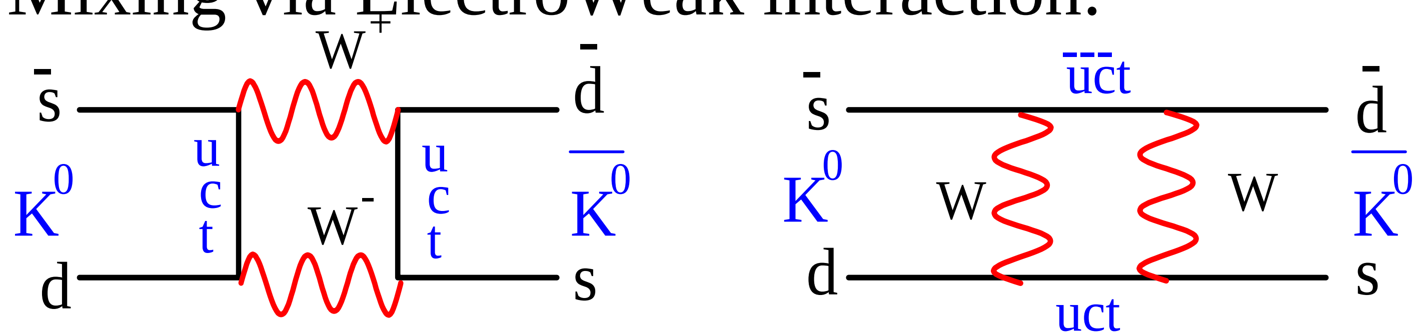
A New Measurement of Re(ε'/ε) from KTeV at Fermilab

1) Introduction to CP Violation in the Kaon System
2) The KTeV Experiment at Fermilab
3) Analysis of Re(ε'/ε)
4) New 1997 Result, and Re-analysis of 1996 Result

The Neutral Kaon System

- $K^0(s\bar{d})$, $\overline{K^0}(\bar{s}d)$ are quark flavor eigenstates
- Mixing via ElectroWeak interaction:



- In CP conserving limit, mass eigenstates=CP eigenstates: $K_1 \propto K^0 + \overline{K^0}$ (CP+1), $K_2 \propto K^0 - \overline{K^0}$ (CP-1)

Expect K_1 to be much shorted lived than K_2,

since $M_K - 3M_{\pi 0} \ll M_K - 2M_{\pi 0}$

CP Violation in Kaons

- 1st Observation of CP Violation was $K_L \rightarrow \pi\pi$ (1964):

$$A(K_L \rightarrow \pi\pi)/A(K_S \rightarrow \pi\pi) \cong \varepsilon \approx 2x10^{-3}$$

- Bulk of effect is from mixing asymmetry:

$$A(K^0 \rightarrow \overline{K^0}) \neq A(\overline{K^0} \rightarrow K^0)$$

- Mass Eigenstates: $K_S \propto K_1 + \varepsilon K_2$, $K_L \propto \varepsilon K_1 + K_2$

$$\tau_L \approx 580\ \tau_S,\quad \Delta m \approx 1/2\tau_S$$

CP Violation in the Standard Model

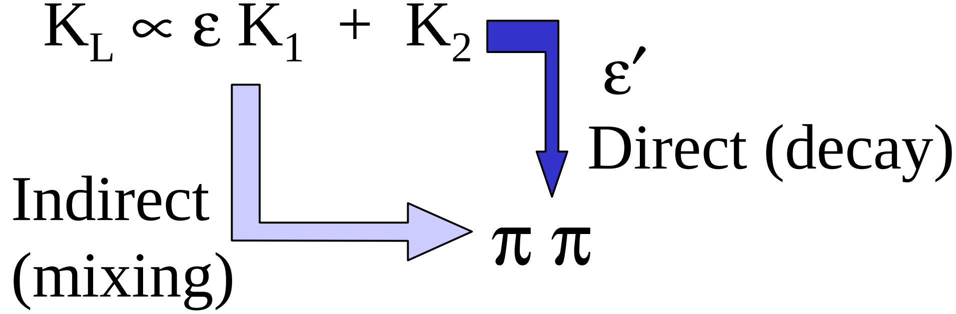
- CP Violation is accommodated in imaginary part of quark mixing parameters:

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

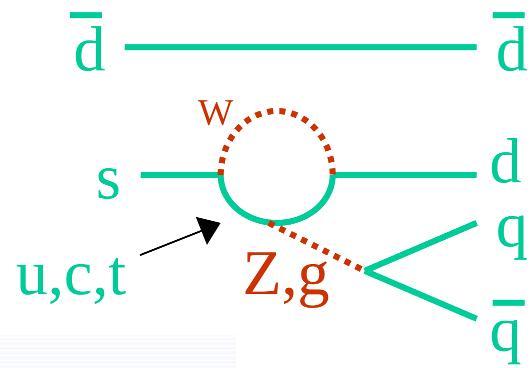
$$V \cong \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Direct CP Violation

- Direct CP Violation: $K_L \propto \varepsilon K_1 + K_2$



- CP Violation in Decay Amplitudes: EW and Stong Penguins



- Small effect on CP violating K_L Amplitudes:

$$\frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \approx \varepsilon + \varepsilon'$$

$$\frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} \approx \varepsilon - 2\varepsilon'$$

ε'/ε in the Standard Model

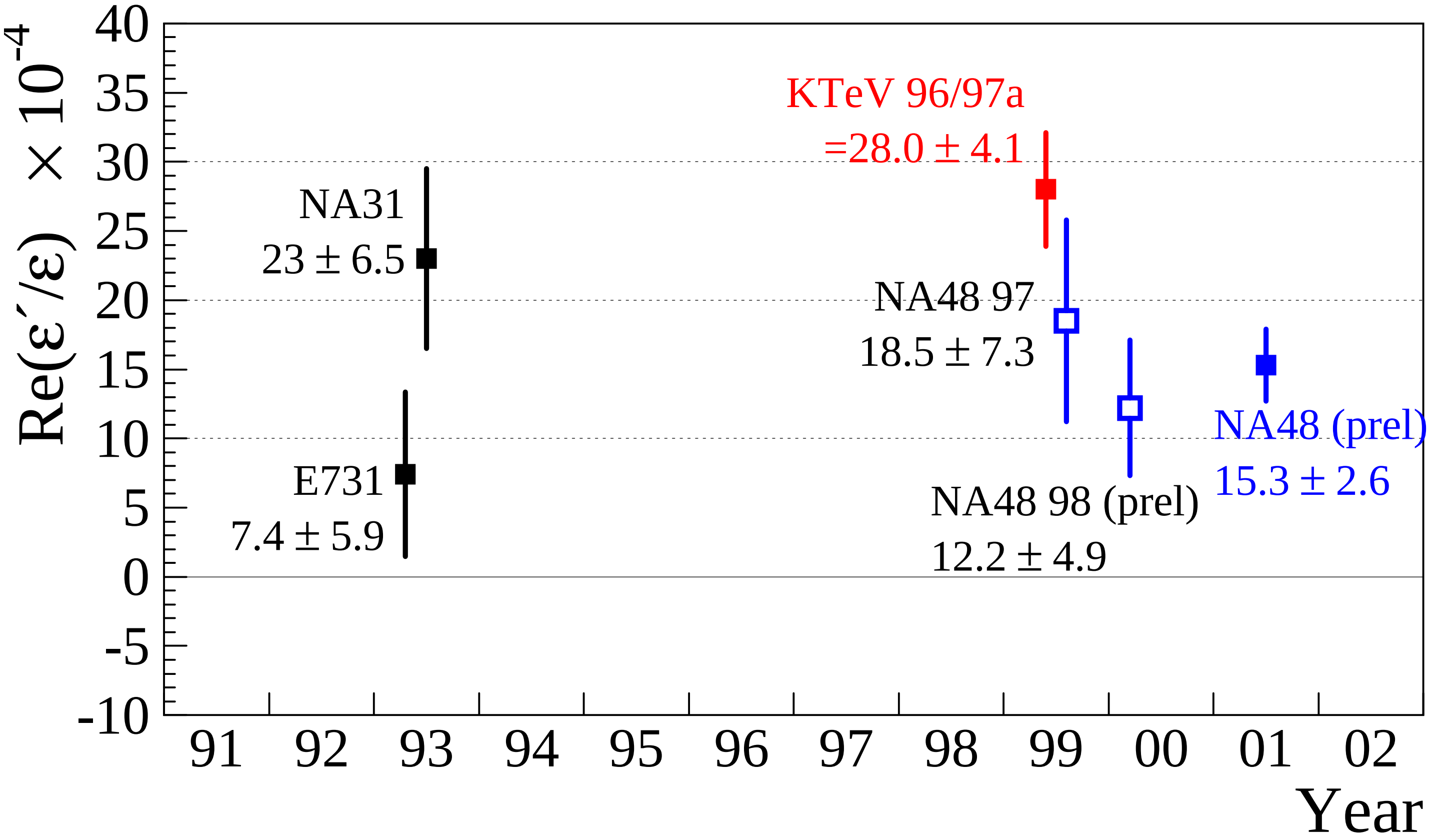
- $\varepsilon' \propto Im(A_2/A_0)$: $A_{0,2}$ – $I=0,2$ Final State
- $\varepsilon'/\varepsilon = Im(\lambda_t) \times [\, c_0 + R_s(c_6 B_6^{(1/2)} + c_8 B_8^{(3/2)})]$
  - $c_{0,6,8}$ – Wilson Coefficients, NLO (~ ±10%)
  - $Im(\lambda_t)$ – $Im(V_{td}V_{ts}^*)$ (~ ±40%)
  - $B_{6,8}^{(1/2)}$ – Hadronic matrix elements of effective 4 quark operators – non perturbative, difficult to calculate.
- ε'/ε calculations vary…

$(4.6\pm3.0)\times10^{-4}$ -Ciuchini, *et al*. 97

Buras, et al., 99 {
$(5.7\pm3.6)\times10^{-4}$ -m_s=130 ±20 MeV
$(9.1\pm5.7)\times10^{-4}$ -m_s=110 ±20 MeV

$(17^{+14}_{-10})\times10^{-4}$ -Bertolino, *et al.*, 98

Previous Measurements



- Pre-June, 2001: World Average $\varepsilon'/\varepsilon = (18.0 \pm 2.0) \times 10^{-4}$, poor agreement among experiments.

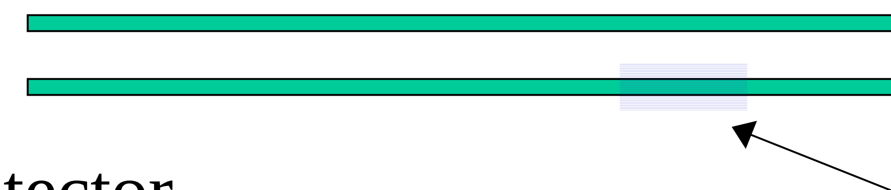
KTeV at Fermilab

- Kaons at the TeVatron
- Three Physics Programs:
  - Rare K decays: E799
  - Hyperon Physics: E799/E832
  - ε'/ε: E832
- $\delta(\varepsilon'/\varepsilon) = O(10^{-4})$

University of Arizona, UCLA ,UCSD, Universidade Estadual de Campinas, University of Chicago, University of Colorado, Elmhurst College, Fermilab, Osaka University, Rice University, Universidade de São Paulo, University of Virginia, University of Wisconsin

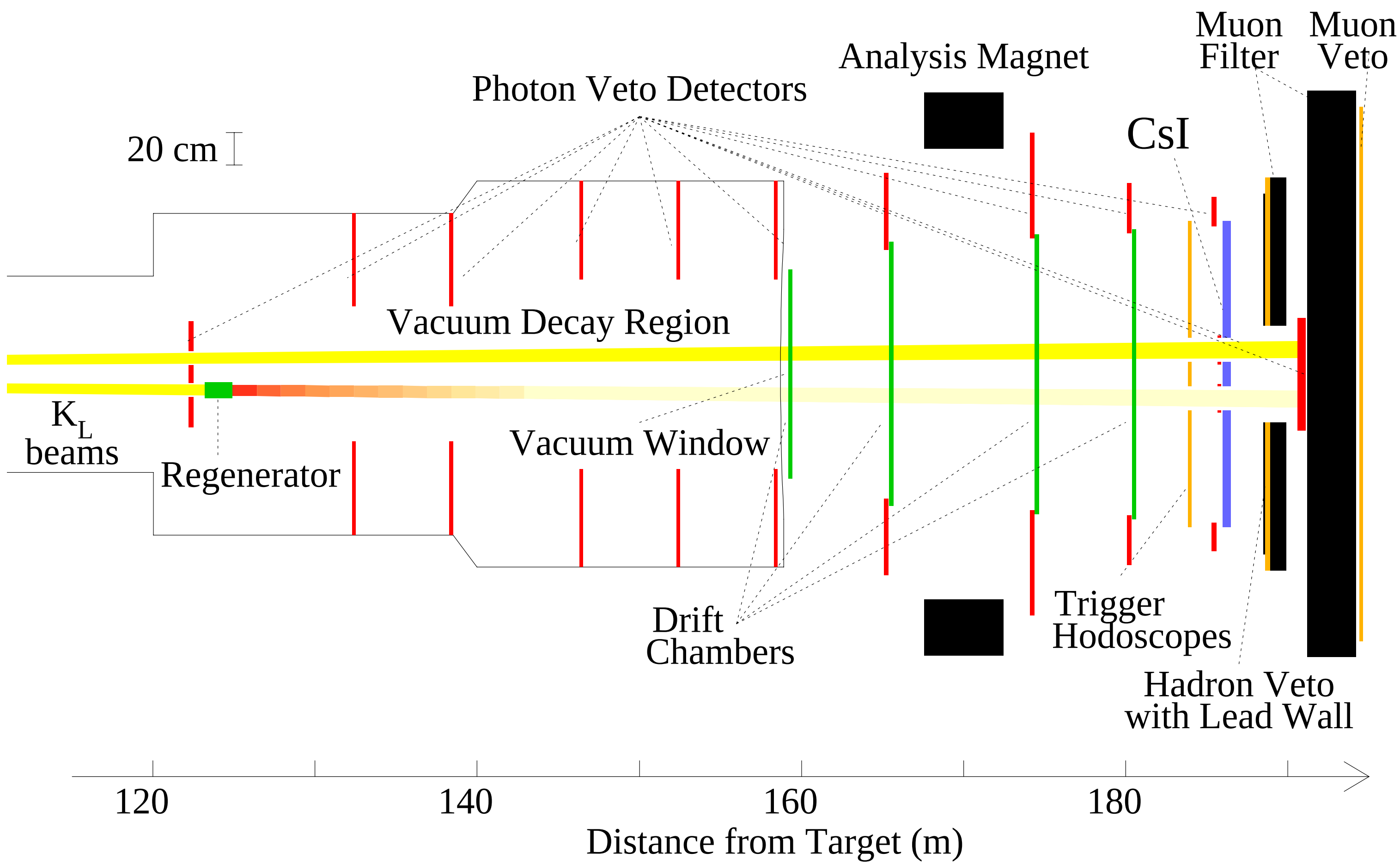
Measuring ε'/ε

- $$\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \approx 1 + 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$
- Simultaneous K_L and K_S beams: 20-200 GeV
  - Produce 2 K_L beams 160 m upstream of the detector
  - Coherent regeneration of K_S in 1.8m of plastic scintillator 35 m upstream of detector



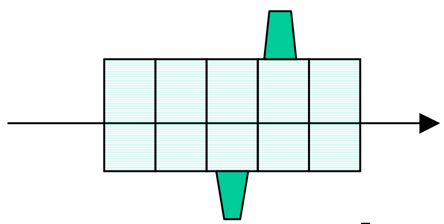
- Detector
  - Spectrometer for $\pi^+\pi^-$
  - CsI EM Calorimeter for $\pi^0\pi^0 \to 4\gamma$

KTeV Detector

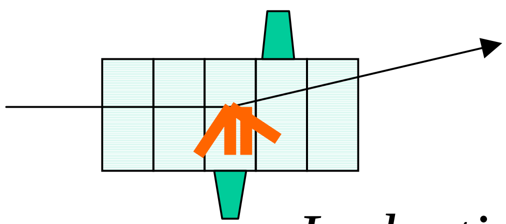


Coherent Regeneration

- Difference in K^0 and $\overline{K^0}$ forward scattering amplitude in matter
- $\rho \approx 0.02 – 0.04$, with power law dependence in P_K
- Coherent effect
  - Distinguish from inelastic K_S production via scintillation light from recoil in interactions
  - Subtract diffractive and remaining inelastic and background offline



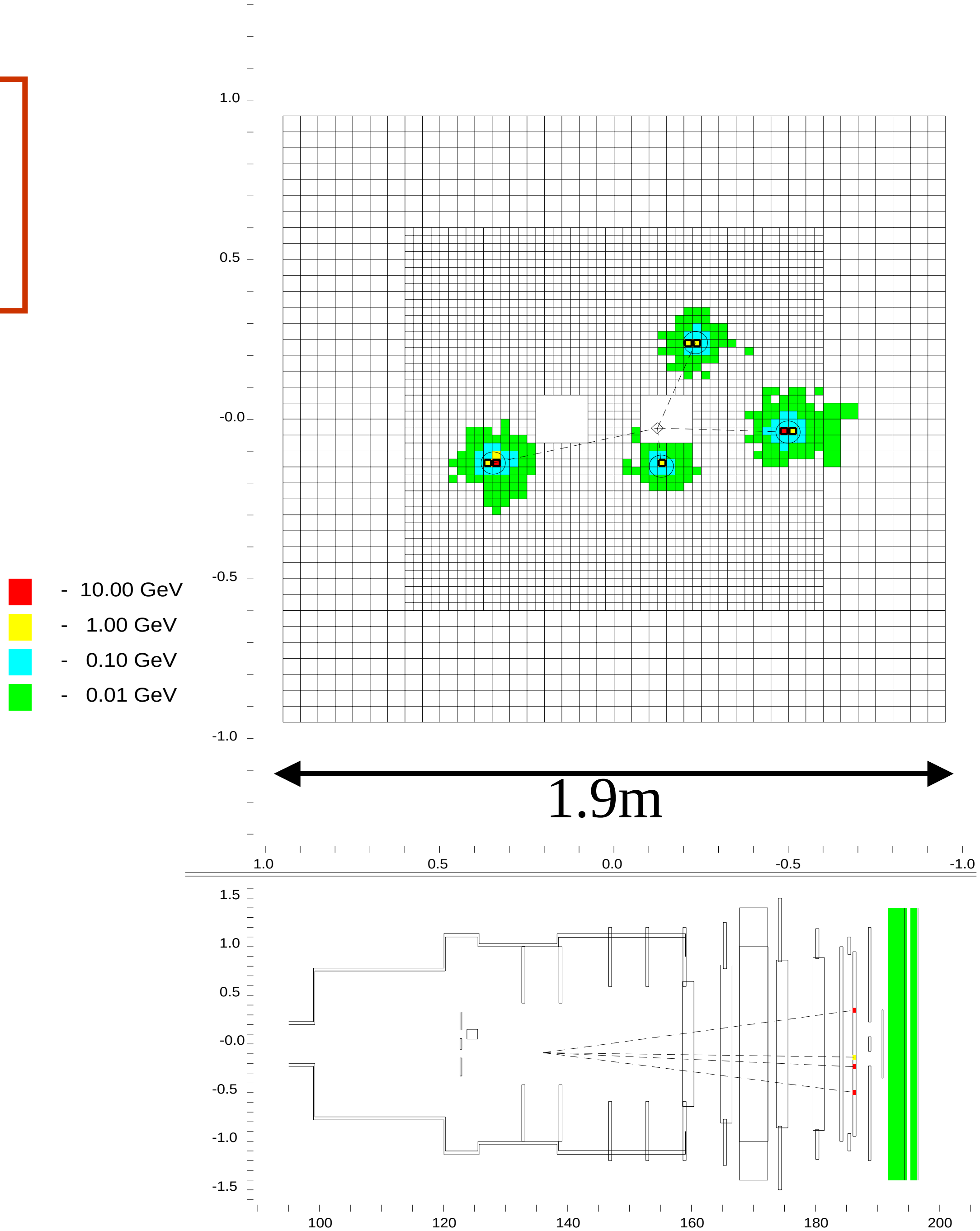
Coherent

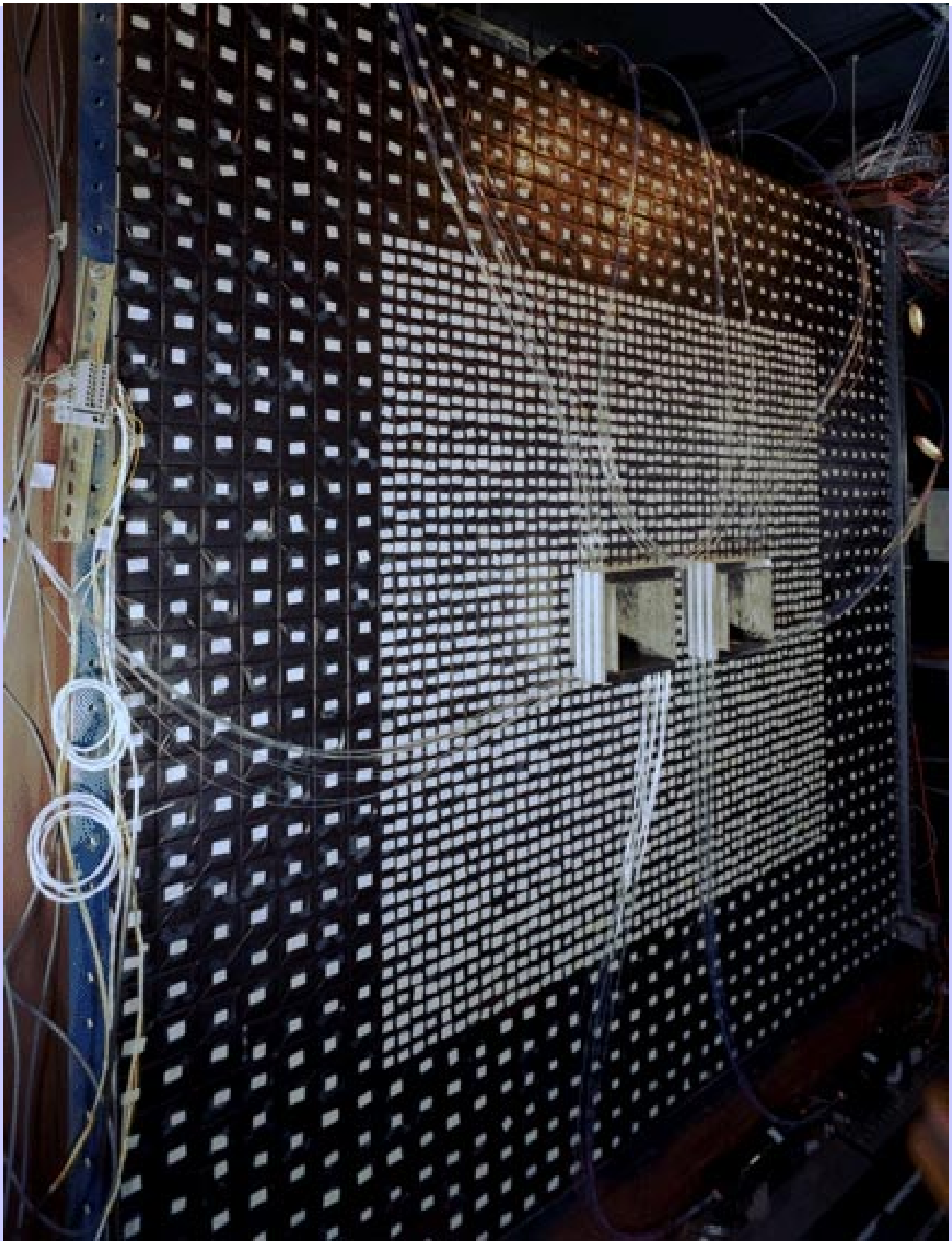


Inelastic

Cesium Iodide Calorimeter

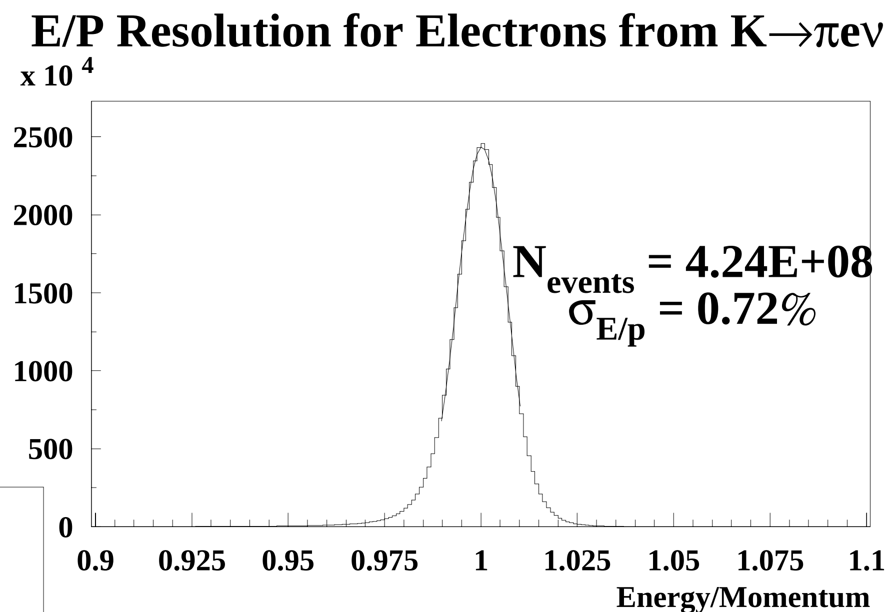
- 3100 Crystals of 27 X_0 Pure CsI (50cm)
- High Linearity Phototubes
- 8 Range, Deadtimeless, Pipelined ADC

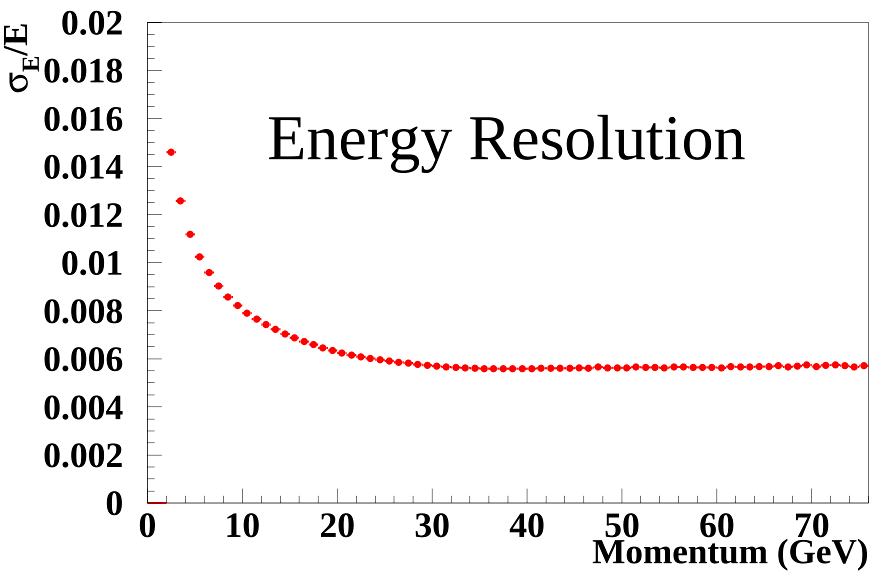




CsI Performance

- CsI Calibrated with $e^{\pm}$ from 420 Million $K \rightarrow \pi e \nu$





$K \to \pi\pi$ Trigger

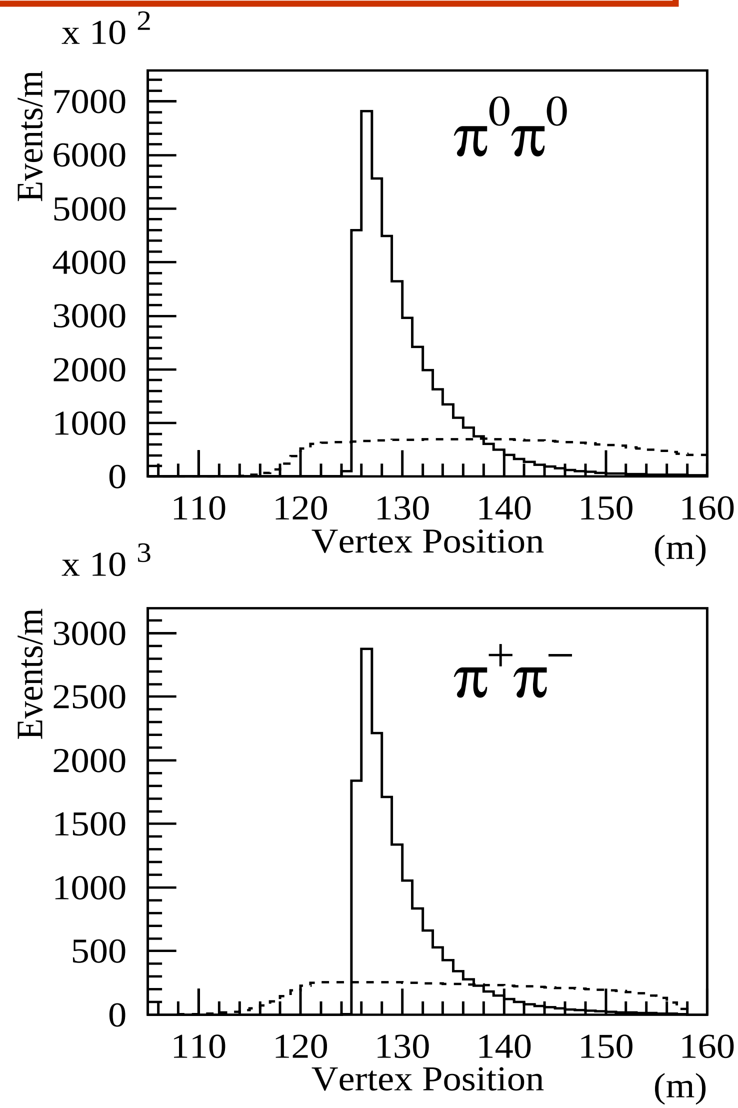
- High Rate Environment
  - $\sim$ few 100 KHz Kaon decay rate
  - CP violating BR's $\mathcal{O}(10^{-3})$

Trigger Element	Charged inefficiency	Neutral inefficiency	Rate
Level 1 (deadtimeless)	0.3%	0.6%	50 KHz
Level 2 ($2\mu s$ deadtime)	0.1%	1.0%	10 KHz
Level 3 (software filter)	0.08%	.04%	2 KHz

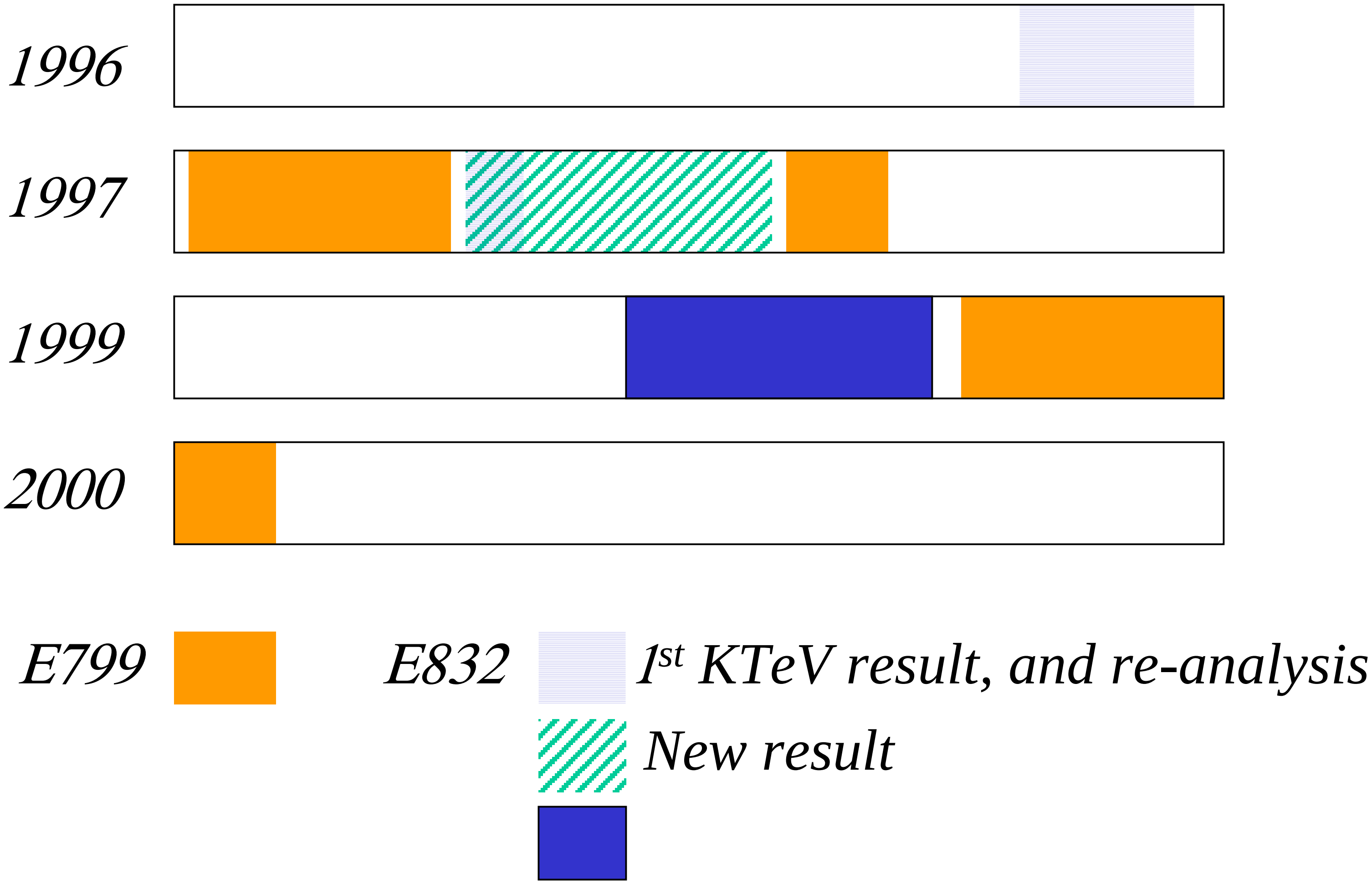
  - L1+L2 Live time: 65%
  - L3 Live time: 99.9%

ε'/ε Standard Analysis

- Count $K_{L,S}$ to $\pi^+\pi^-$ and $\pi^0\pi^0$
- Background Subtraction – non $\pi\pi$ and non-coherent $K\rightarrow\pi\pi$
- Very different K_L and K_S lifetimes:
  - Need acceptance correction from Monte Carlo simulation of detector + overlay of accidental activity
- Fit for ε'/ε
  - Account for full kaon wave function in each beam



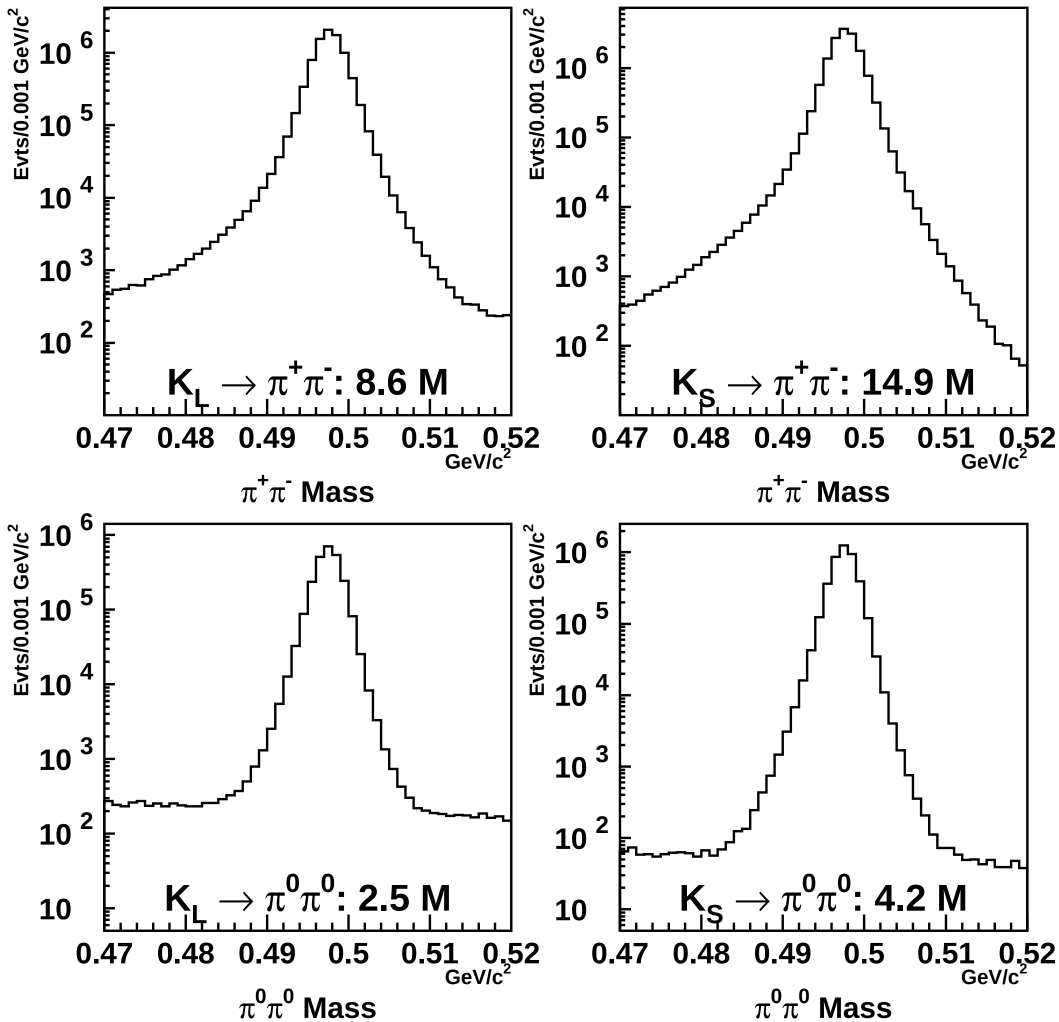
KTeV Data Taking



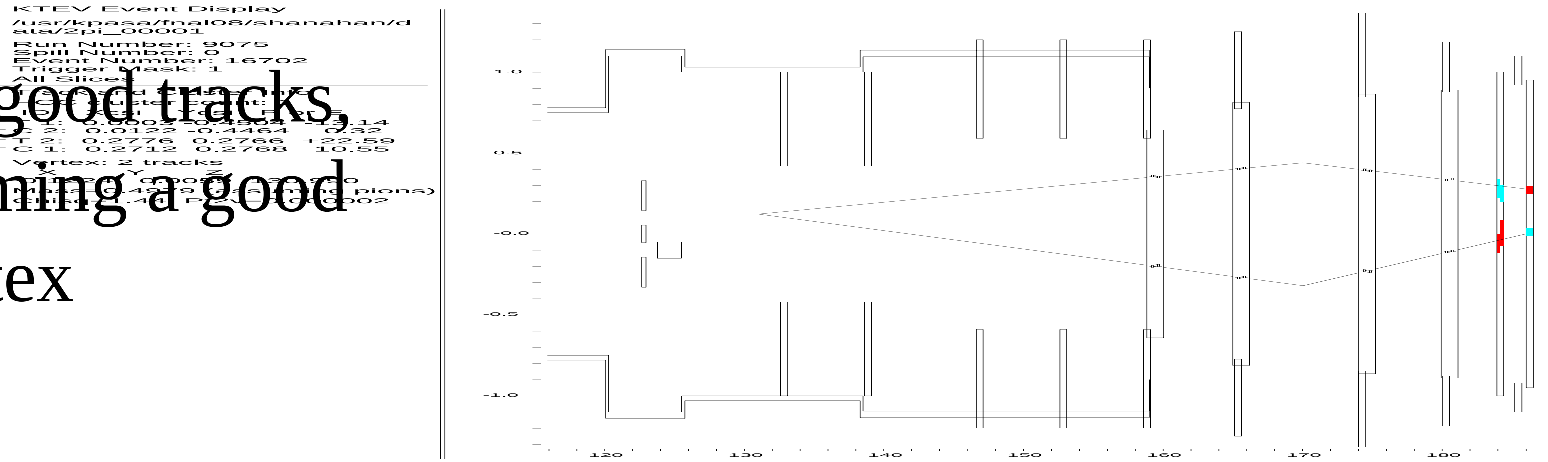
Event Sample

Year	K_L $\pi^+\pi^-$ (10^6)	K_L $\pi^0\pi^0$ (10^6)	K_S $\pi^+\pi^-$ (10^6)	K_S $\pi^0\pi^0$ (10^6)	Statistical error (10^{-4})
96/97a (PRL)	2.6	0.9	4.5	1.4	3.0
97	8.6	2.5	14.9	4.2	1.73
Combined	11.2	3.4	19.4	5.6	~1.5

Reconstructed Invariant Masses

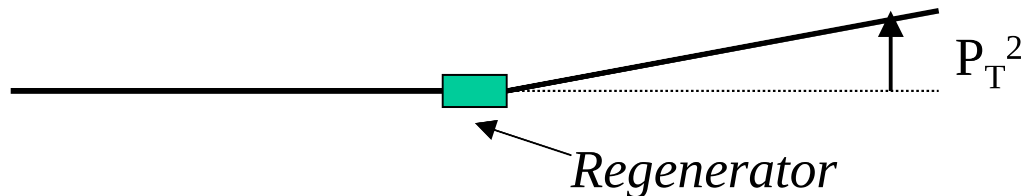


$\pi^+\pi^-$ Reconstruction



- 2 good tracks, forming a good vertex

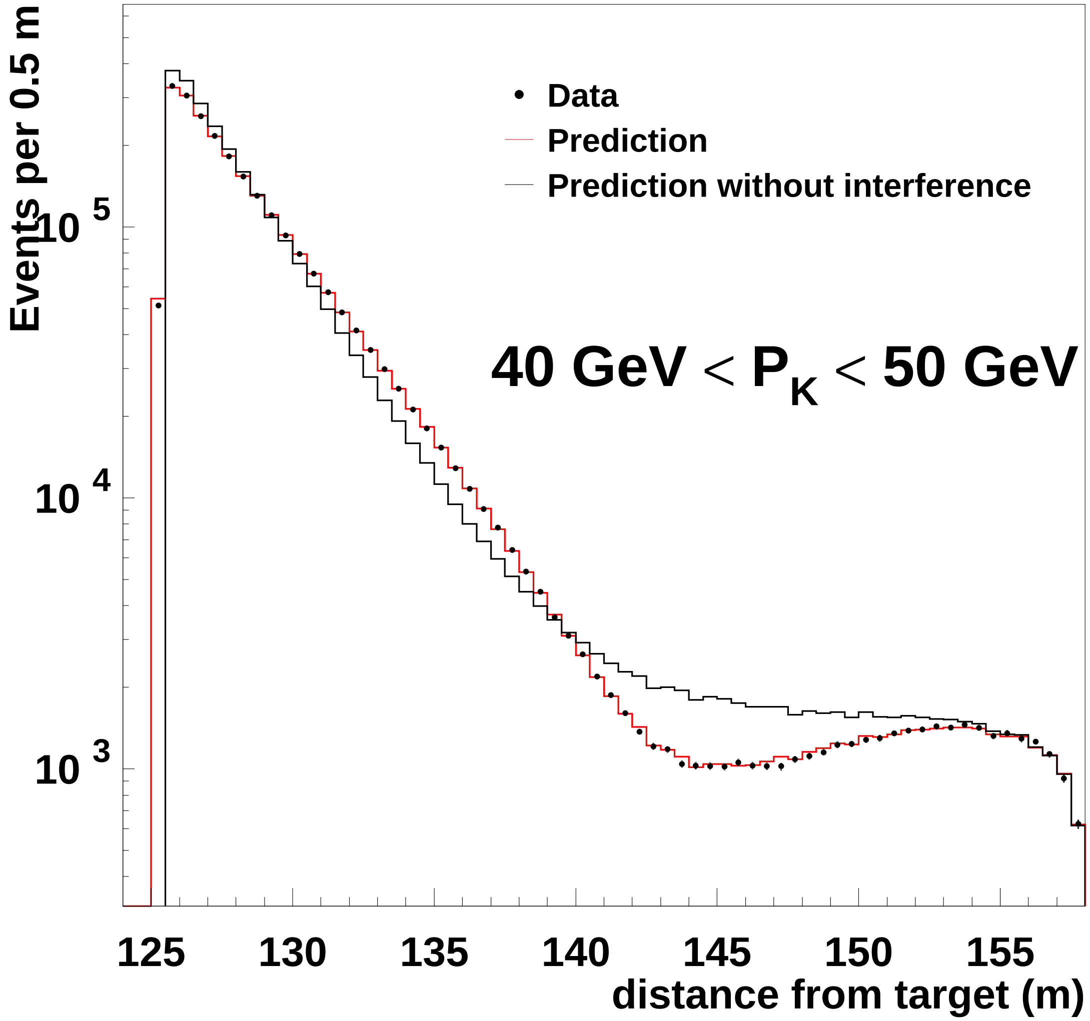
- Cuts



Track Quality	
Vertex χ^2	
Muon Veto	reject $K \rightarrow \pi\mu\nu$
E/p	reject $K \rightarrow \pi e\nu$
"pπ" Mass	reject $\Lambda \rightarrow p\pi$
Regenerator Veto	noncoherent KS
P_T^2	nocoherent KS, non $\pi\pi$

$m_{\pi\pi}$
E
Zvtx

Interference in K→ππ



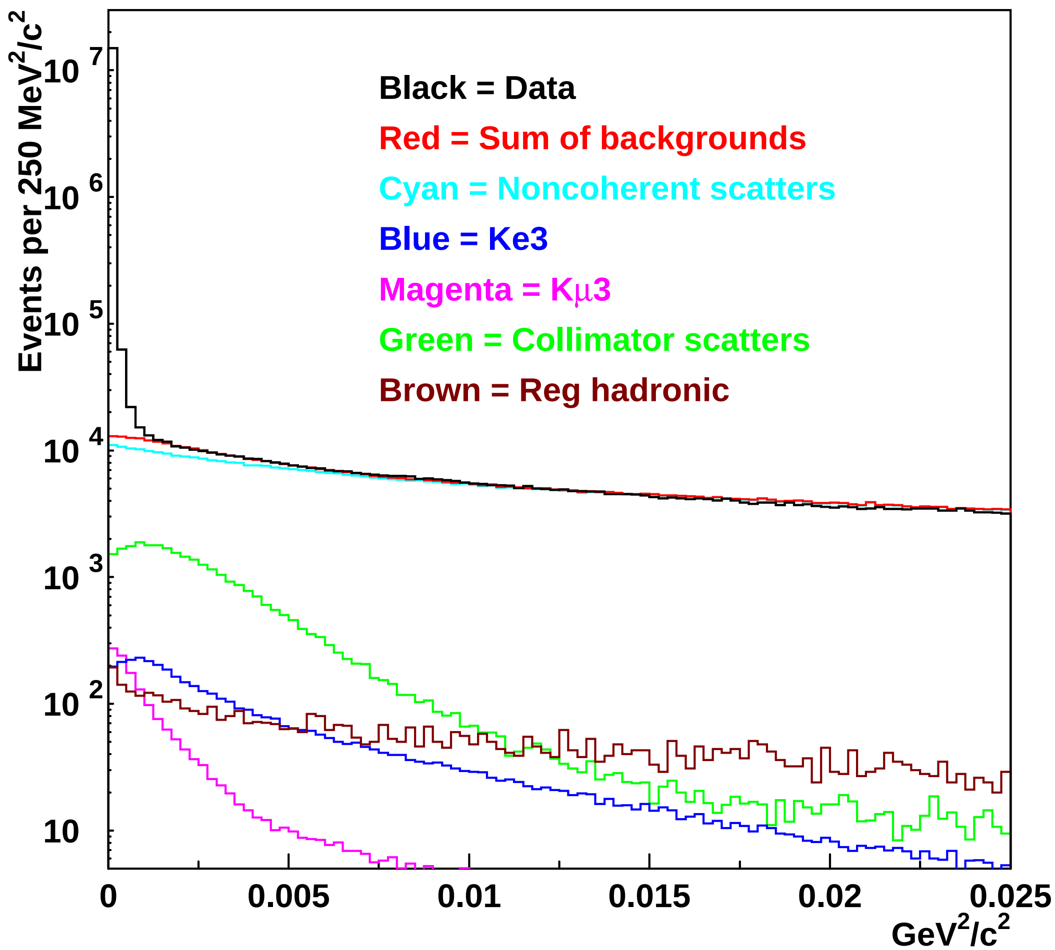
Regenerator Vertex Z distribution

Backgrounds to $\pi^+\pi^-$

- Non-coherent KS regeneration
  - Scattering in regenerator
  - Scattering in collimators
- $K \rightarrow \pi l \nu$
- Beam interactions in REG Pb

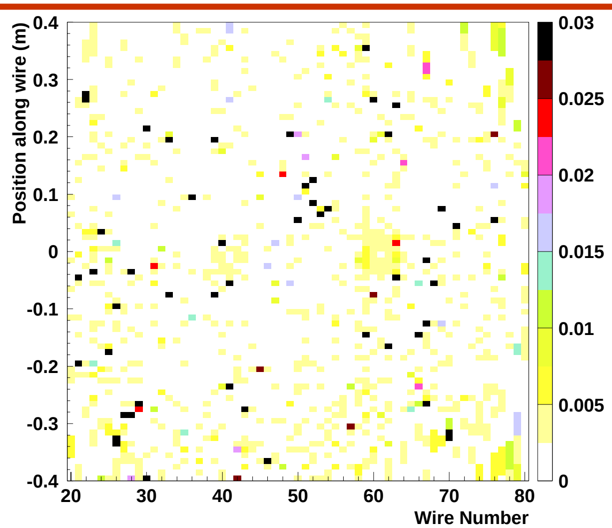
Total: .098% VAC
.081% REG

Data and predicted background contribution, 40-160 GeV

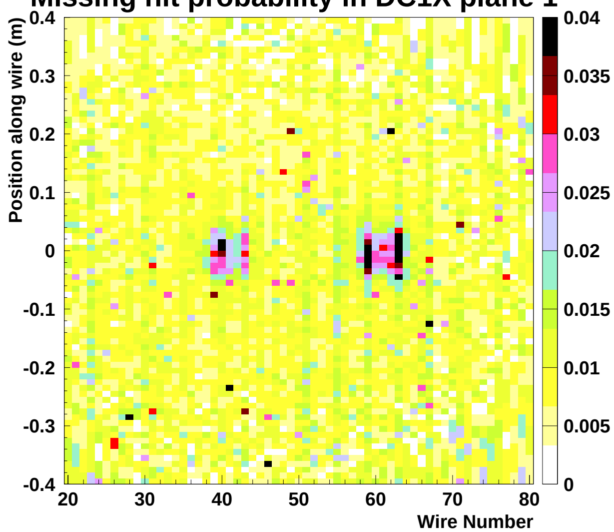


P_T^2 for reg data and backgrounds

Monte Carlo Simulation



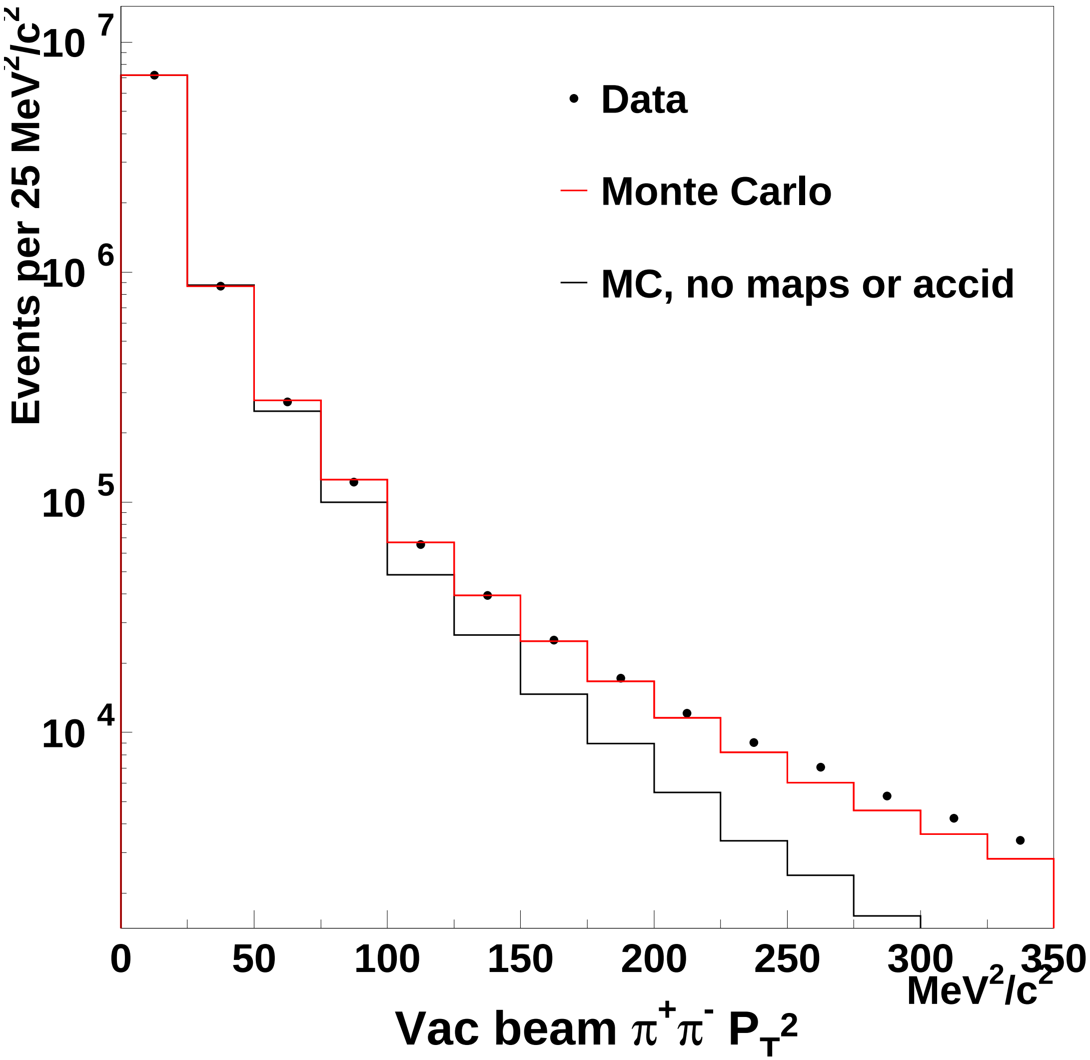
Missing hit probability in DC1X plane 1



Delayed hit probability in DC1X plane 1

- Detector apertures/ performance
- Overlay real random activity
- E.g.: Delayed hit problem
  - Worst for tracks near Drift Chamber sense wires

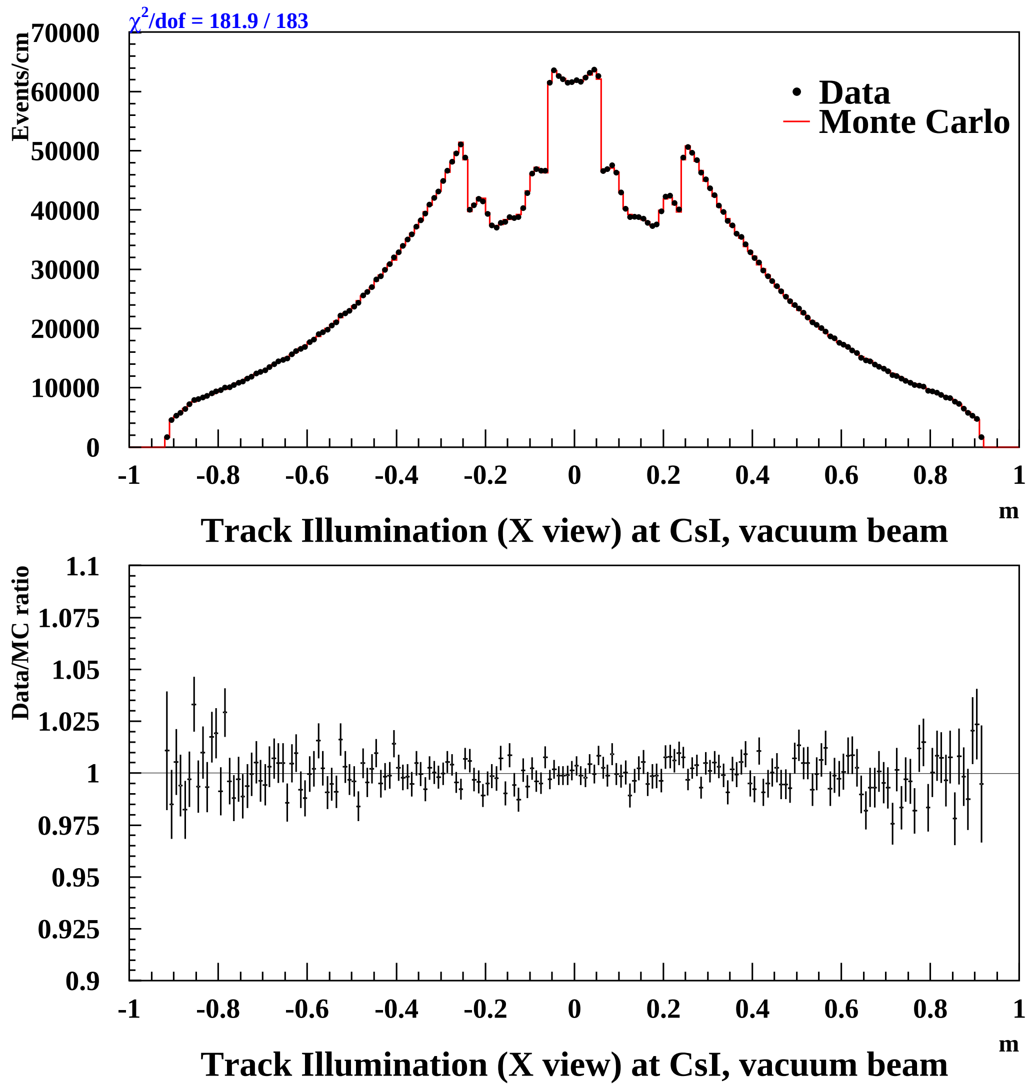
Simulation Results



Acceptance

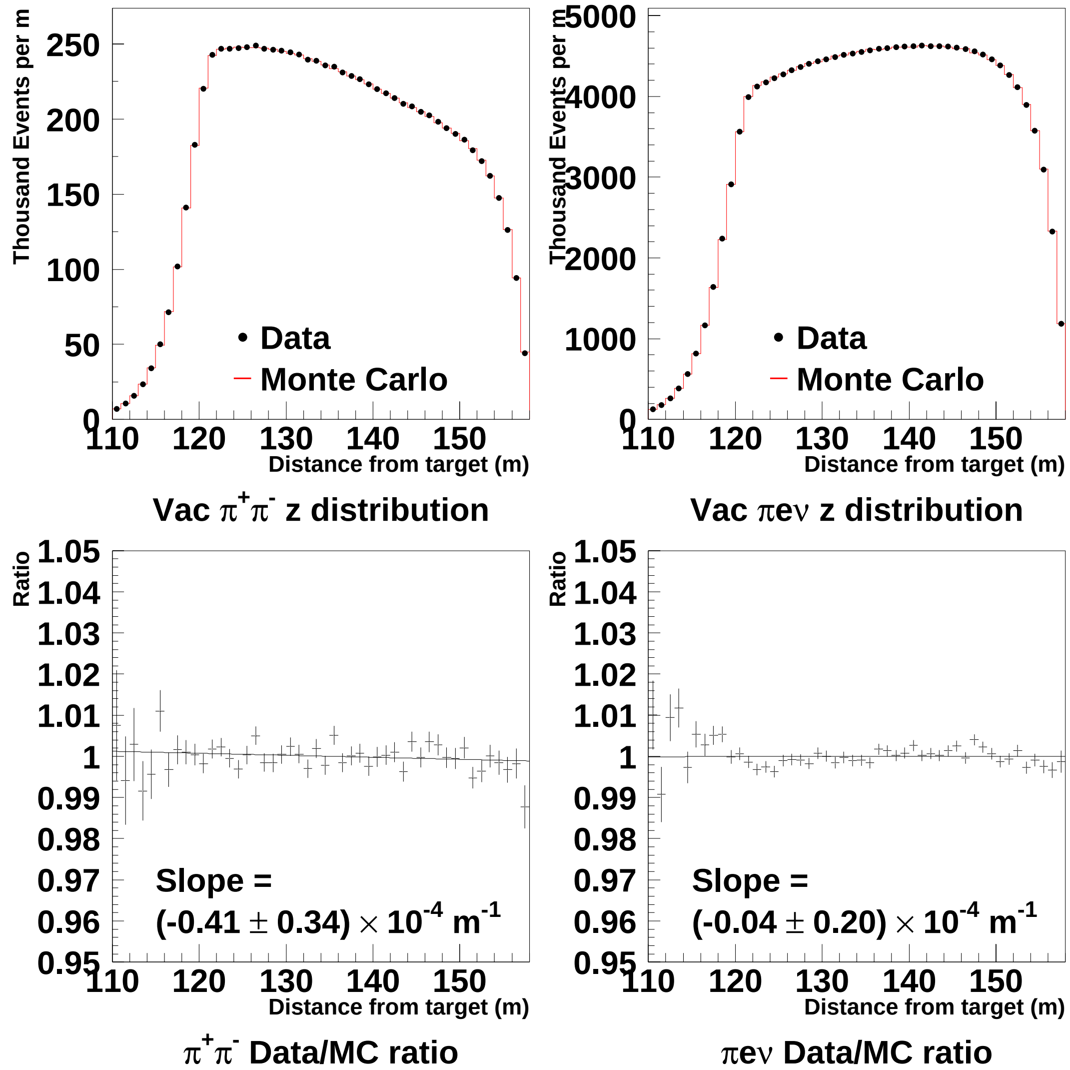
Data-MC comparison of π track illumination at CsI

MC tuned with 10s of millions of CP conserving decays



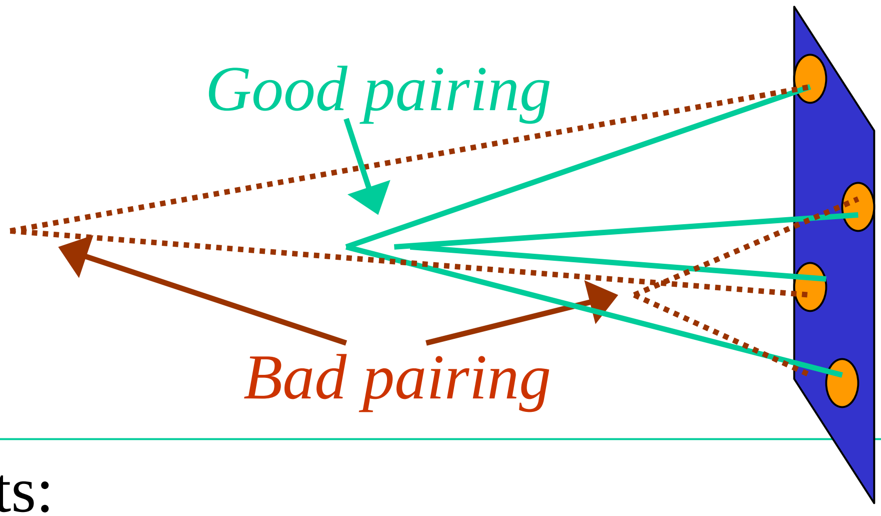
Acceptance Test

- Comparison of Data and MC Z vertex Distributions
  - Test of acceptance in variable most relevant to K_L-K_S difference
- Set systematic uncertainty based on $\pi^+\pi^-$:
  - $\delta(\varepsilon'/\varepsilon)=0.53\text{x}10^{-4}$



$\pi^0\pi^0$ Reconstruction

- Vertex for each pair of photons found assuming π^0 mass
- Choose pairing with most consistent π^0 vertices
- Calculate $\pi^0\pi^0$ mass
  - No direction information – use energy centroids

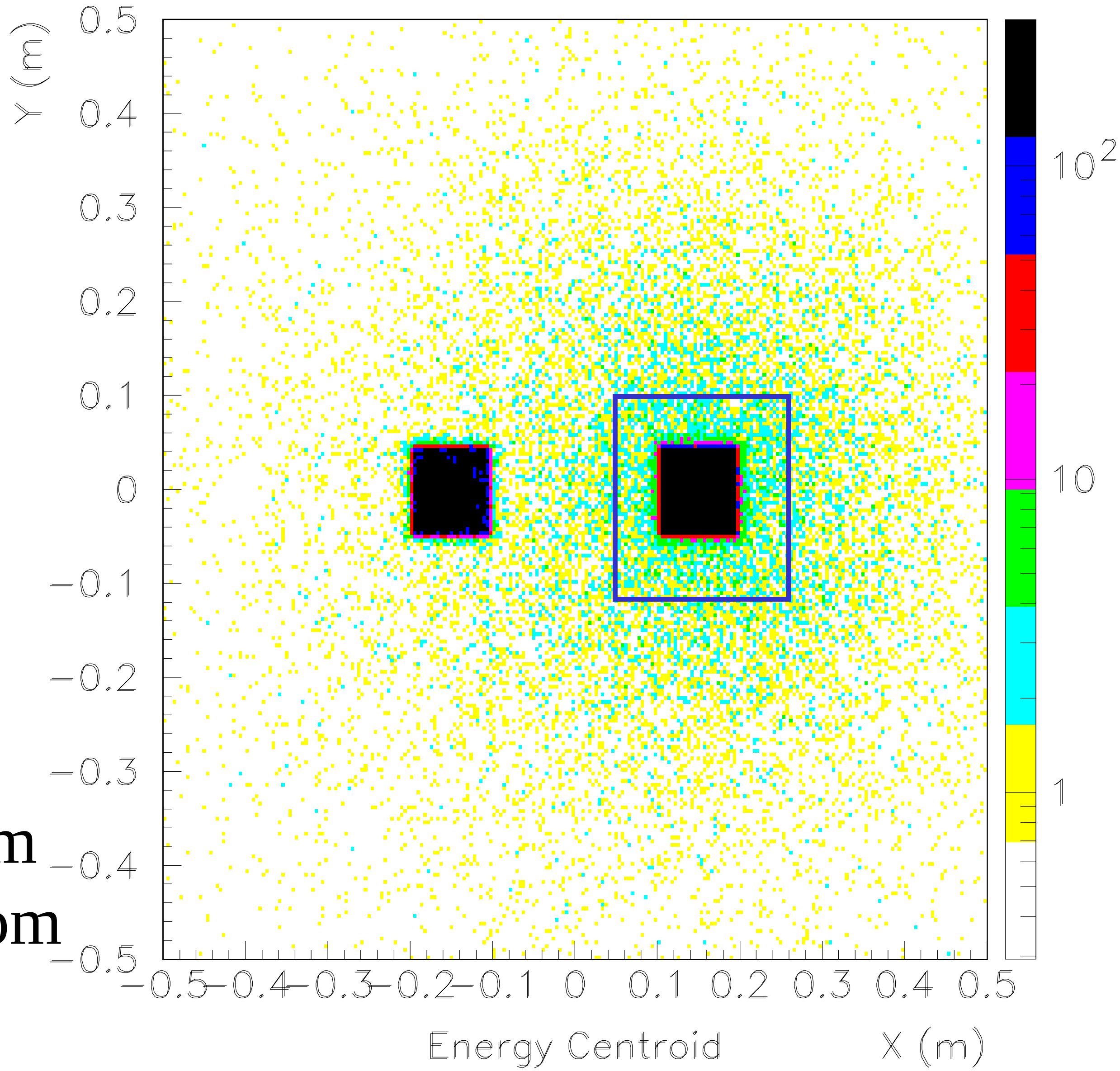


Cuts:

Photon Veto	$3\pi^0$
Cluster Shape χ^2	"Fused" γs ($3\pi^0$)
Vertex Pairing χ^2	Mispairs, $3\pi^0$
Regenerator Activity	Non-coherents
$(X,Y)_{CE}$	Non-coherents
$M_{\pi^0\pi^0}$, E_K, Z_{vtx}	
Extra intime photons in CsI	$3\pi^0$

$\pi^0\pi^0$ Center of Energy

- Cut on center of energy
  - In 1 cm^2 square rings
- Simulate Regenerator scattering spectrum using p_t^2 shape from $\pi^+\pi^-$

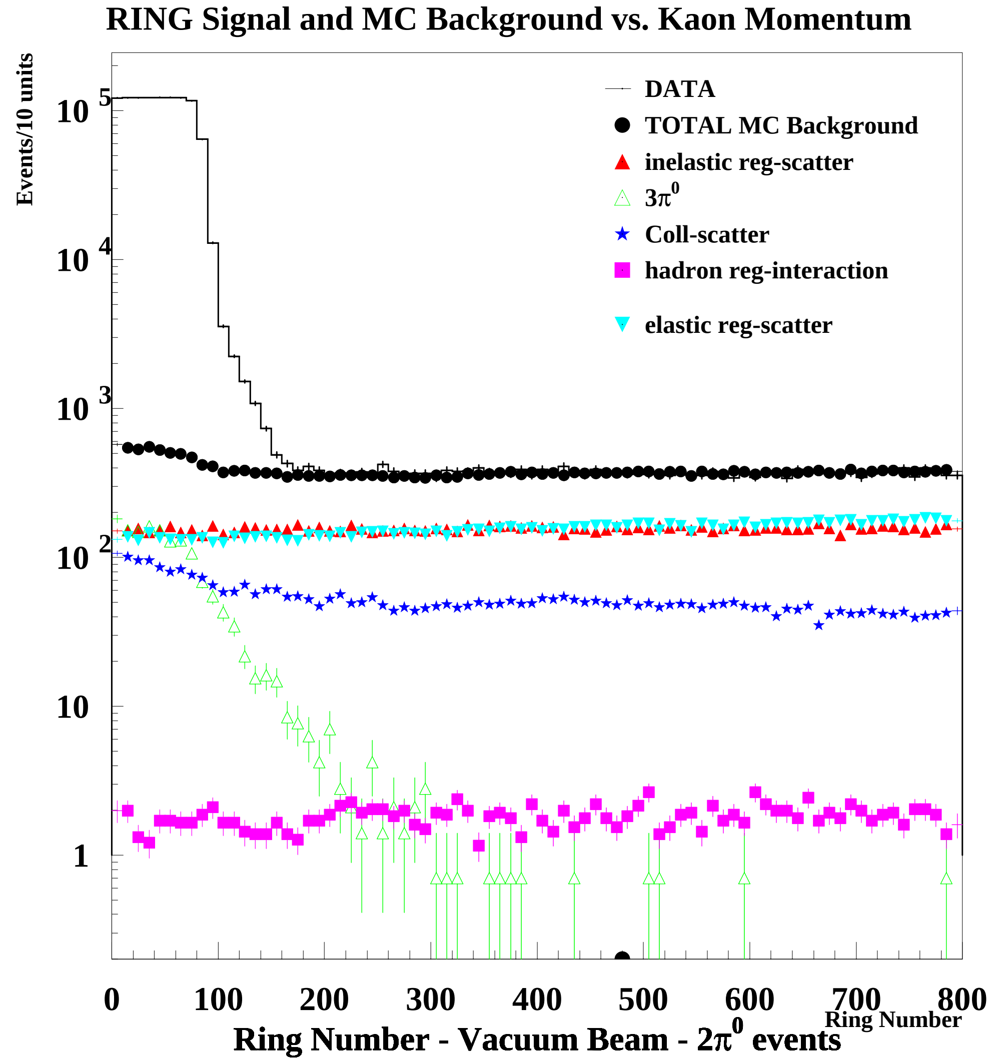


Backgrounds to $\pi^0\pi^0$

- Dominant BG: Regenerator Scatters
  - Modeled from $K\rightarrow\pi^+\pi^-$ p_T^2 Spectrum
  - Separate normalization of diffractive and inelastic K_S production

REG Beam: 1.27%

VAC Beam: 0.50%



Energy Scale

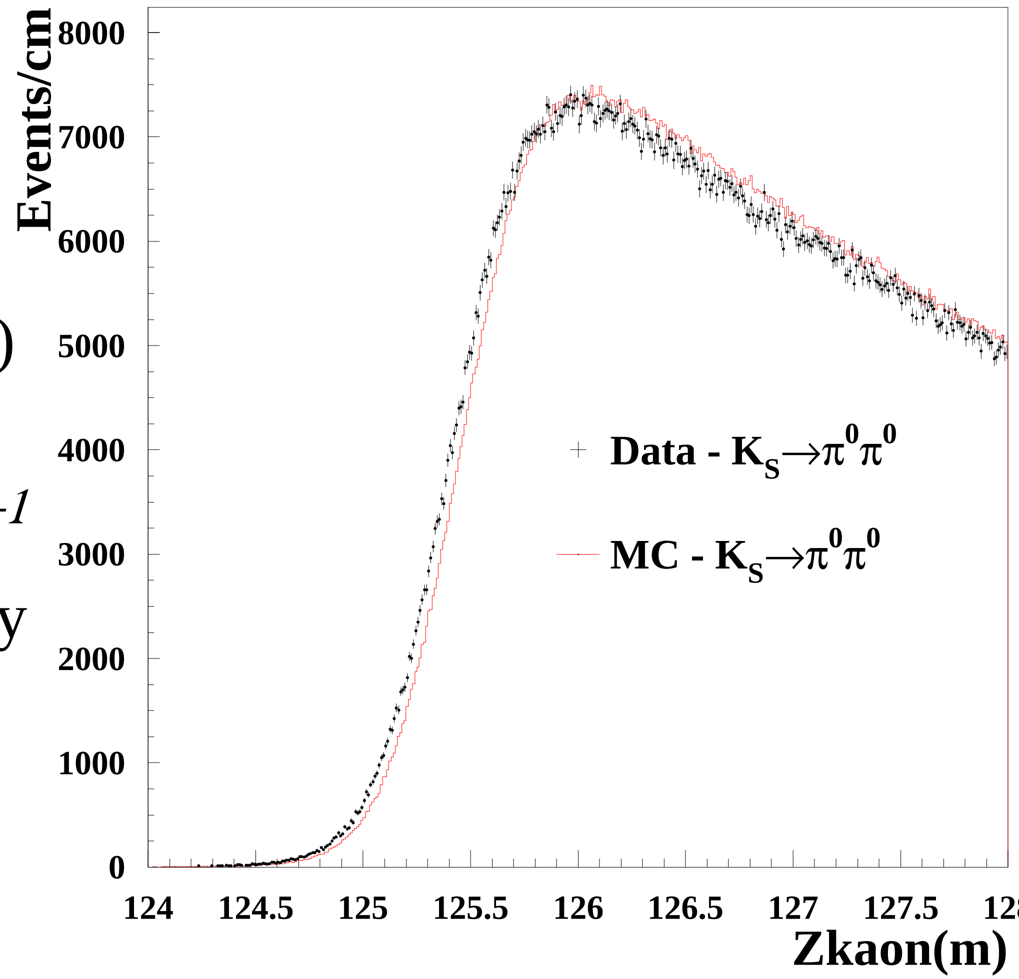
- Energy Scale:

$$\Delta Z \equiv Z_{CSI} - Z_{vtx} = \frac{\sqrt{E_1 E_2}\, r_{12}}{m_{\pi^0}}$$

$$E \rightarrow E(1+\delta) \Rightarrow \Delta Z \rightarrow \Delta Z(1+\delta)$$

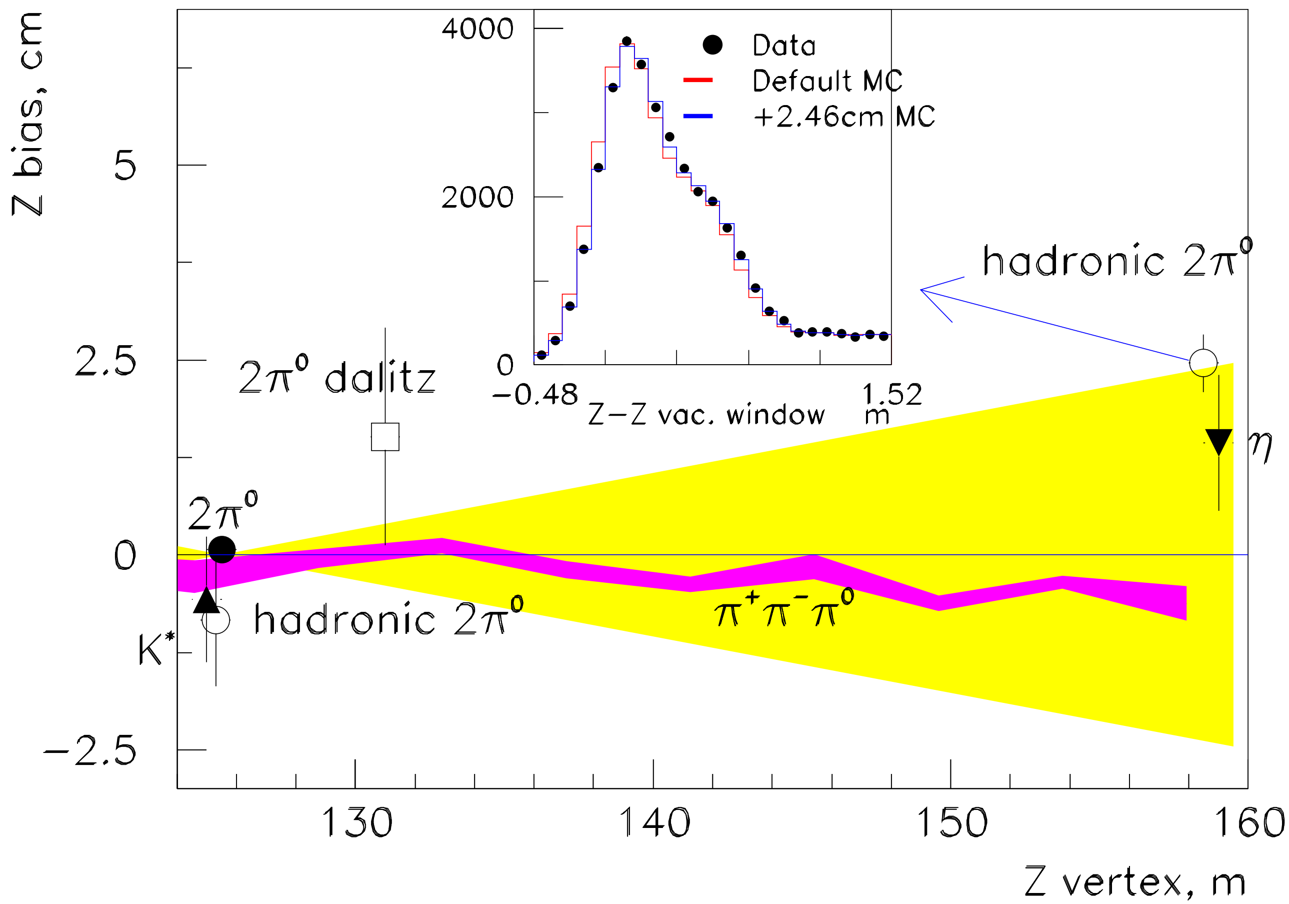
- Apply correction $(1+\delta)^{-1}$
  - Relative Data-MC energy scale correction:

  Make data and MC regenerator edge line up.



Regenerator Edge Data-MC Overlay

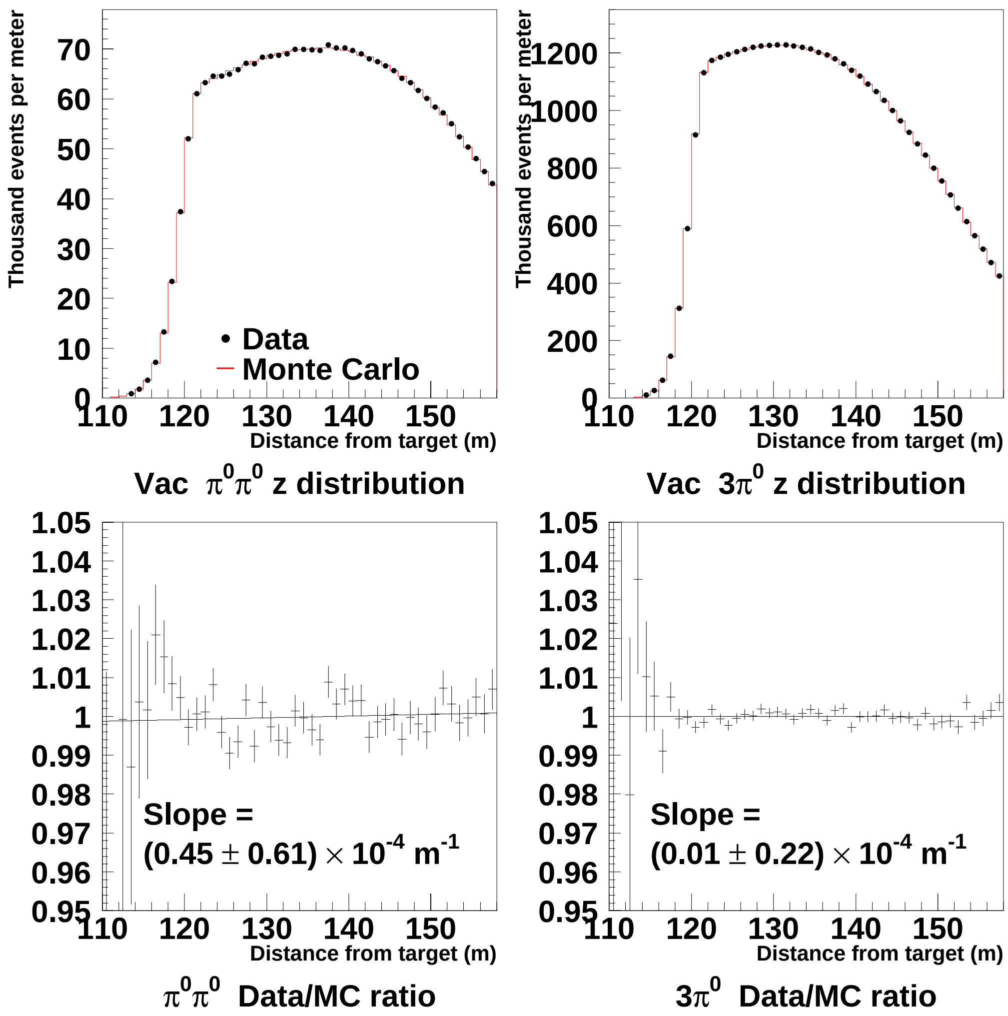
Energy Scale Cross Check



- Beam interactions
  - Regenerator Pb
  - Vacuum window
- $K \to \pi^+\pi^-\pi^0$
- For systematic:
  - Apply extra energy scale, varying linearly from Regenerator, to fix Z_{VACWIN}
- $\delta(\varepsilon'/\varepsilon)=1.37\text{x}10^{-4}$

Acceptance Test

- Set systematic uncertainty from $3\pi^0$
- $\delta(\varepsilon'/\varepsilon)=0.26\text{x}10^{-4}$

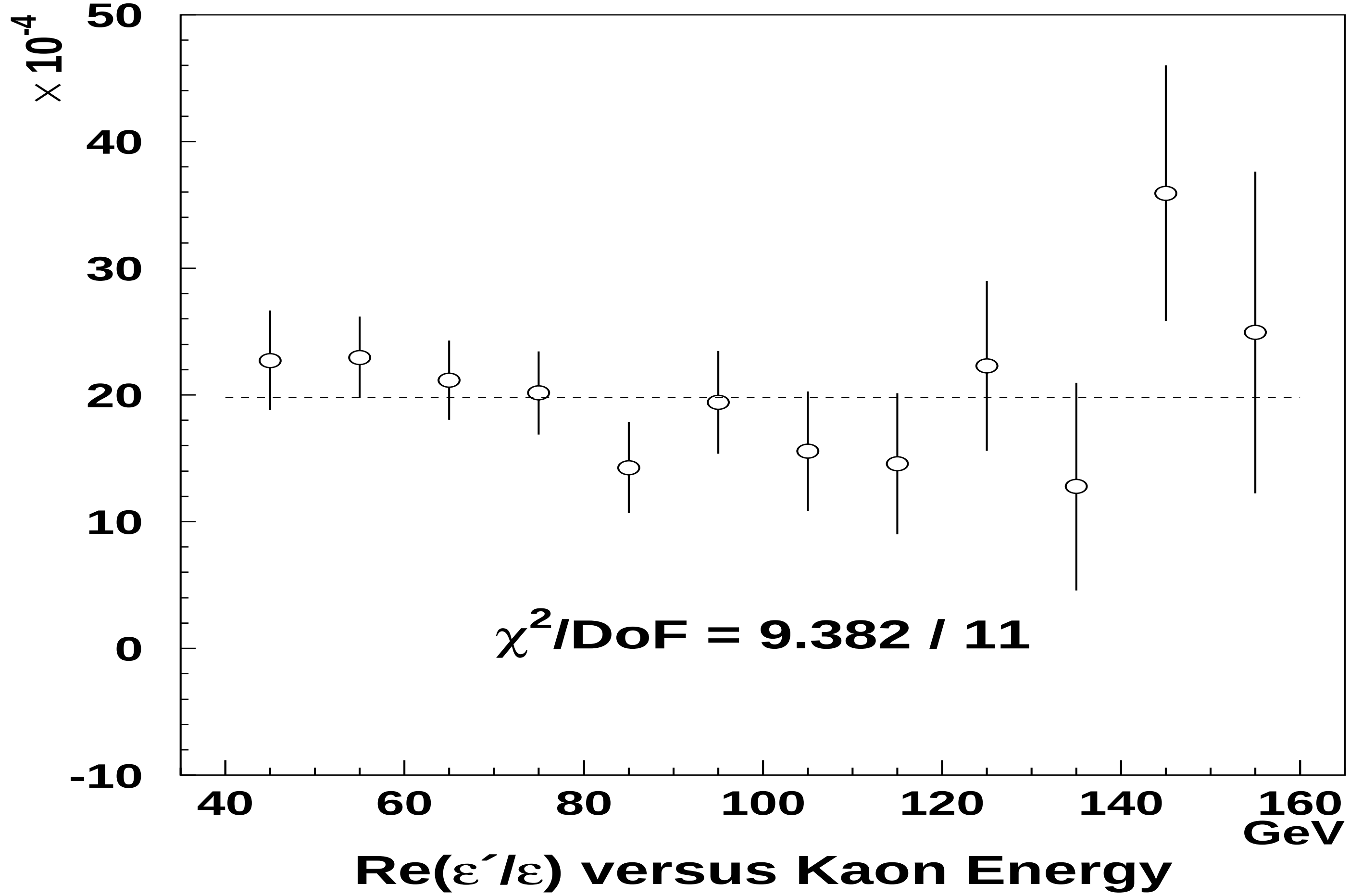


Systematic Uncertainties

Source of uncertainty	Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$	from $\pi^0\pi^0$
Class 1: Data collection		
Trigger and level 3 filter	**0.62**	**0.16**
Class 2: Event reconstruction, selection, backgrounds		
Energy/Resolution scale	**0.16**	**1.37**
Calorimeter nonlinearity	—	**0.66**
Detector calibration, alignment	**0.28**	**0.38**
Analysis cut variations, Reconstruction	**0.25**	**0.37**
Background subtraction	**0.2**	**1.06**
Class 3: Detector acceptance		
Limiting apertures	**0.33**	**0.48**
Detector resolution	**0.15**	**0.08**
Drift chamber simulation	**0.37**	—
z dependence	**0.53**	**0.26**
Monte Carlo statistics	**0.33**	**0.49**
Class 4: Kaon flux and physics parameters		
Regenerator-beam attenuation:		
Energy dependence	**0.19**	
Δm, τ_S, regeneration phase, screening	**0.39**	
TOTAL	**2.39**	

Table 9: Table of systematics on $Re(\epsilon'/\epsilon)$ in the format of the PRL, updated for the 1997B analysis.

KTeV 1997 ε’/ε Result



$Re(\varepsilon'/\varepsilon)=(19.8\pm1.7(stat)\pm2.3(syst)\pm0.6(mc\ stat))x10^{-4}$

Reweighting Analysis

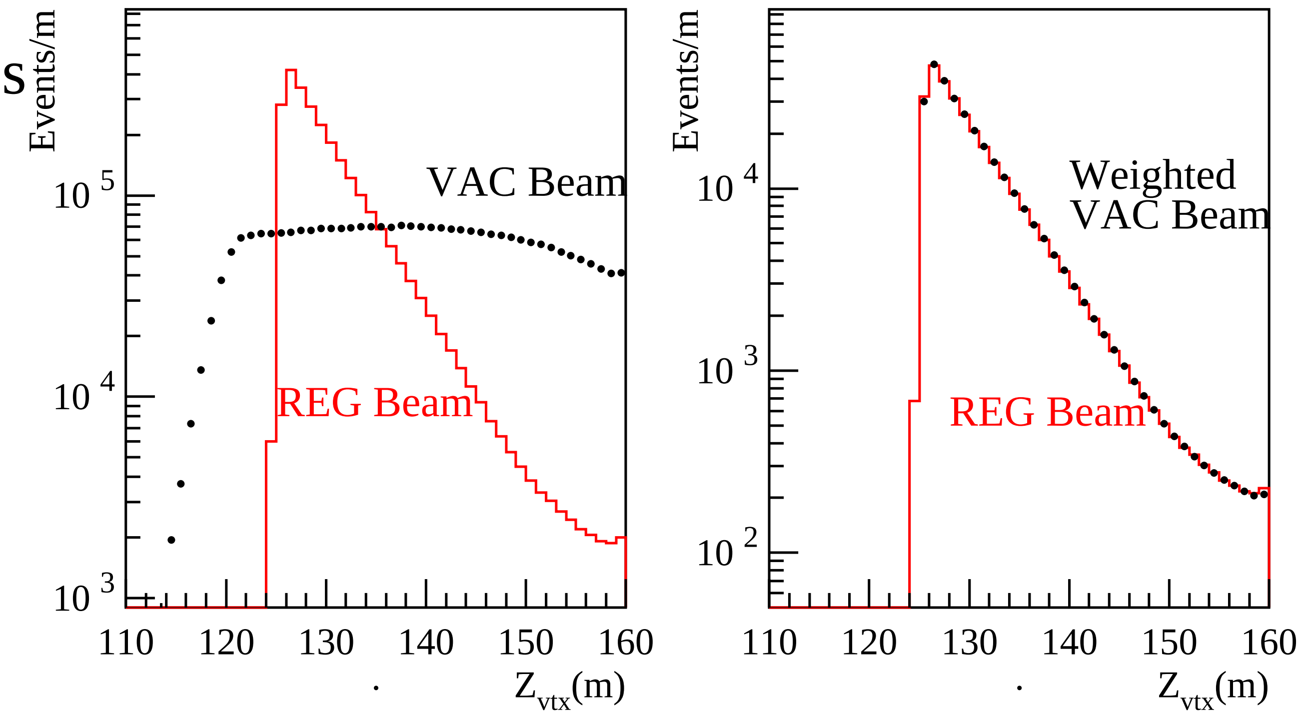
- MC acceptance correction is only ~5% on the double ratio
  - … but this is ~90×10^{-4} on ε'/ε
- We have strong cross checks on our acceptance calculation
  - E.g., purely geometrical MC accounts for about 90% of the acceptance correction
- However, an "MC independent" measurement is desirable:
- Reweighting:
  - reweight VAC beam to have same p,Z distribution as REG
  - Similar to NA48 method (CERN), but more complicated due to substantial interference of K_L and K_S

$$w(p,z) = \frac{prob(REG; p,z)}{prob(VAC; p,z)}$$

Pros and Cons of Reweighting

- Reweighting completely removes biases from lifetimes and geometry
- Reweighting de-emphasizes tracks near beam regions
  – Less susceptibility to rate and accidental effects

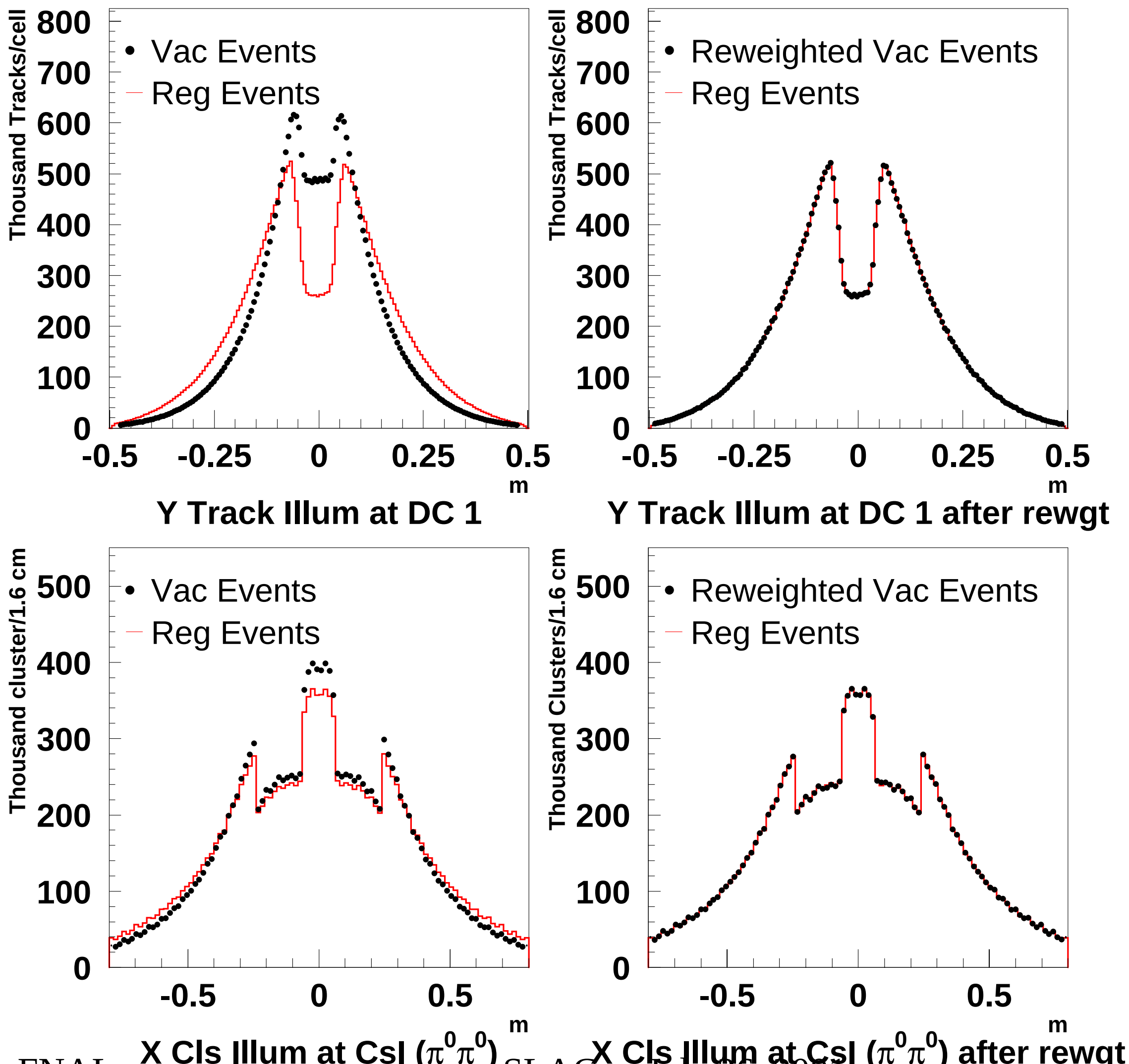
Vertex Distributions - 1997 Dataset



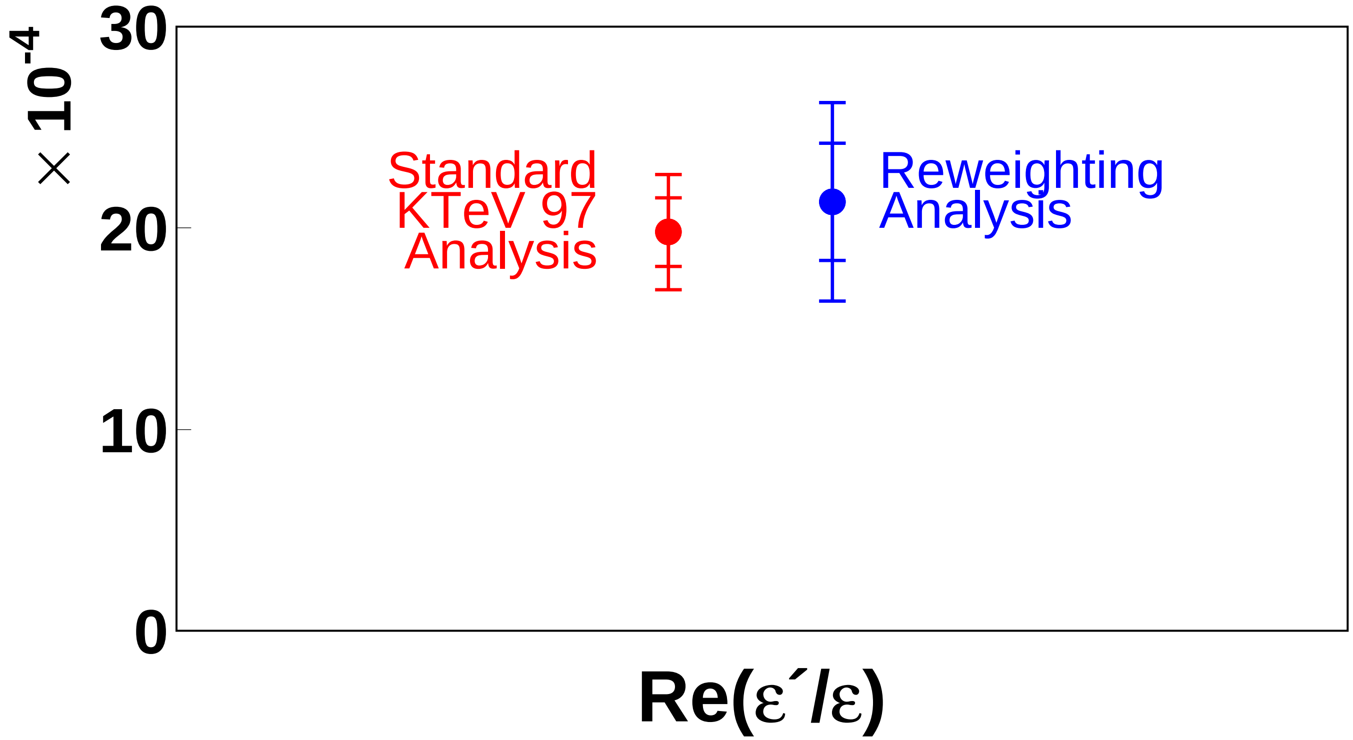
- Statistically weaker
  – $\delta(\varepsilon'/\varepsilon)$: $1.7\times10^{-4} \rightarrow 3.0\times10^{-4}$

Examples of Reweighting

Data vs. Data



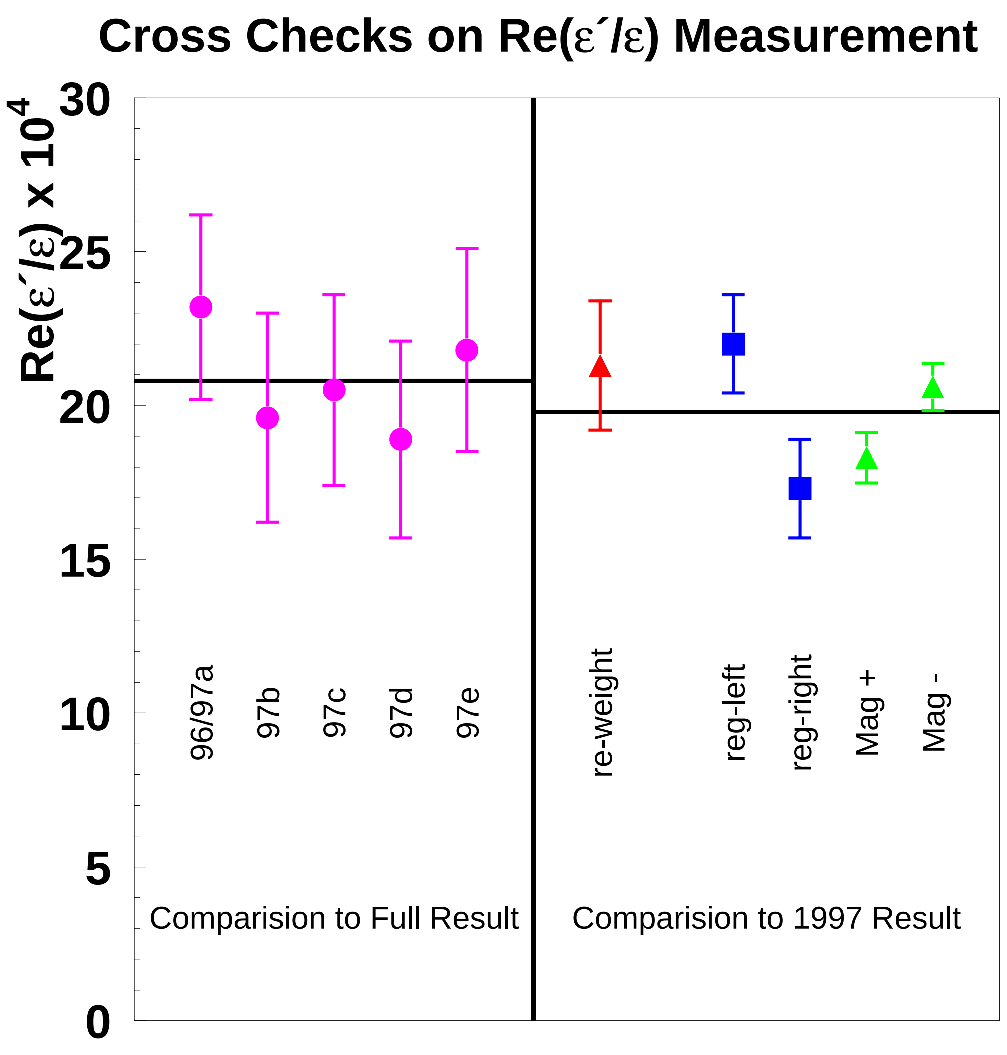
Reweighting Result



With preliminary understanding of correlated uncertainties,
$\Delta(\varepsilon'/\varepsilon)=(1.5 \pm 2.1(stat) \pm 3\ (syst)\ )\ x10^{-4}$

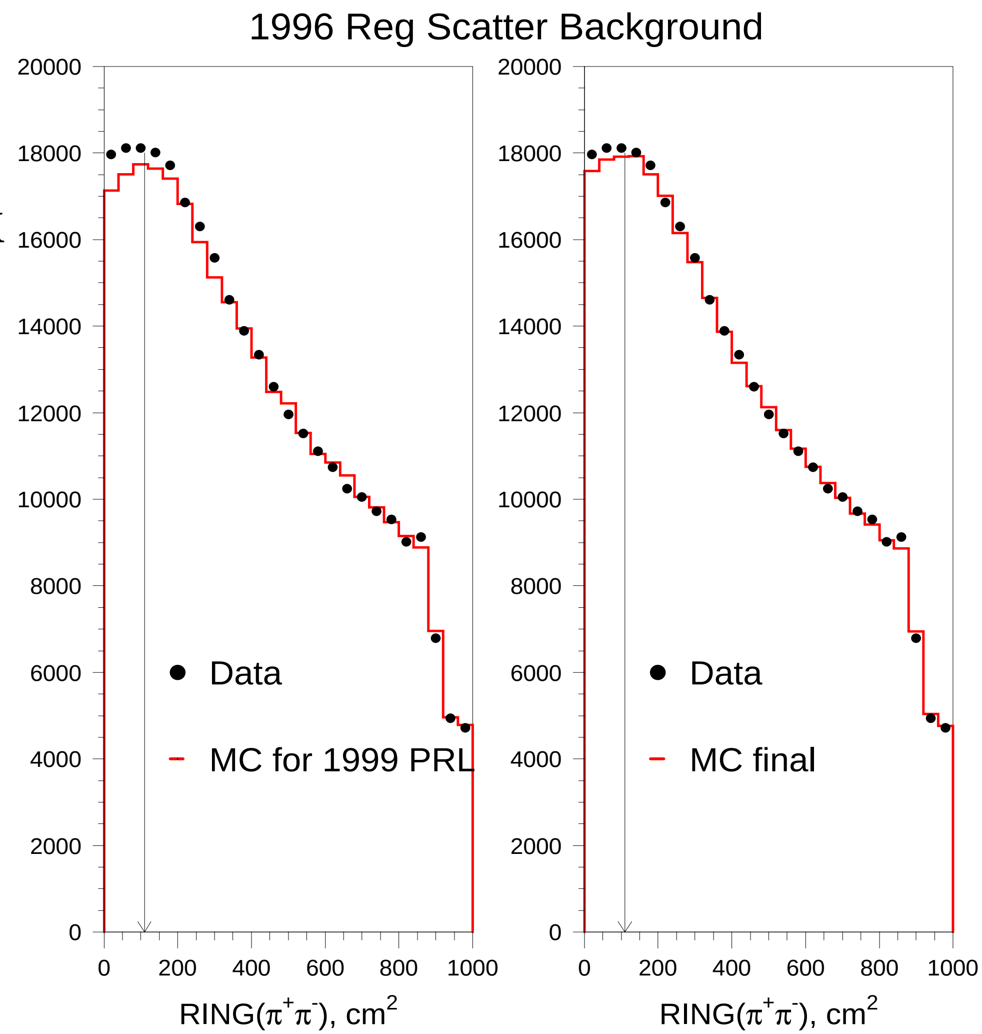
- Preliminary reweighting results (NOT the official KTeV Number….)
  - $Re(\varepsilon'/\varepsilon)=21.3\pm2.9(stat)\ \pm4.0(syst)$
  - *Hope to reduce systematic…*

Other Cross Checks



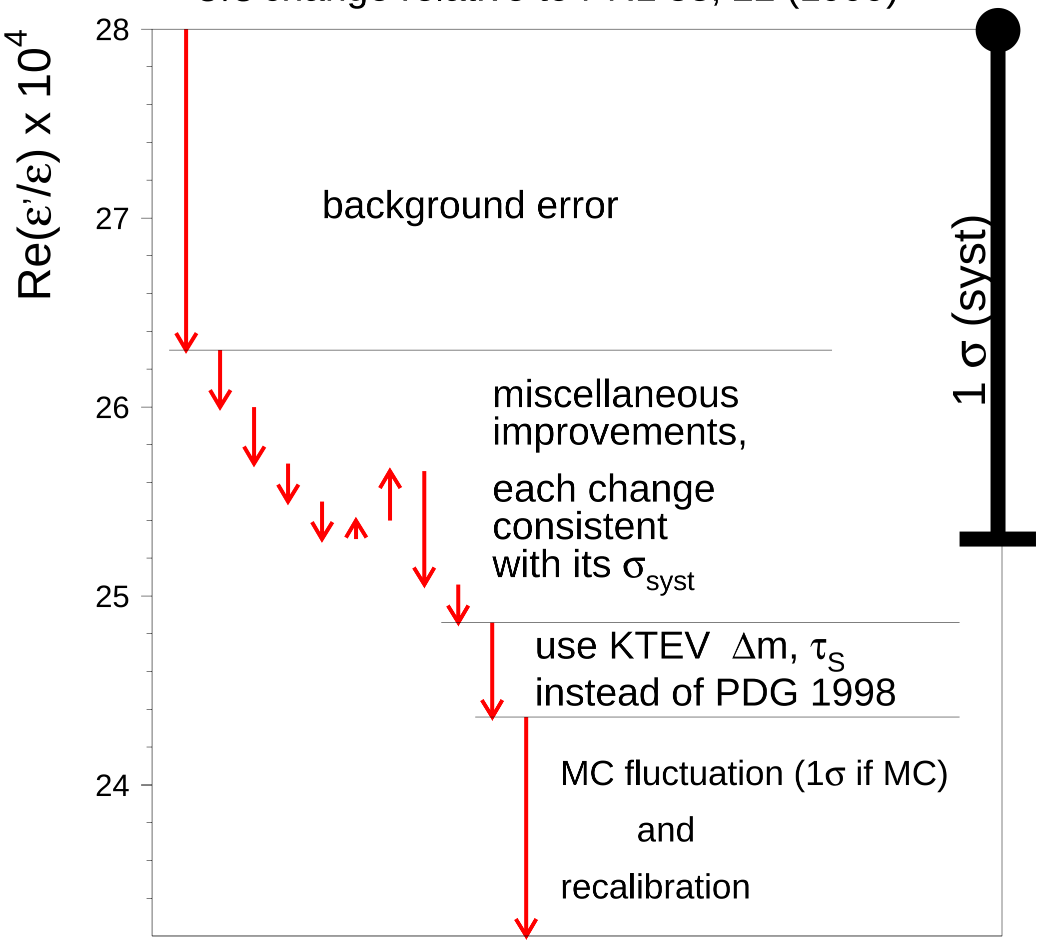
Re-Analysis of 1996/97a Result

- Miscellaneous improvements
  - e.g. recalibration, Mask Anti, DC Simulation
- Mistake found in $\pi^0\pi^0$ scattering background
- External parameters
  - Δm, τ_S from KTeV (was PDG98)



Updated 1996/97a Results

ε'/ε change relative to PRL 83, 22 (1999)



New 1996 Result:

$\varepsilon'/\varepsilon = (23.2 \pm 3.0\ (stat) \pm 3.2\ (syst) \pm 0.7\ (MC\ st)) \times 10^{-4}$

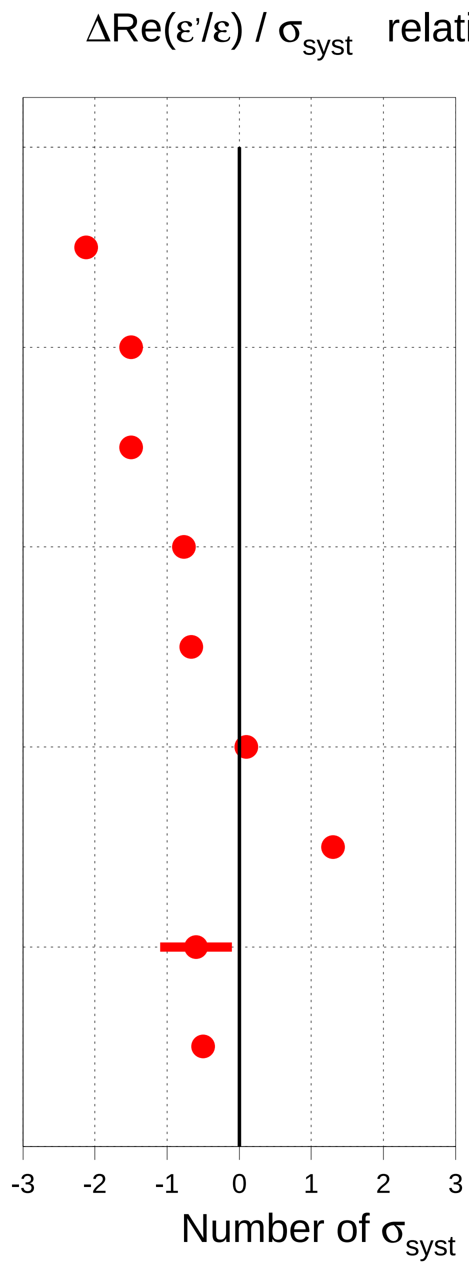
Old Result: (superceded)

$\varepsilon'/\varepsilon = (28.0 \pm 3.0\ (stat) \pm 2.7\ (syst) \pm 1.0\ (MC\ st)) \times 10^{-4}$

Note: sources of shifts are not correlated

Shifts in Updated Analysis

Each consistent
With quoted
Systematic uncertainty



comment (ΔRe(ε'/ε))
$2\pi^0$ background (-1.7×10^{-4})
reg screening (-0.3×10^{-4})
reg attenuation (-0.3×10^{-4})
$\pi^+\pi^-$ reg edge (-0.2×10^{-4})
collimator scatter (-0.2×10^{-4})
$2\pi^0$ analysis (0.1×10^{-4})
Mask Anti geometry (0.26×10^{-4})
Absorber scatter (-0.6×10^{-4})
$2\pi^0$ reg edge (-0.2×10^{-4})

and 1997 Results

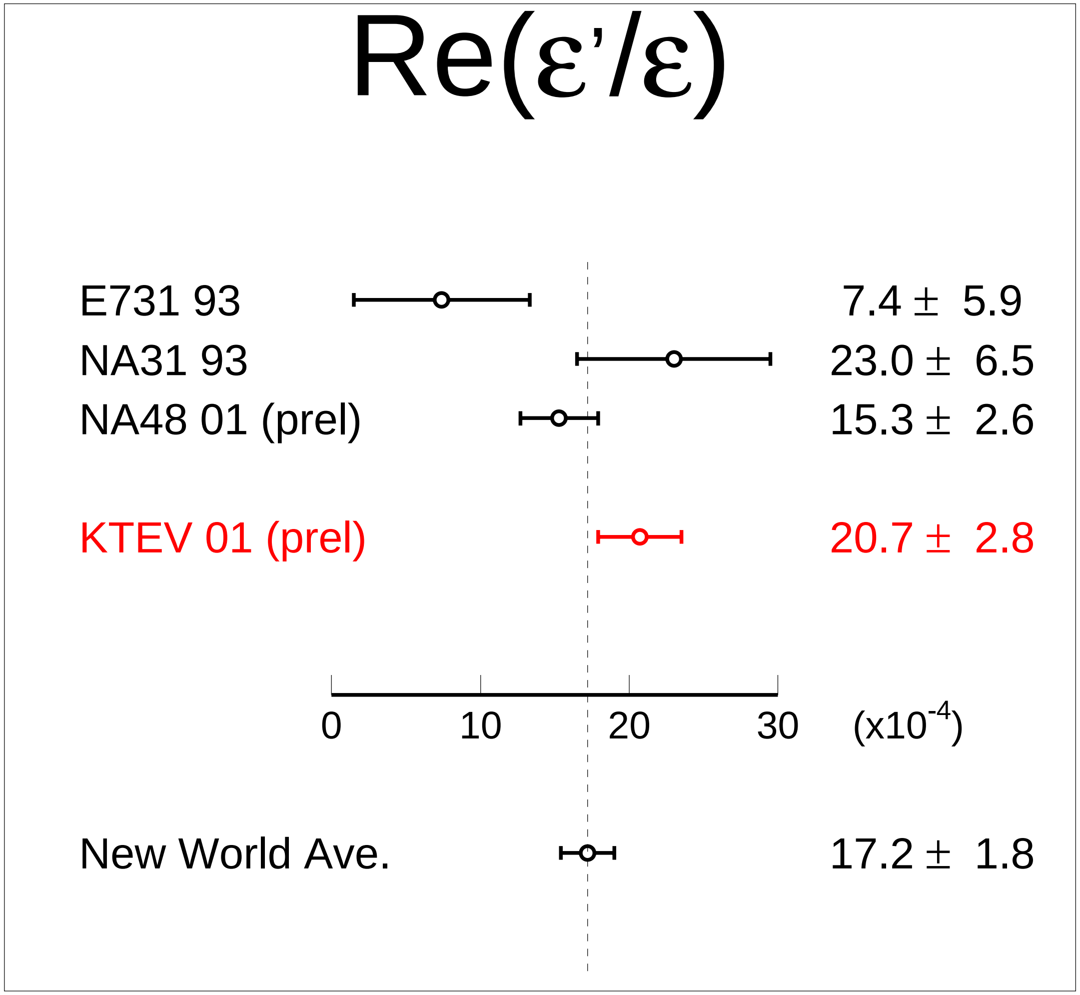
Systematic Uncertainties for Combined Result

Source of uncertainty	Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$	from $\pi^0\pi^0$
Class 1: Data collection		
Trigger and level 3 filter	**0.56**	**0.18**
Class 2: Event reconstruction, selection, backgrounds		
Energy/Resolution scale	**0.16**	**1.27**
Calorimeter nonlinearity	—	**0.66**
Detector calib, align	**0.28**	**0.38**
Analysis cut variations	**0.23**	**0.37**
Background subtraction	**0.20**	**1.07**
Class 3: Detector acceptance		
Limiting apertures	**0.30**	**0.48**
Detector resolution	**0.15**	**0.08**
Drift chamber simulation	**0.37**	—
z dependence	**0.89**	**0.32**
Class 4: Kaon flux and physics parameters		
Reg-beam attenuation	**0.19**	
Δm, τ_S	**0.24**	
Reg phase screening	**0.31**	
TOTAL	**2.36**	

Re(ε'/ε)=(20.7
±1.5(stat)
±2.4(syst)
±0.5(MC Stat)
)x10^{-4}

Re(e'/e)=(20.7 ± 2.8)
x 10^{-4}

World Data on Re(ε'/ε)

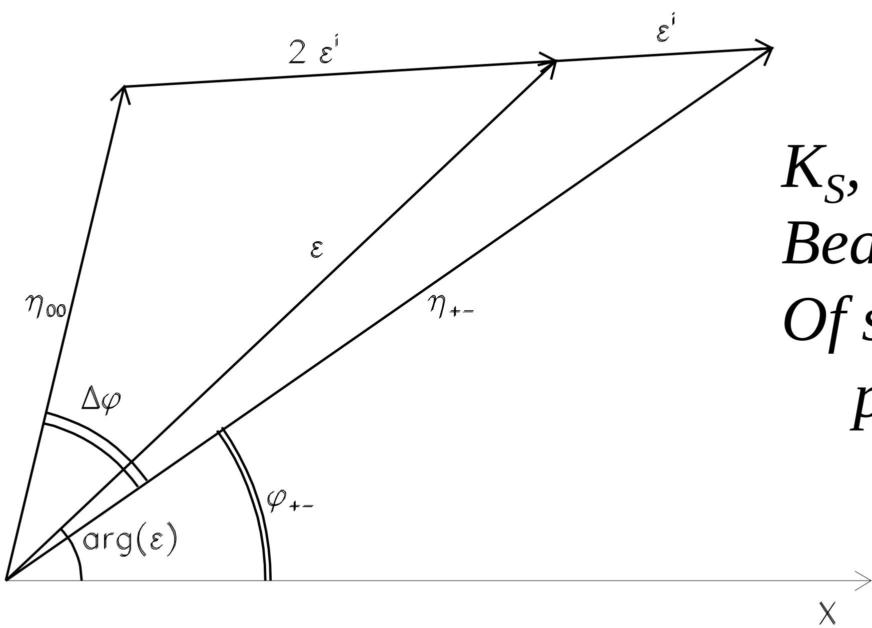


- World Average:
  - (17.2±1.8)x10^{-4}
- Probability=13%

Kaon System Parameters

With the interference information in the regenerator beam, KTeV can measure the kaon sector parameters:

- $\Delta m = m_{K_L} - m_{K_S}$
- τ_S
- ϕ_{+-}, phase of η_{+-}
- $\Delta\phi = \phi_{00} - \phi_{+-}$ [$\not{CPT}$]



K_S, K_L, and Interference in REG Beam allows measurement Of several Kaon system parameters

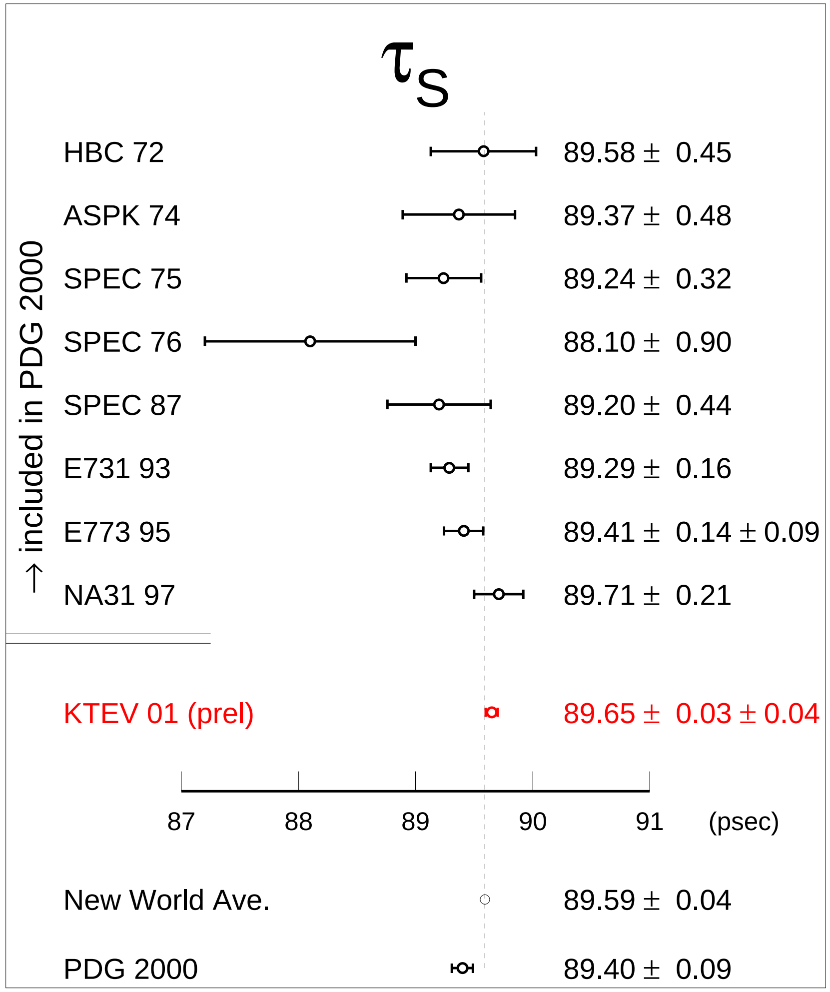
$$\mathrm{Im}(\epsilon'/\epsilon) = -\tfrac{1}{3}\Delta\phi \quad [\not{CPT}]$$

Have made new measurements of the above. $\mathrm{Re}(\epsilon'/\epsilon)$ fit uses our best values.

Measured in KTeV

PRELIMINARY:

$$\Delta m = (5262 \pm 7.7\ (\text{exp}) \pm 13\ (\text{th.})) \times 10^{6} \hbar s^{-1}$$
$$\tau_S = (8967.1 \pm 3.5\ (\text{exp}) \pm 4\ (\text{th.})) \times 10^{-14} s$$
$$\phi_{+-} = 44.11 \pm 0.72\ (\text{stat}) \pm 1.1\ (\text{syst})$$
$$\Delta\phi = 0.41^\circ \pm 0.22^\circ (\text{stat}) \pm 0.53^\circ (\text{syst})$$



Conclusions

- KTeV has new Re(ε'/ε) result with improved error
- Re-analysis of 1996 result
- Combined KTeV Result:
  - Re(e'/e)=$(20.7\pm2.8)\times10^{-4}$
- World data now in significantly better agreement
  - World Average: $(17.2\pm1.8)\times10^{-4}$
  - 13% CL
  - ε'/ε now known to ~10%
- More data from 1999 run!