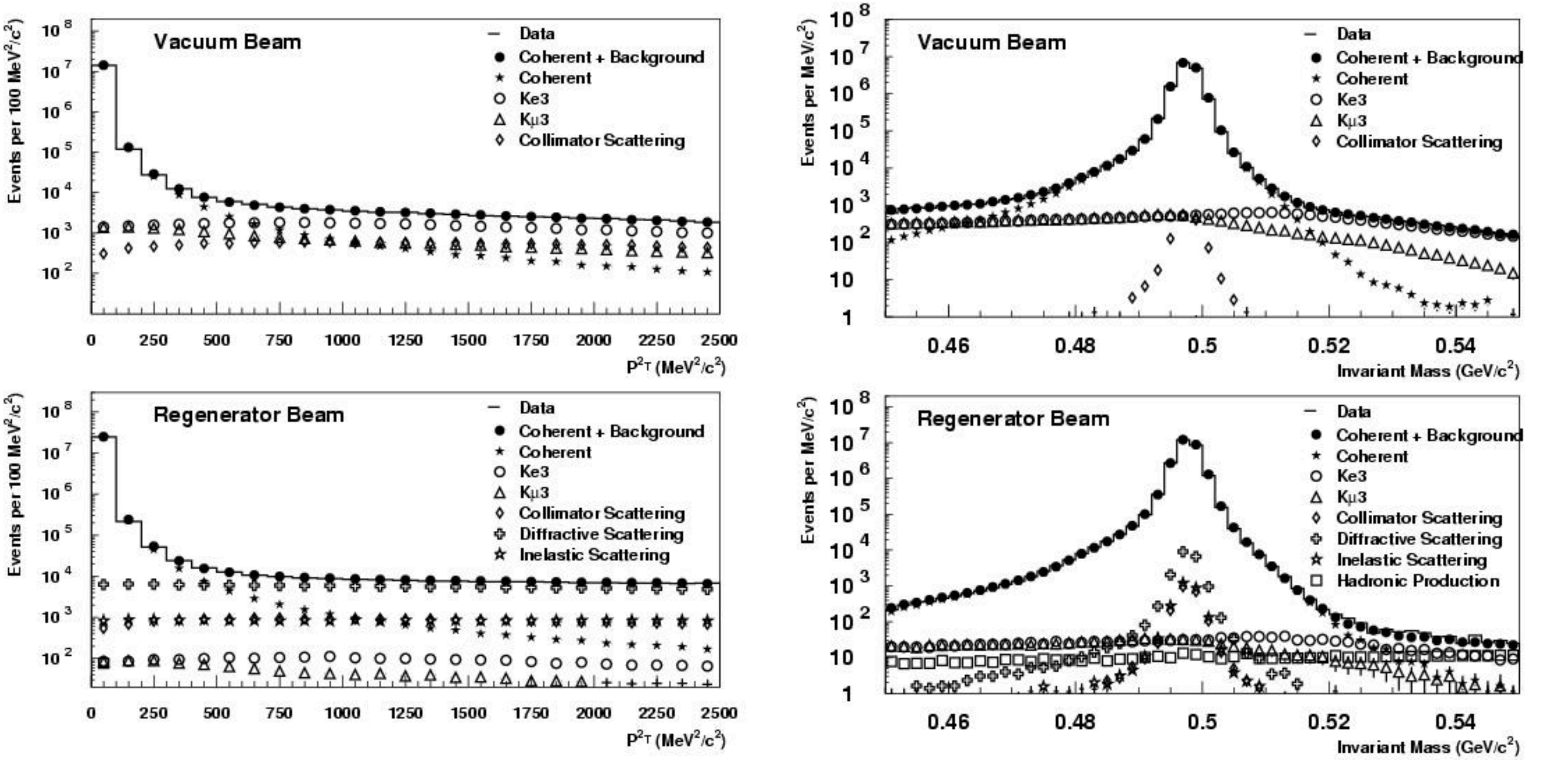
Extra Slides

Charged Mode Background

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

Charged Mode Background

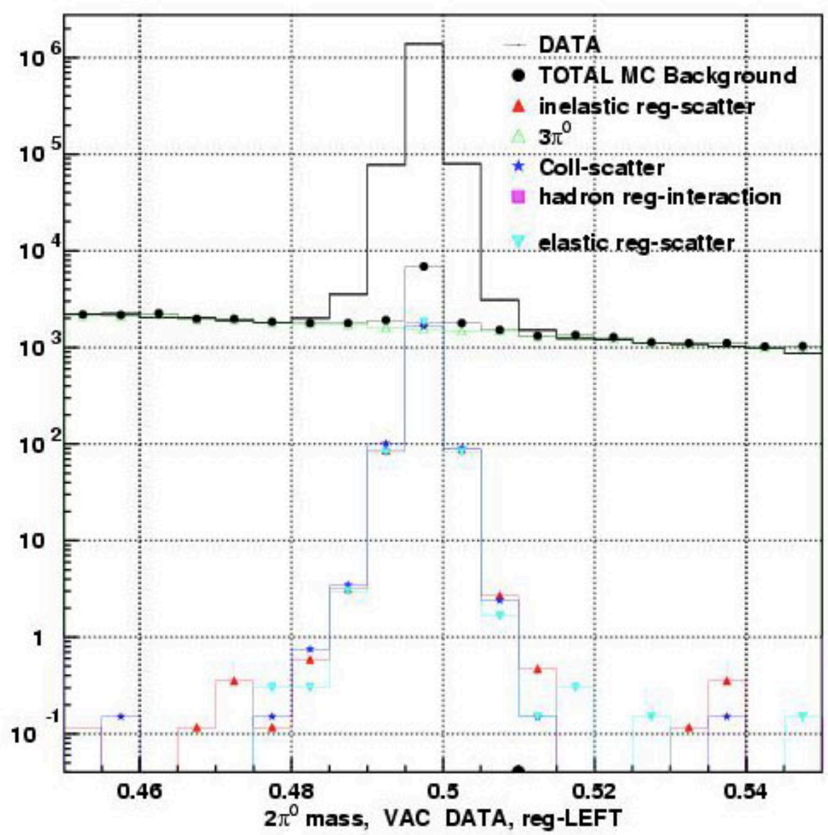


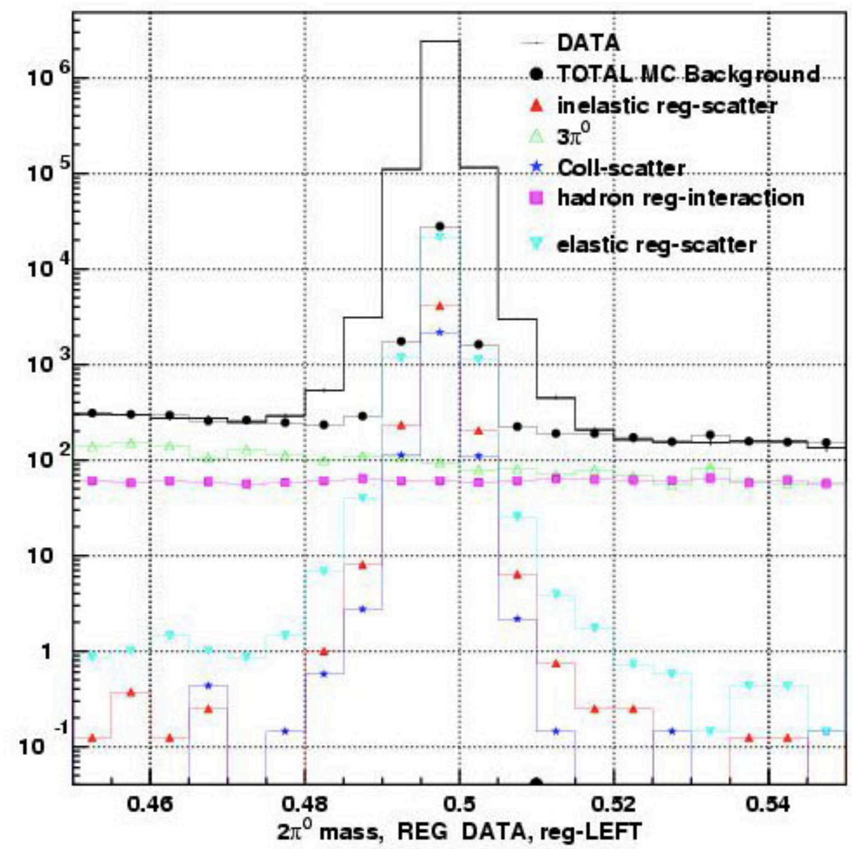
Neutral Mode Background

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%

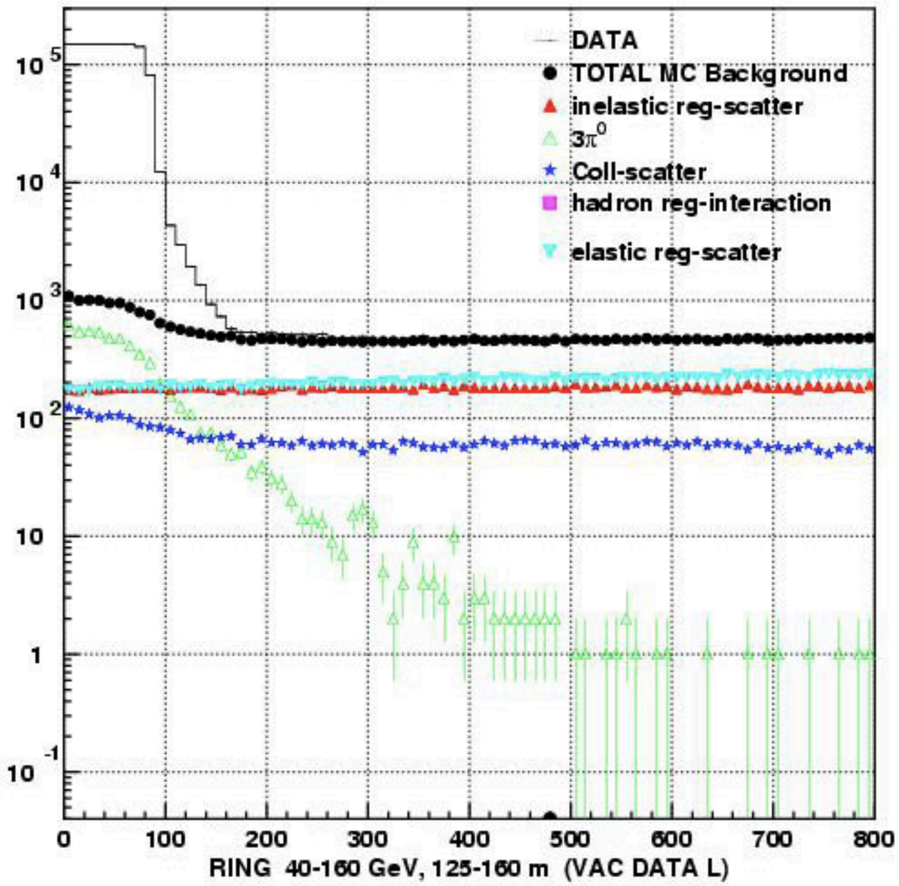
Table 5.3: Summary of $K \to \pi^0\pi^0$ background levels. Note that photon mispairing is not subtracted from the data and is not included in the total background sum.

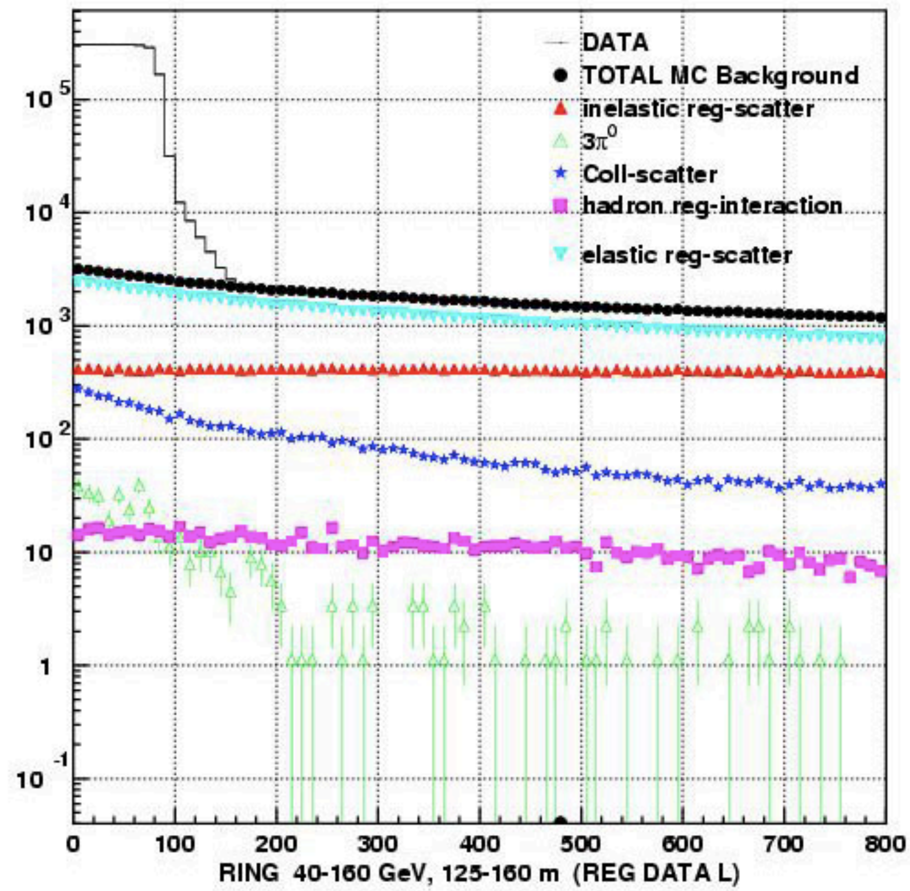
Neutral Mode Background





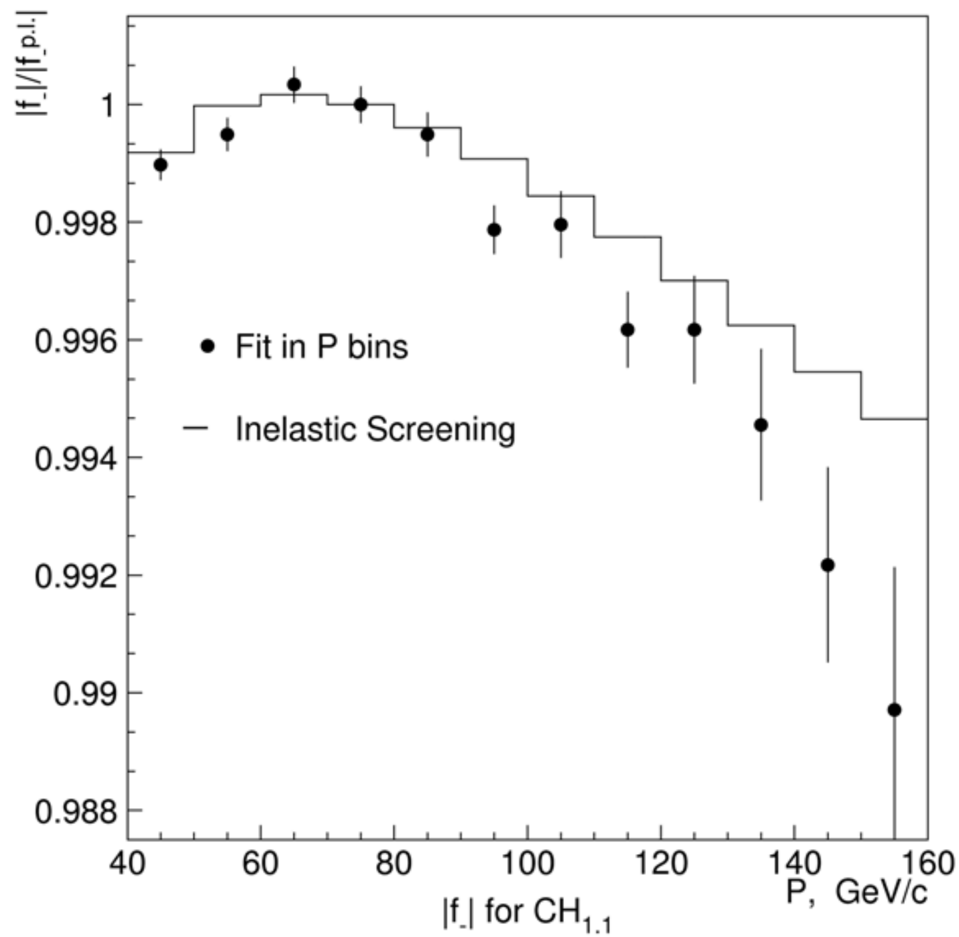
Neutral Mode Background





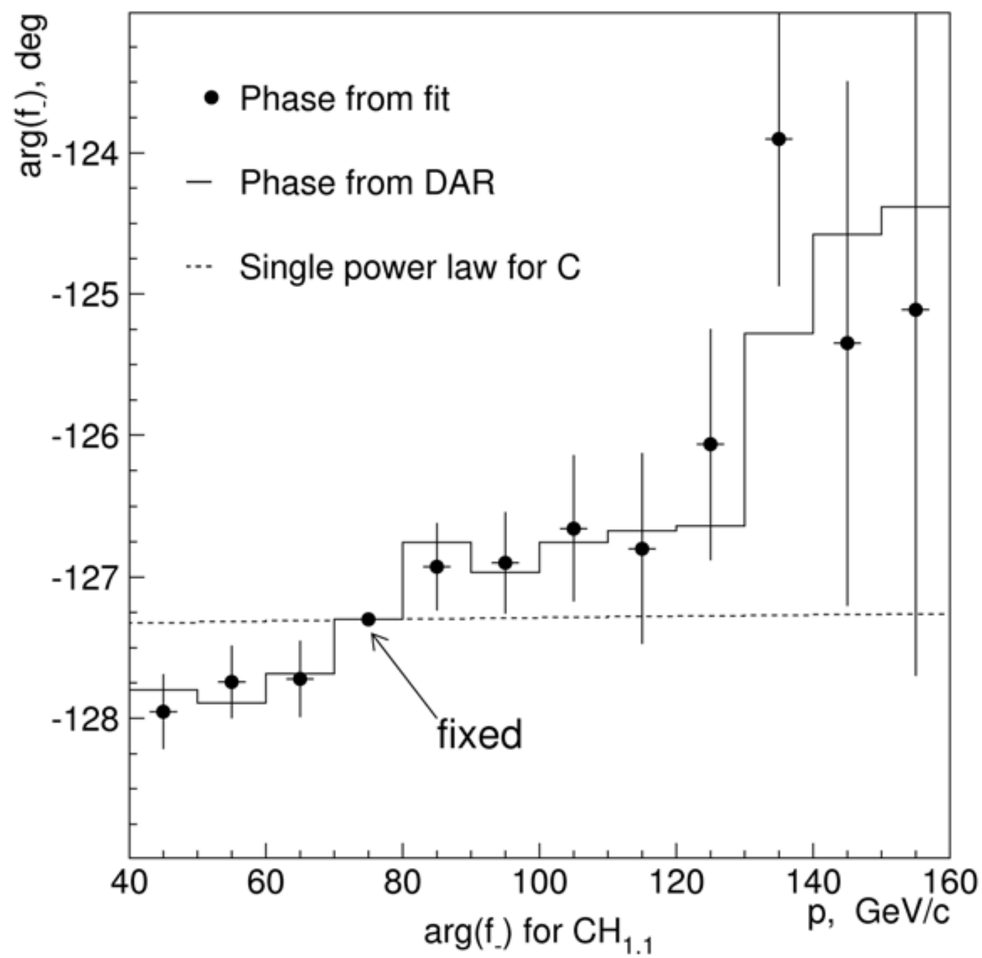
Screening Corrections

- Regeneration described by power law in fit
- Nuclear screening corrections required
  - Use elastic and inelastic models
- Check corrections by fitting regeneration amplitude in p bins
- Good agreement at low momentum



Screening Corrections

- For p binned fit, evaluation 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



Regeneration

$$\rho = i\pi N L f_{-} g(L)$$

$$f_{-} \equiv \hbar \frac{f(0) - \overline{f}(0)}{p}$$

$$|f_{-}(p)| = |f_{-}(70\ GeV/c)| \left(\frac{p}{70\ GeV/c} \right)^{\alpha}$$

Analyticity $\phi_f = -\frac{\pi}{2}(2 + \alpha)$

Regenerator Scattering Background

$$\frac{d^3 N_{regscat}}{dp_T{}^2\, d\tau\, dp_K} = M(p_K) \times T(p_K) \times S(p_K) \times \sum_{j=1}^{6} A_j e^{\alpha_j p_T{}^2} \left| \hat{\rho}_j e^{\Lambda_S t} + \eta e^{\Lambda_L t} \right|^2$$

- $M(p_K)$: Malensek energy spectrum
- $T(p_K)$: Kaon transmission
- $S(p_K)$: Absorber scatter correction

1. Inelastic K_S-like scattering
2. Lead scattering
3. Single carbon scattering
4. Multiple carbon scattering
5. Hydrogen scattering
6. Inelastic K_L-like scattering

$\varphi_{\hat{\rho}_j}$ *and* α_j For lead scattering, have momentum dependence not explicit in this equation.