KTeV CsI Calorimeter: Performance & History

Elizabeth Worcester

Project X Physics Study

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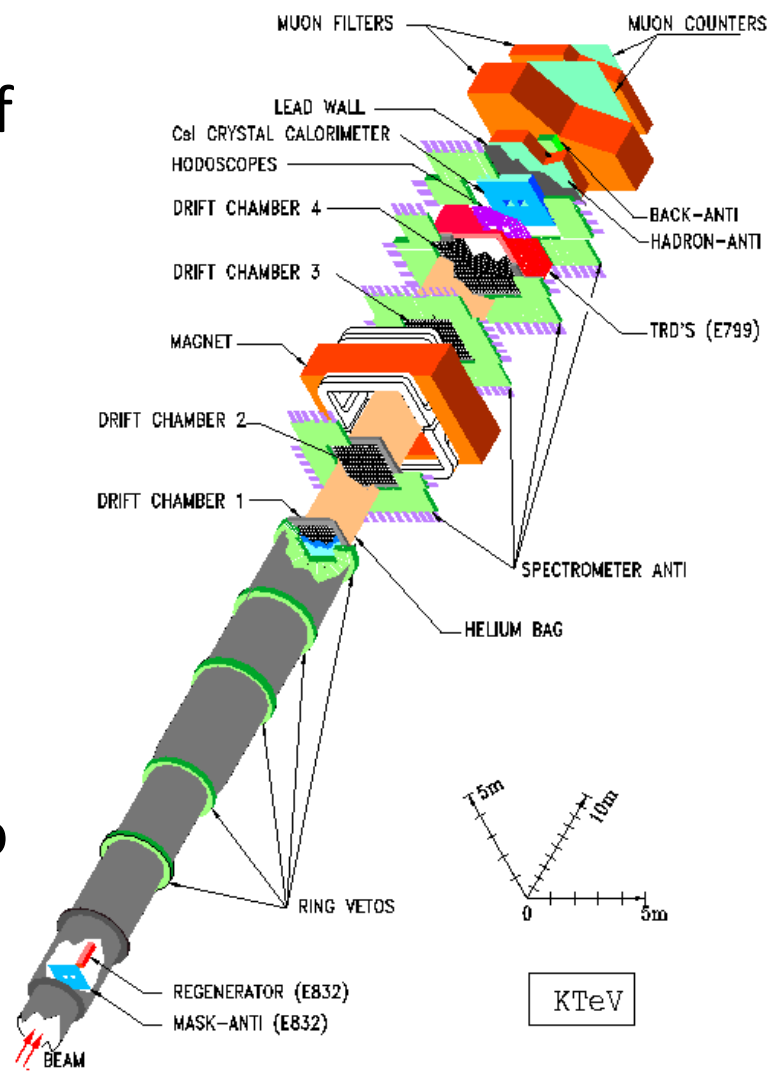
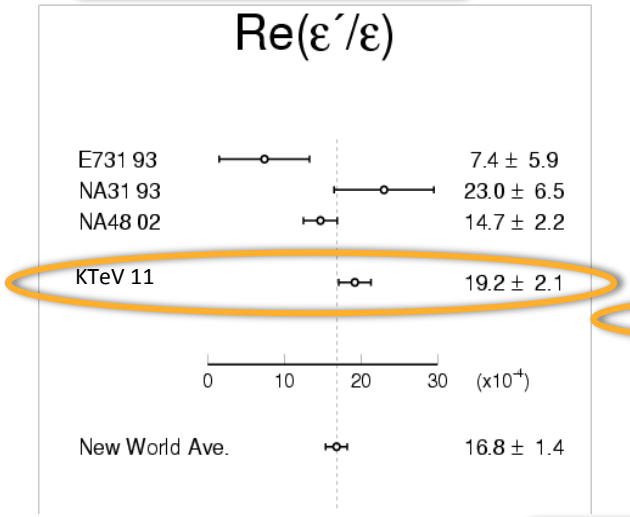
KTeV Experiment

- Precision measurement of Re(ε′/ε) (E832) and rare kaon decays (E799)
- Charged spectrometer to reconstruct $K \rightarrow \pi^+\pi^-$ decays
- CsI calorimeter to reconstruct $K \rightarrow \pi^0\pi^0$ decays
- Detailed MC simulation to correct acceptance
- Collected data in 1996, 1997, and 1999

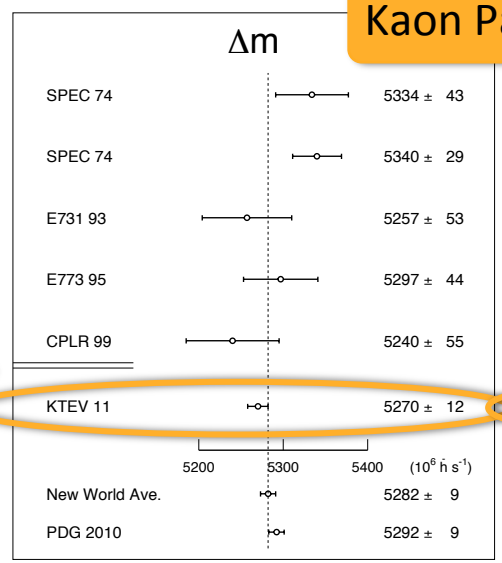


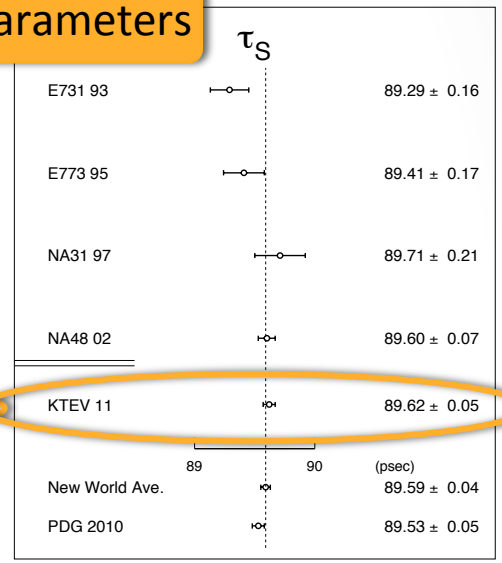
KTeV E832 Results

Direct CP Violation

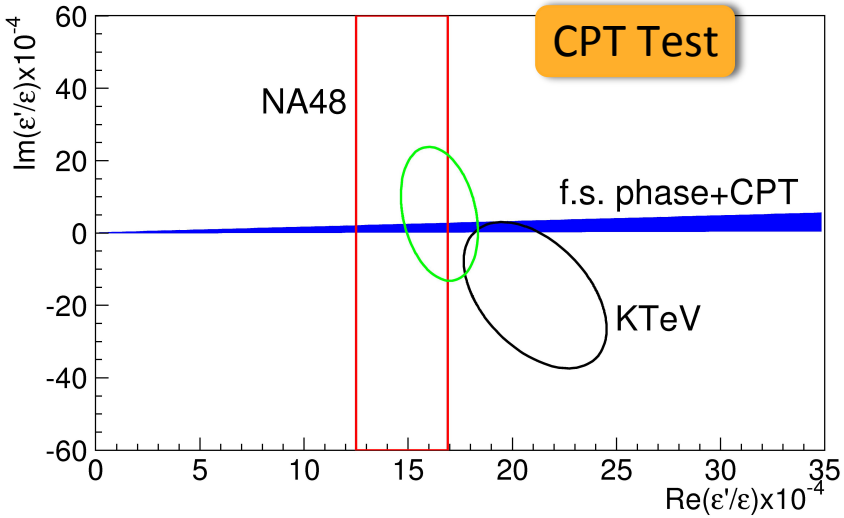


Kaon Parameters

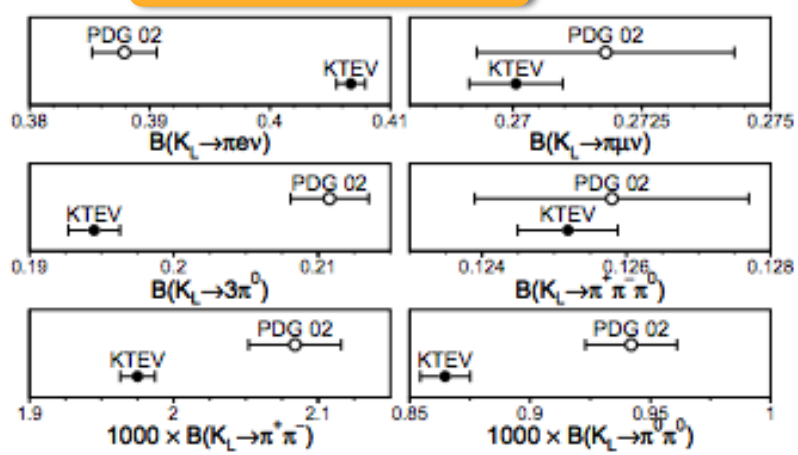




CPT Test



Vus Determination



Measuring Re(ε′/ε)

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

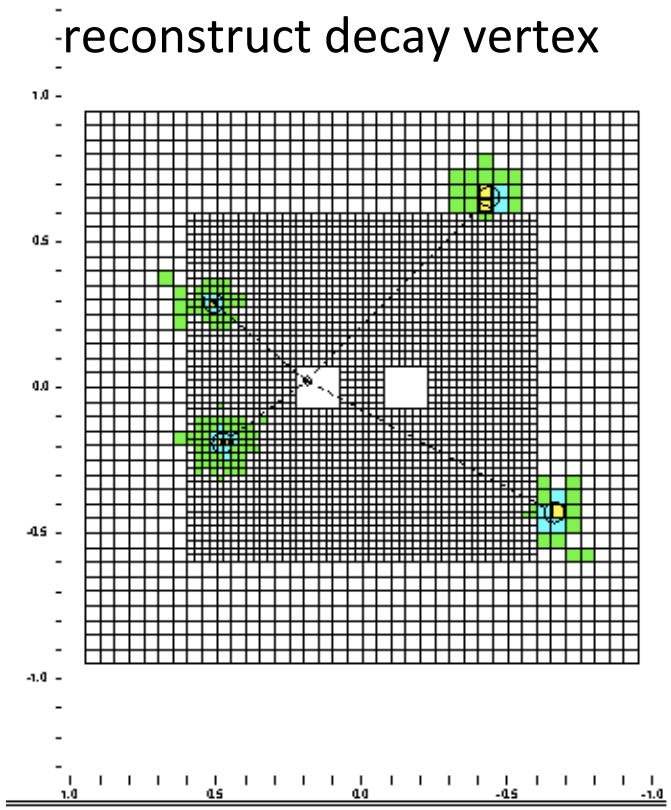
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

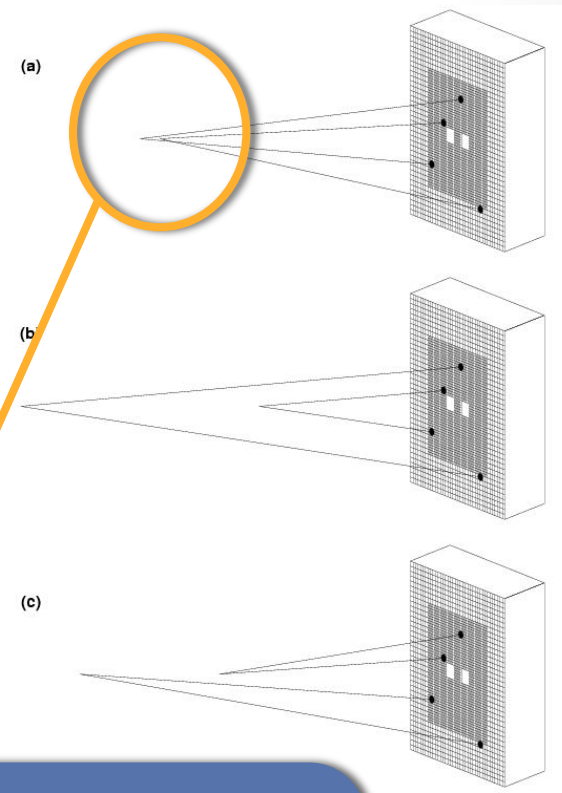
$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left(\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 - 1\right)$$

$K \rightarrow \pi^0\pi^0$ Reconstruction

Signal is 4 photon showers in calorimeter

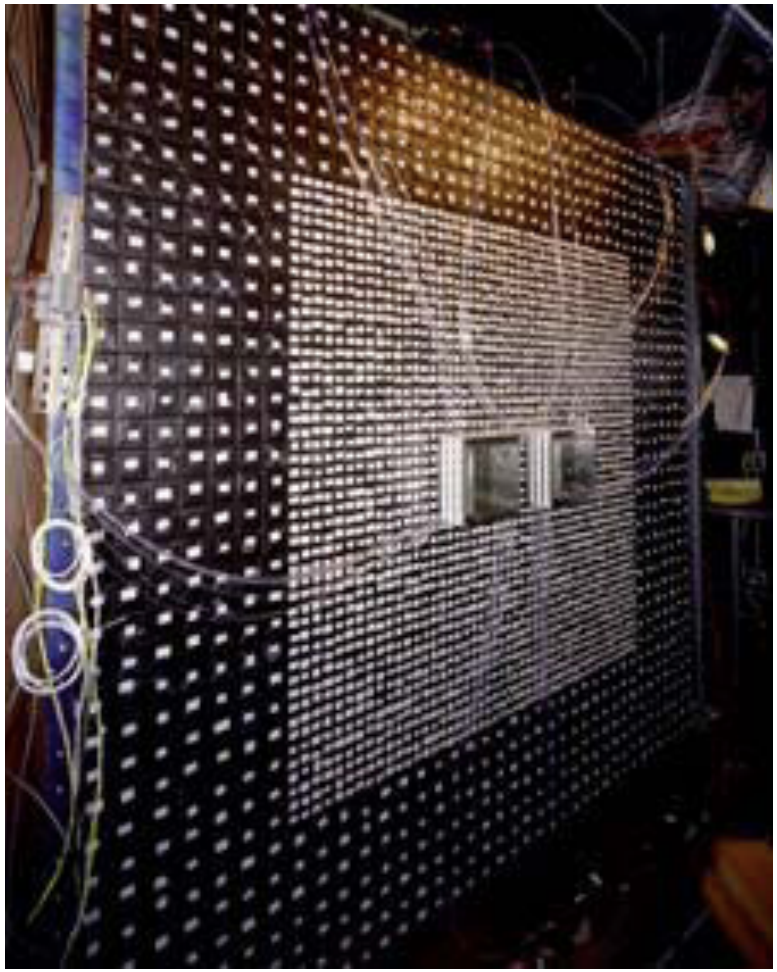
- Measure position and energy
- Use pion mass constraint to reconstruct decay vertex





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

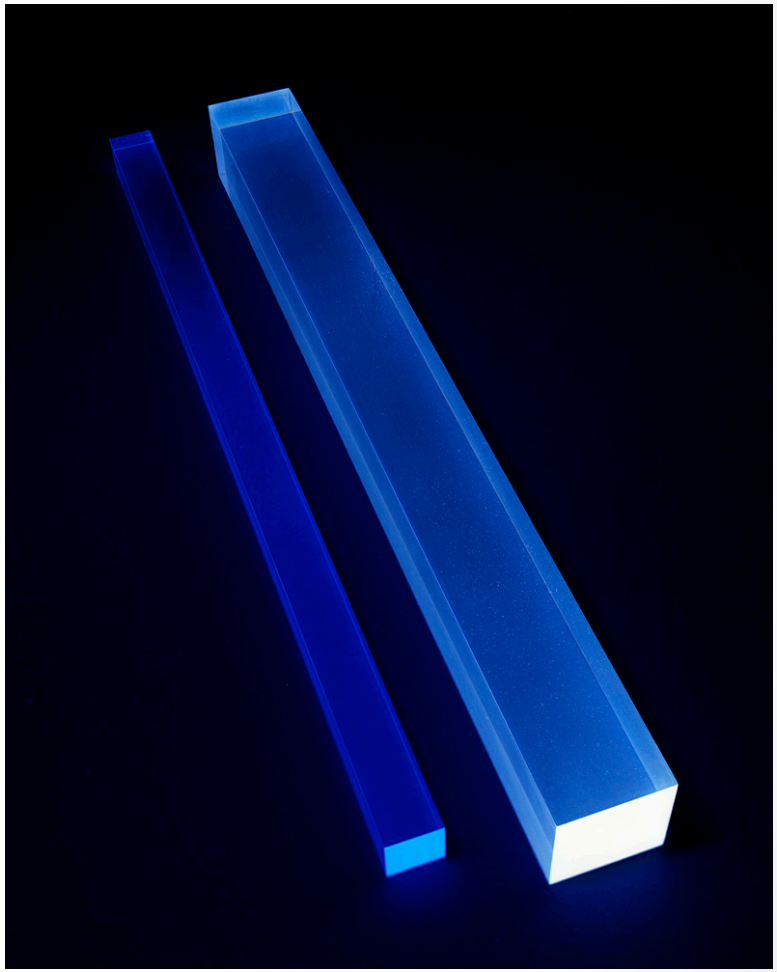
CsI Calorimeter



- 3100 pure CsI crystals viewed by PMTs
  - Small crystals 2.5×2.5×50 cm^3
  - Large crystals 5.0×5.0×50 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%

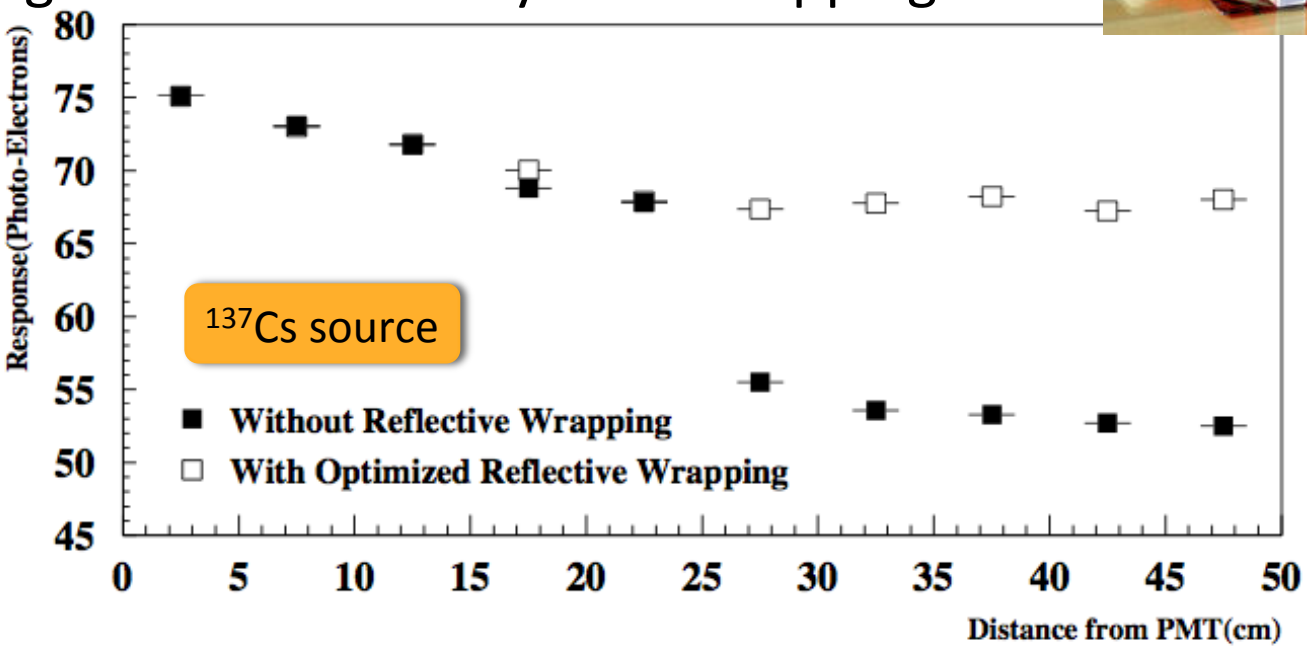
Pure CsI Crystals

- Produced by 3 manufacturers
- 2232 small crystals
  - $2.5 \times 2.5 \times 50\ cm^3$
- 868 large crystals
  - $5.0 \times 5.0 \times 50\ cm^3$
- 80% glued 25 cm crystals
- Fast scintillation component
  - 315 nm
  - decay times 10ns/36ns
  - 80% of light
- Slow scintillation component
  - 480 nm
  - decay time 1 μs
- Radiation length: 1.85 cm
- Nuclear interaction length: 36.5 cm
- Moliere radius: 3.8 cm

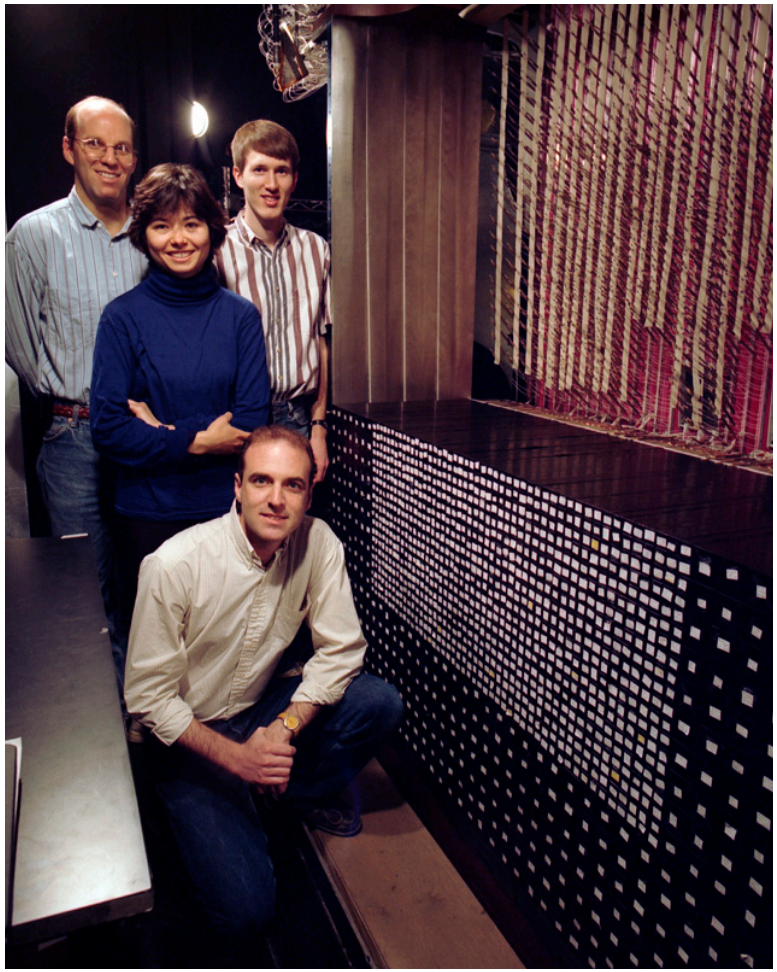


Wrapping Crystals

- Each crystal wrapped in 12 μm aluminized mylar
- Fraction of reflective wrapping tuned individually for each crystal to improve longitudinal uniformity
- Longitudinal uniformity after wrapping ~5%



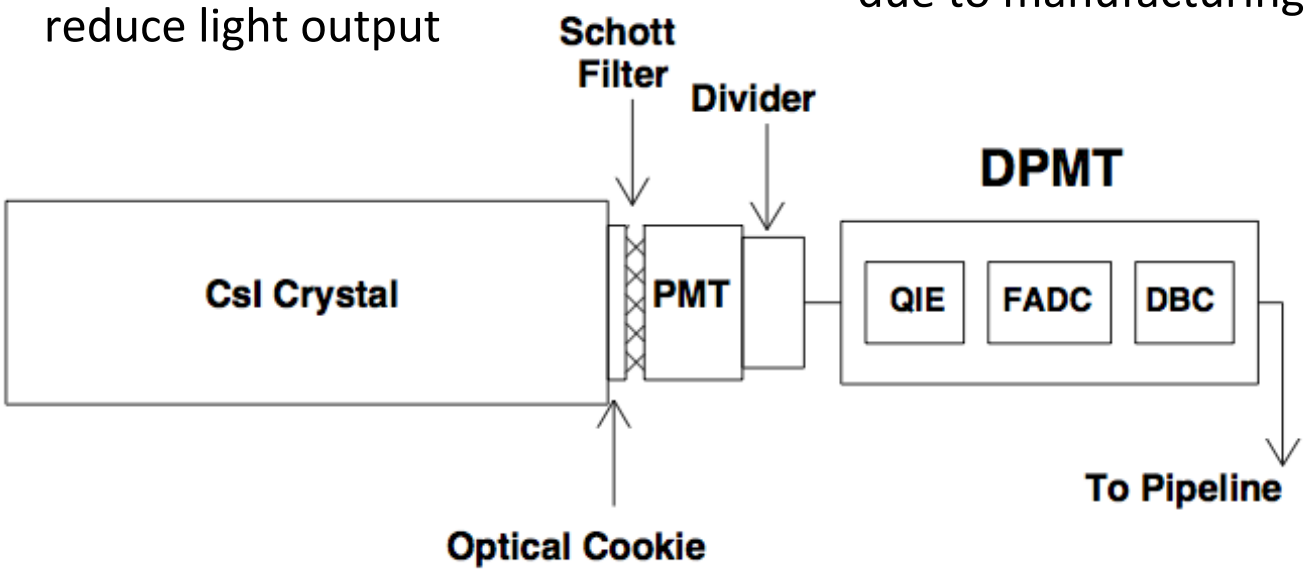
Stacking



- Location of each crystal chosen purposefully
  - Dimensions
  - Radiation hardness
  - Longitudinal uniformity
  - Reflectivity of upstream face wrapping
- Each row tested before next row stacked
- CsI blockhouse temperature/humidity controlled

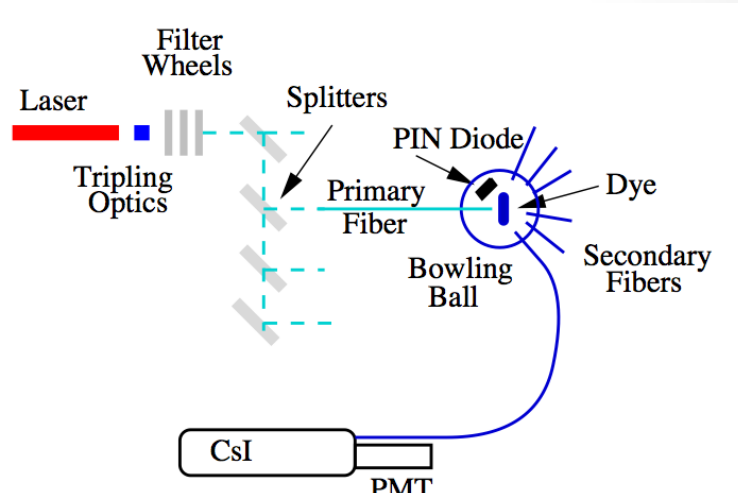
Readout

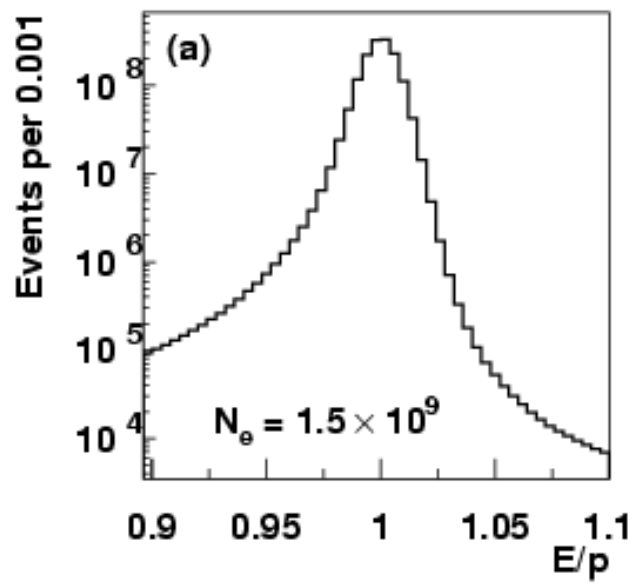
- Hamamatsu PMTS
  - 1.9 cm R5364 & 3.8 cm R5330
  - QE ~25%
- Cookie for optical coupling
- 1mm Schott UV filter
  - reduced slow scintillation component by ~50%
- High light output
  - ~75% of channels masked to reduce light output
- Location of each PMT chosen purposefully
- Custom base (DPMT)
  - Linearity better than 0.1%
  - Dynamic range ~MeV-100 GeV
  - J. Whitmore, Nucl. Instrum. Methods Phys. Res., Sect. A **409,** 689 (1998)**.**
  - Large failure rate in 1996/1997 due to manufacturing error



Calibration

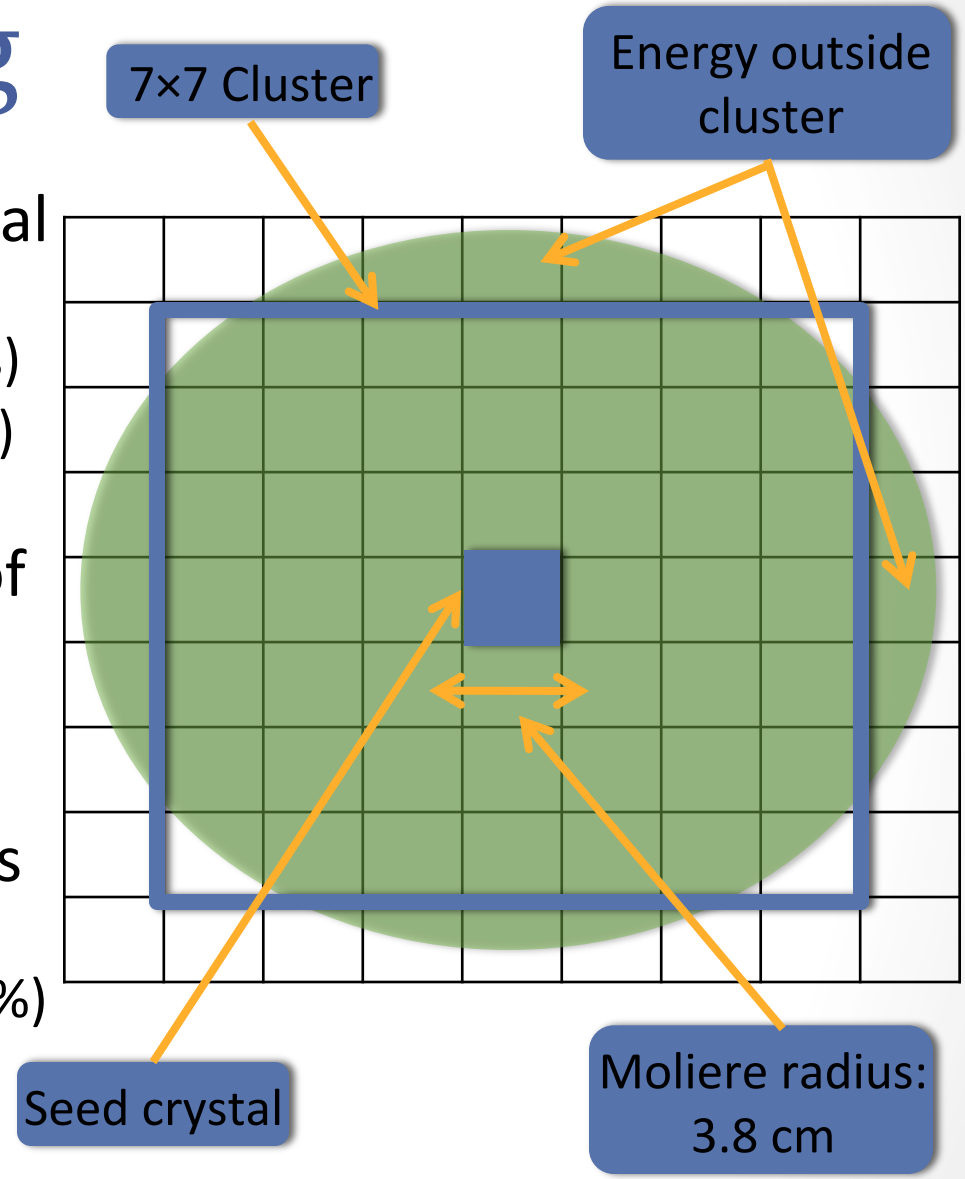
- Laser system
  - Peak wavelength 380 nm
  - Intensity scans over full dynamic range of DPMT
  - Fixed intensity flashes every second through normal data-taking
- Electron E/p
  - Use $K_L \rightarrow \pi^{\pm} e^{\mp} \nu$
  - Set energy scale and apply corrections
  - Final E/p resolution ~0.6%





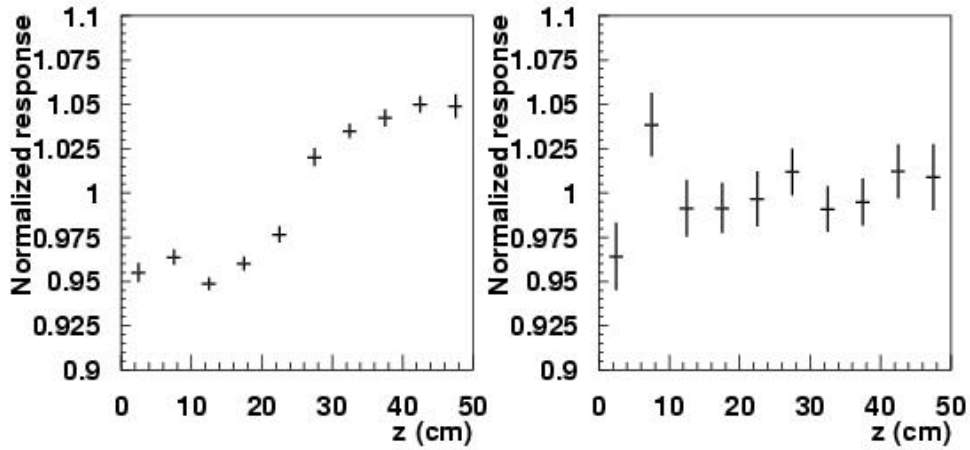
CsI Clustering

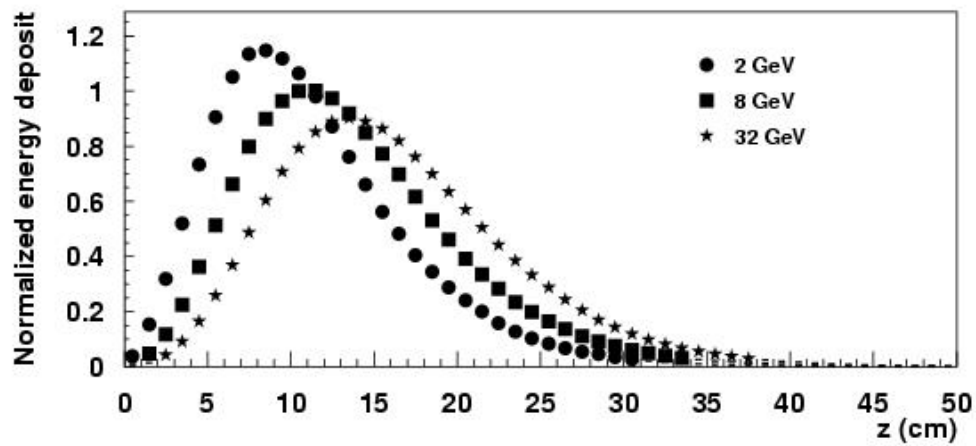
- Build clusters around local energy maxima
  - 7×7 clusters (small crystals)
  - 3×3 clusters (large crystals)
- Determine positions by comparing the fraction of energy in neighboring rows and columns
- Determine energies by summing crystal energies and applying corrections
  - Energy outside cluster (~5%)
  - Energy shared between clusters
  - Variations of CsI response



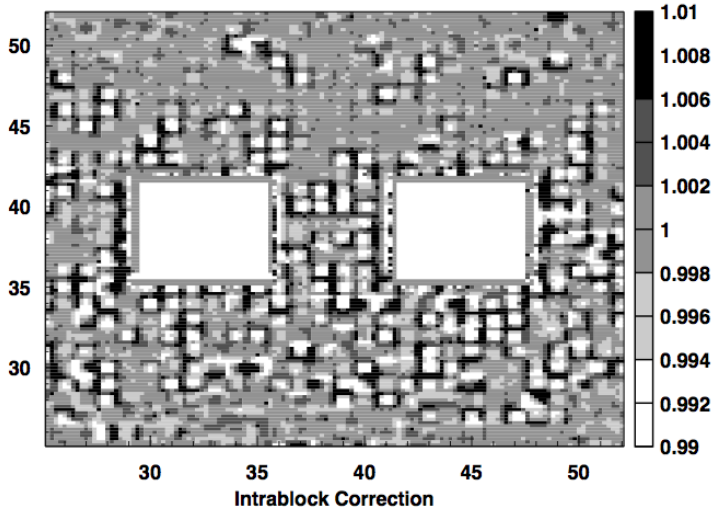
Longitudinal Uniformity Correction

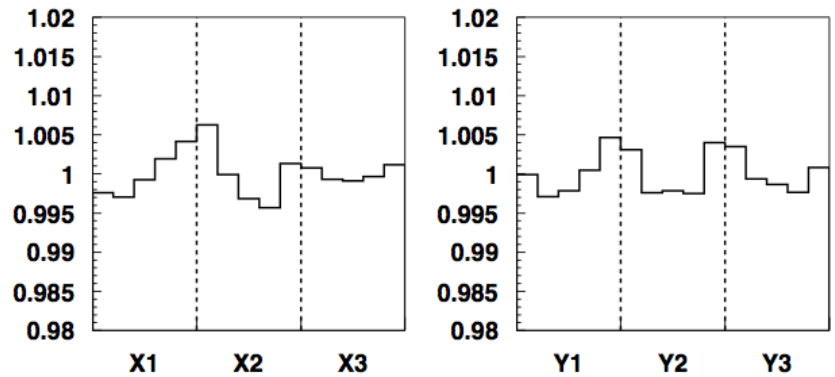
- Longitudinal response of CsI crystals uniform to ~5%
- Response of individual crystals measured in 10 bins using cosmic ray muons passing vertically through CsI
- Longitudinal shower profiles generated using GEANT3
- Longitudinal response of CsI convolved with predicted shower profile for each crystal
- Individual crystal energies corrected





Transverse Uniformity Correction

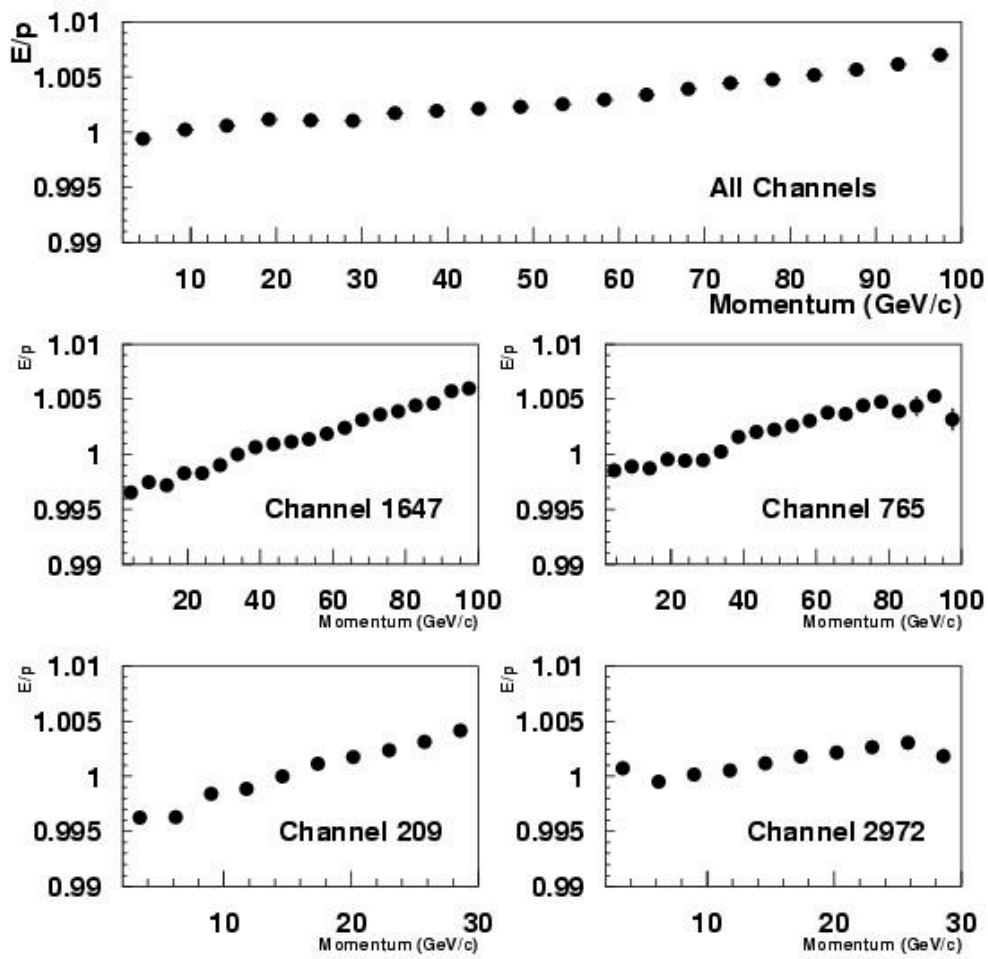




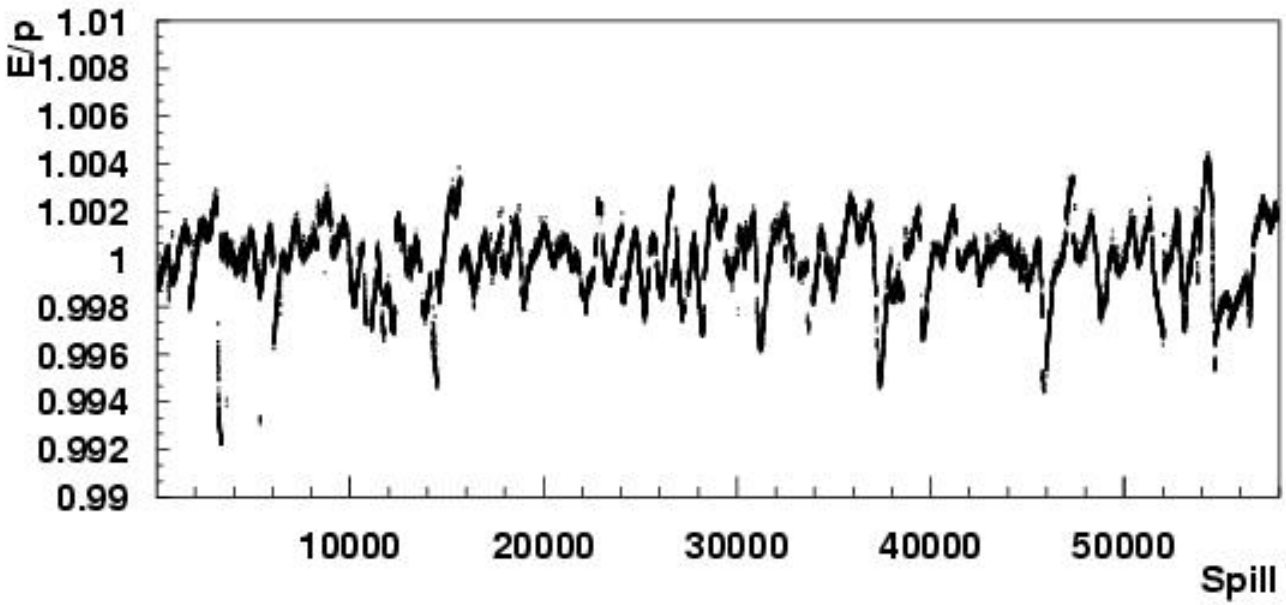
- Out-of-cone correction removes transverse variation from reconstruction
- Residual variation across face of CsI crystal (<1%)
- Never completely understood
  - Residual shortcomings of out-of-cone correction?
  - Physical effect?
- Correction based on E/p in 5x5 bins per crystal, normalized to 1 for each crystal

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 < 1%

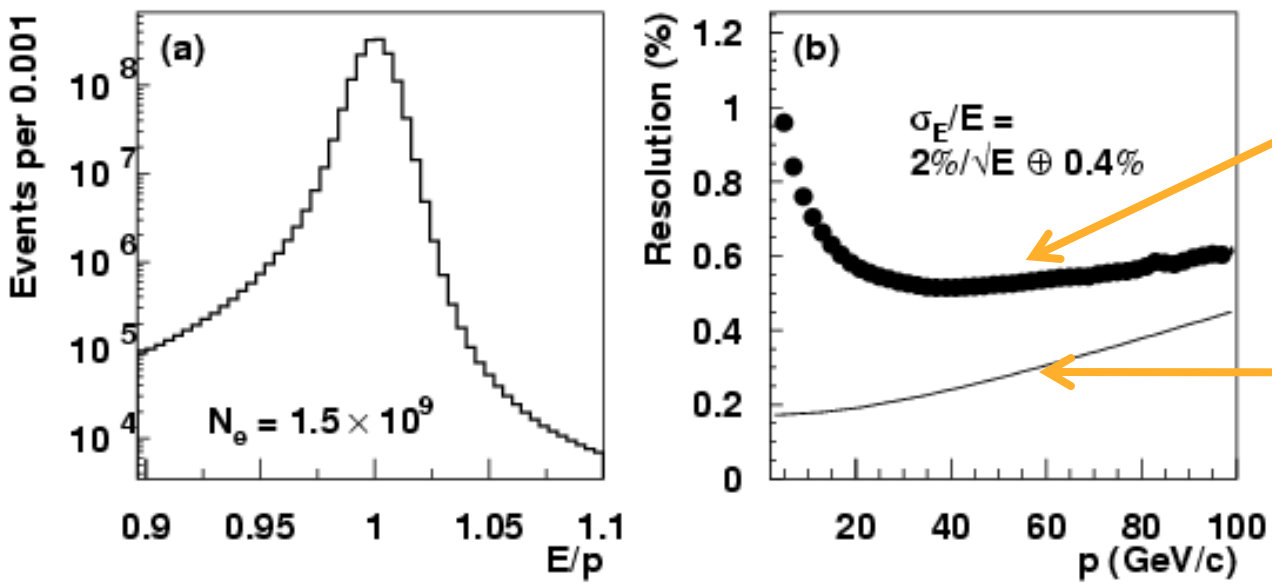


Spill-by-Spill Correction



- 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



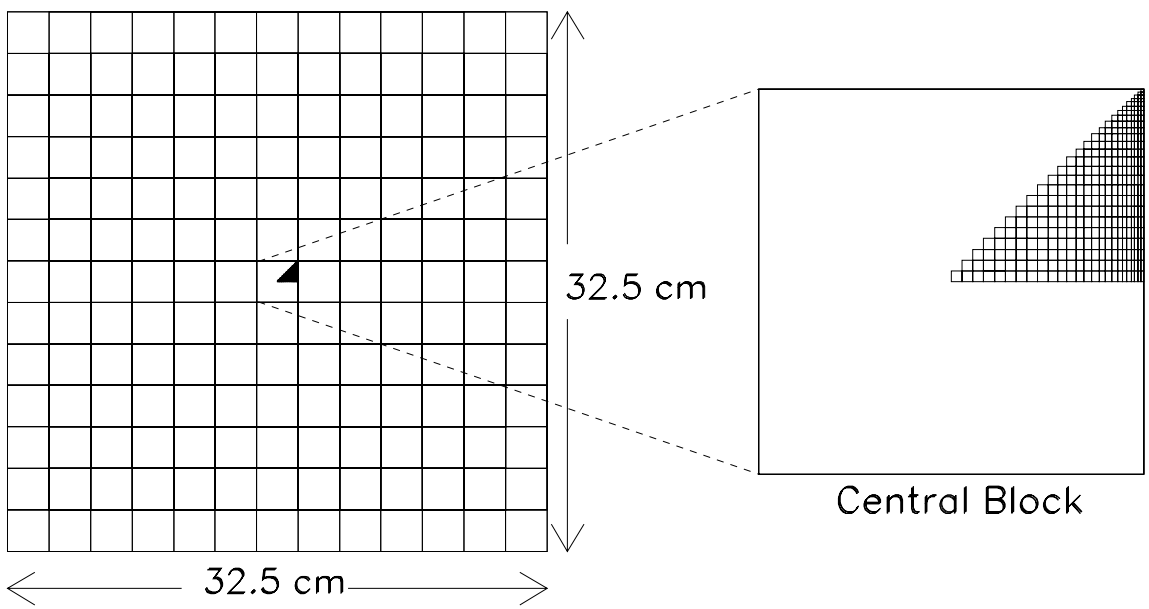
E/P resolution

Estimated momentum resolution

- 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%

EM Shower Simulation

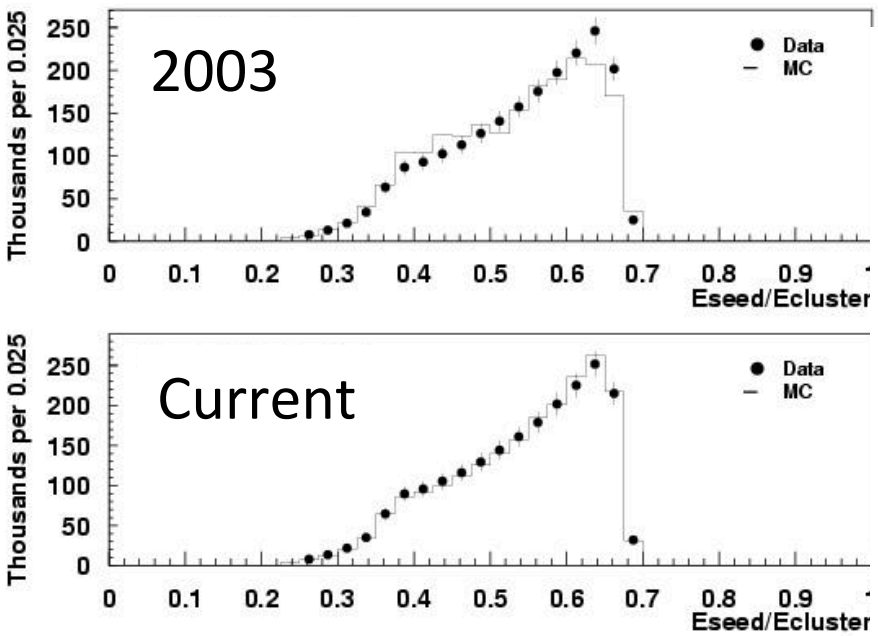
- GEANT shower library
  - 6 energy bins: (2, 4, 8, 16, 32, 64) GeV
    - Smear energy to match data resolution
    - Select bin using logarithmic interpolation
    - Scale energy in each crystal to desired energy
  - 325 position bins distributed over one octant of central crystal
    - Rotate showers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



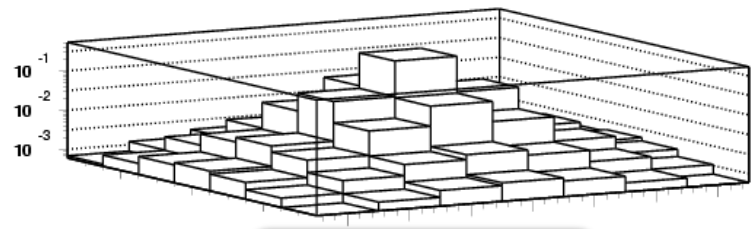
EM Shower Simulation (cont.)

- 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

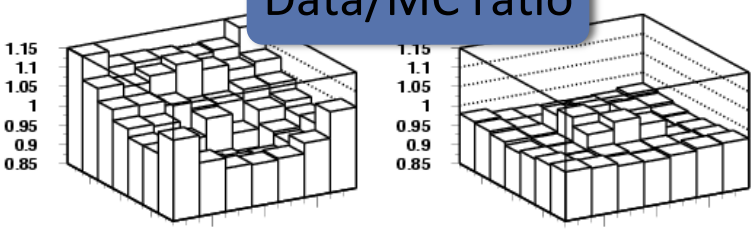
Simulation: Transverse Shower Shape



Fraction of energy per CsI crystal



Data/MC ratio

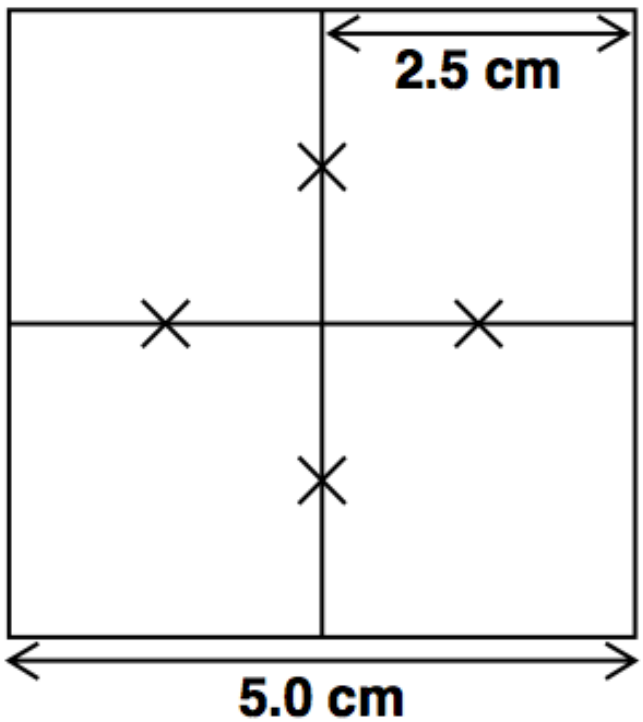


2003 Current

2003: Includes transverse energy correction to match data and MC

Current: No correction required

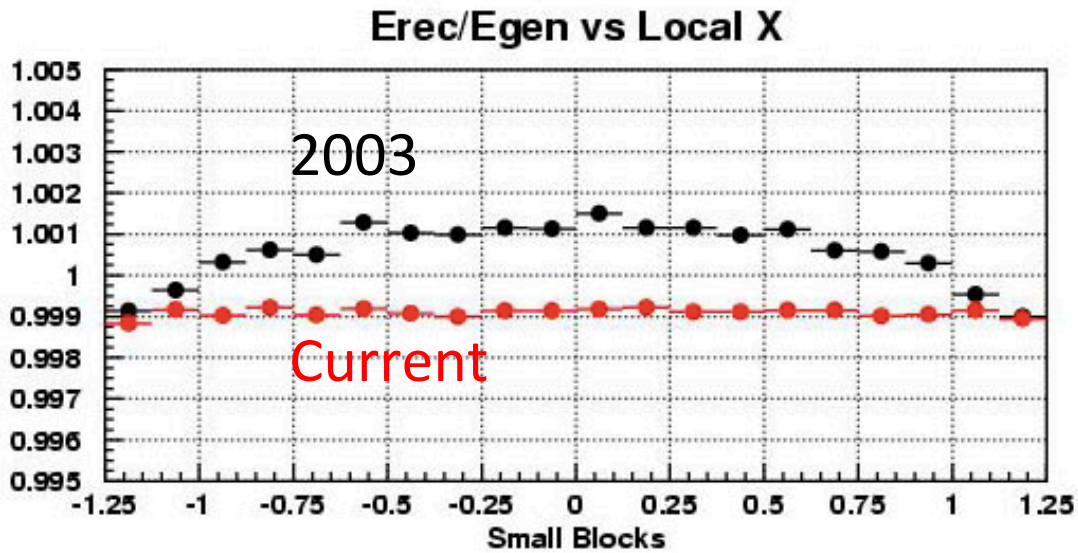
Simulation: Wrapping



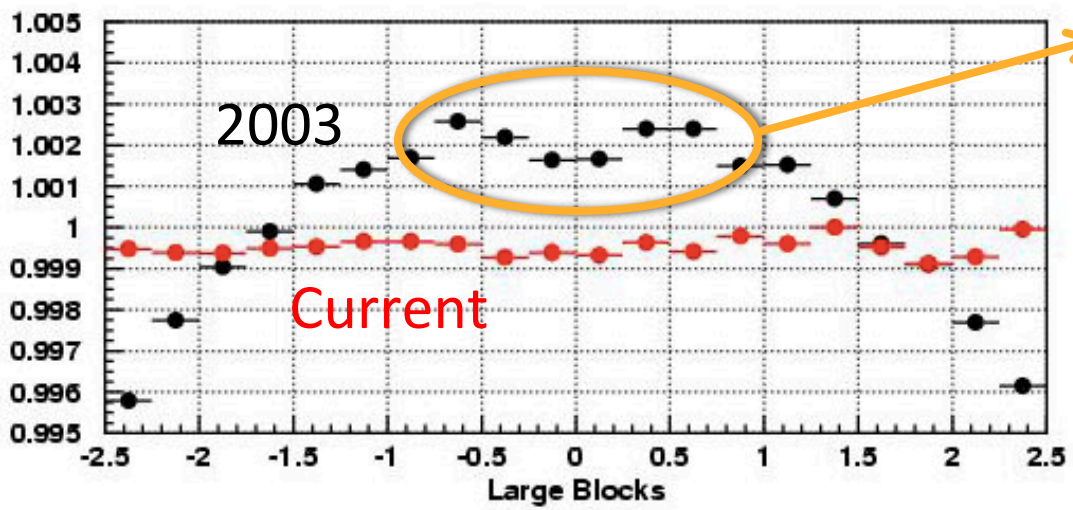
- Shower library generated using an array of small crystals
- In MC, shower from library overlayed on CsI array
- 4 small blocks summed to create large blocks
- Simulation of large blocks includes wrapping that is not really there
- Solution: library stores energy deposit in wrapping, add back in when necessary

Simulation: Wrapping

Small crystals



Large crystals

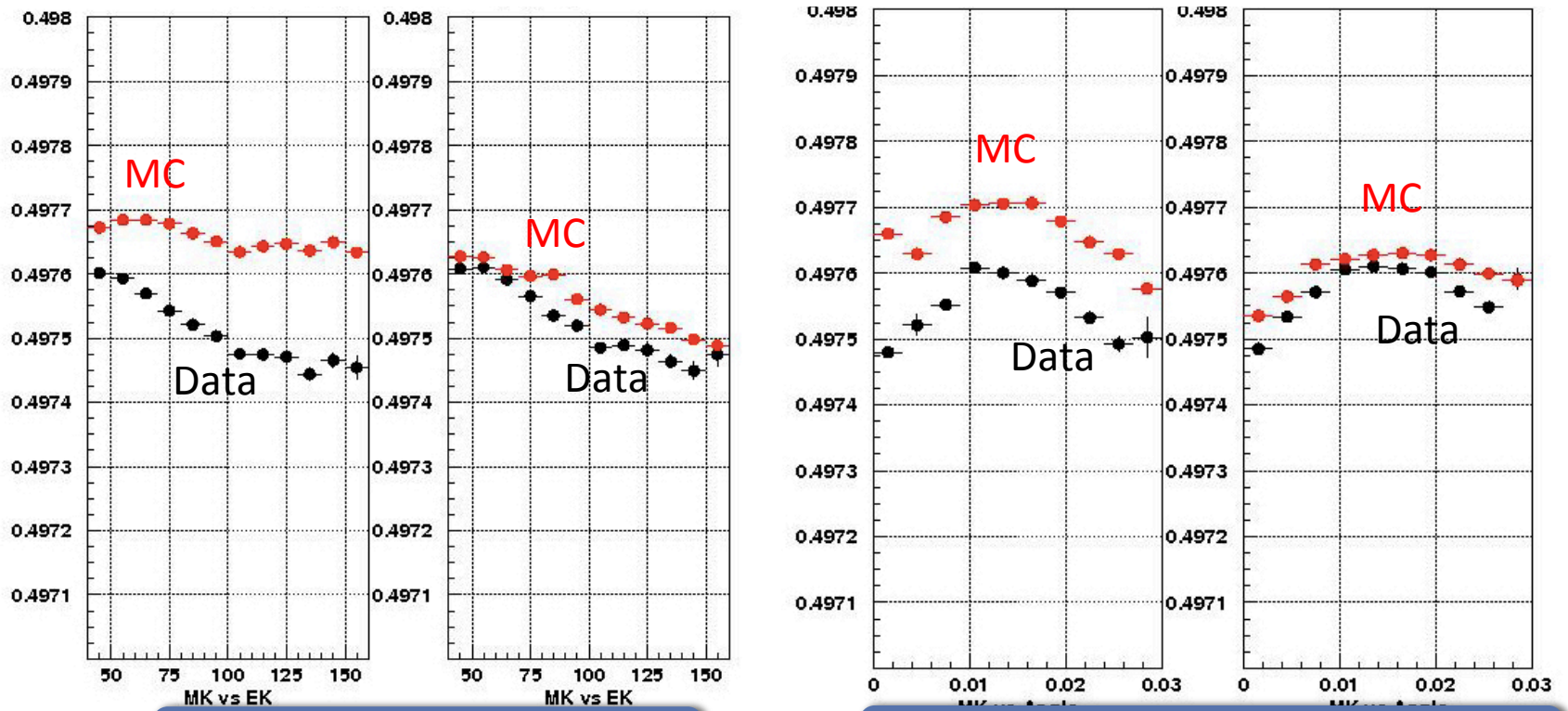


Wrapping!

Energy Linearity (Kaon Mass)

Contribution to Re(ε′/ε) systematic error: ±0.15 × 10^{-4}

2003 Current 2003 Current



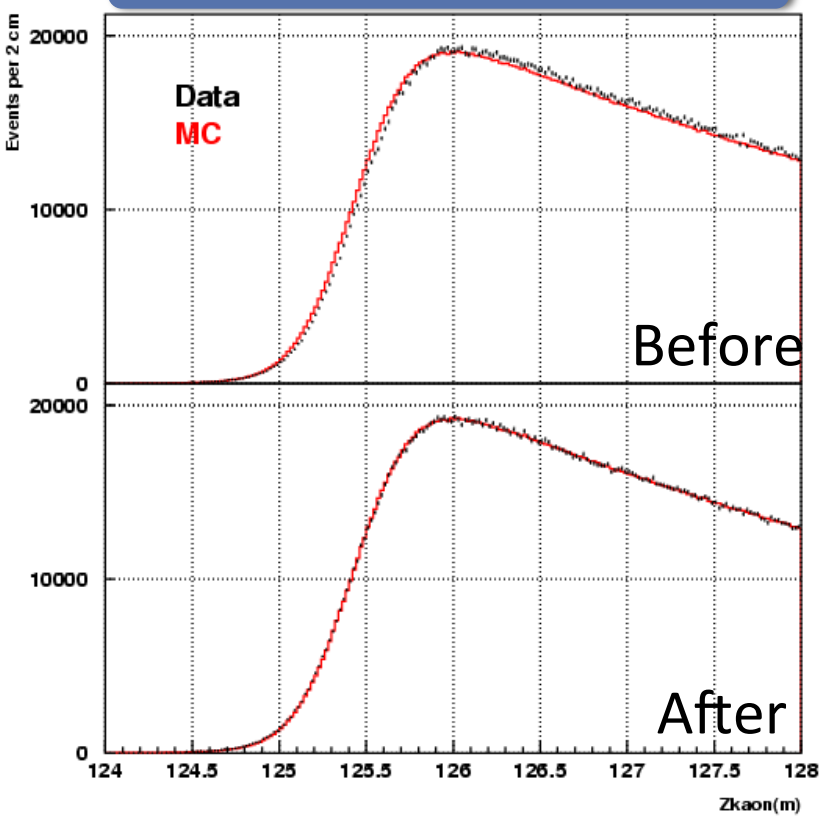
Mass vs. Energy

Mass vs. Photon Angle

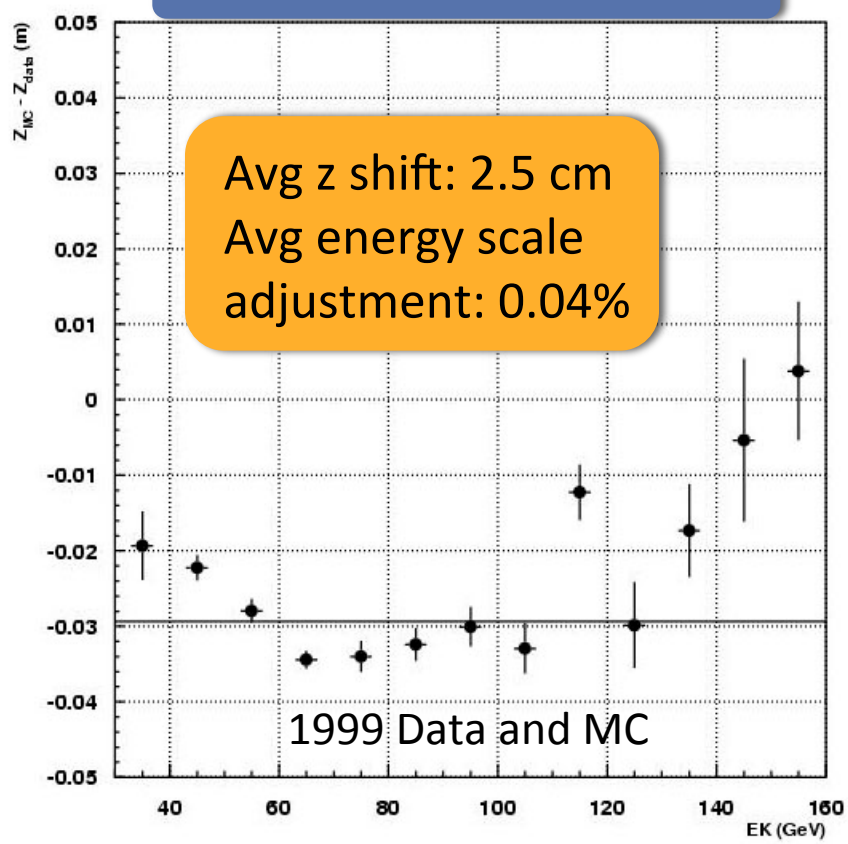
Energy Scale ($K \rightarrow \pi^0\pi^0$)

Contribution to Re(ε'/ε) systematic error: $\pm 0.65 \times 10^{-4}$

z vertex at regenerator edge



z shift to match data to MC



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

Systematic Uncertainty 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	

Conclusions

- KTeV CsI calorimeter extremely successful
  - E/p resolution ~0.6%
  - Position resolution 1.2/2.4 mm
  - Longitudinal response uniform to ~5%
  - Transverse response uniform to ~1%
  - Energy non-linearity <1%

  Before final corrections

  - Reconstructed kaon mass linear within <200 keV
  - Absolute energy scale known to ~0.04%

  After final corrections
- Design considerations
  - Reduce complications when possible
  - Redundant readout/easy access for replacement critical
  - Dead material important
  - Ability to reconstruct angles would have been great (timing? 3d?)
  - Extensive offline analysis required