A New Measurement of ϵ'/ϵ from KTeV

Jim Graham
University of Chicago

FNAL Wine & Cheese
June 8 2001

For the KTeV Collaboration:
Arizona – Chicago – Colorado – Elmhurst
Fermilab – Osaka – Rice – Rutgers
UCLA – UCSD – Virginia – Wisconsin

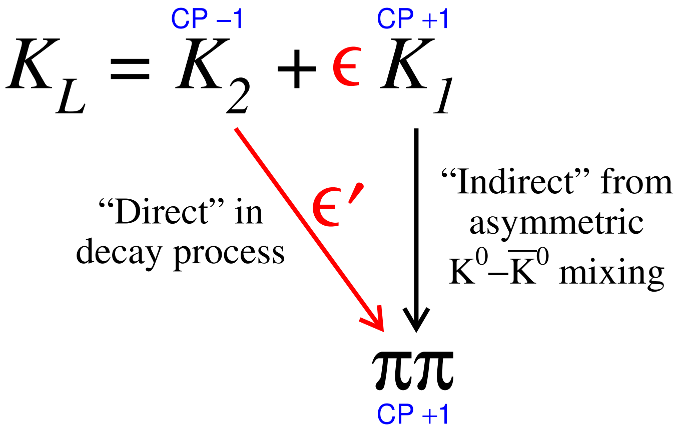
Outline of Talk

1. Introduction to $\mathrm{Re}(\epsilon'/\epsilon)$
2. Experimental status.
3. The KTeV detector and response.
4. Reconstruction of and backgrounds to $K \to \pi^+\pi^-$ and $K \to \pi^0\pi^0$.
5. The acceptance correction.
6. The systematic uncertainty.
7. From counting to fitting $\mathrm{Re}(\epsilon'/\epsilon)$.
8. The result and cross-checks.
9. Conclusions and future prospects.

Introduction to Re(ϵ'/ϵ)

- Weak eigenstates contain small admixture of "wrong" CP state

$$|K_S\rangle \sim |K_1\rangle + \epsilon |K_2\rangle$$
$$|K_L\rangle \sim |K_2\rangle + \epsilon |K_1\rangle$$

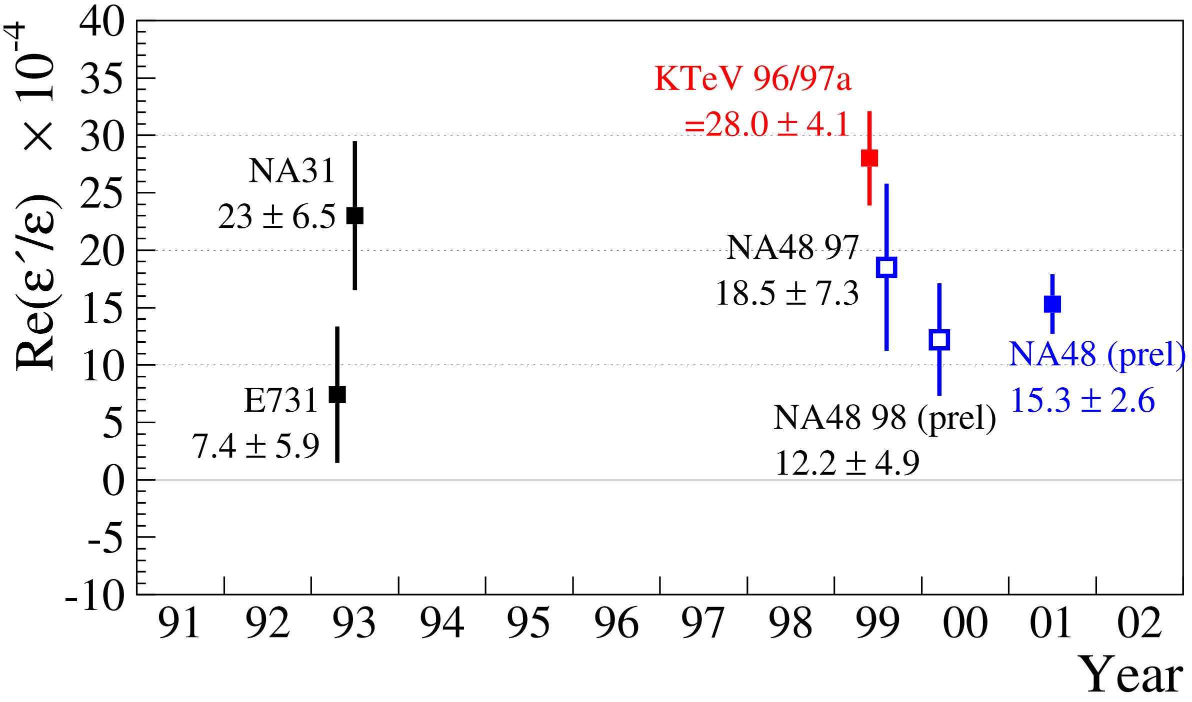


- Useful to define the following measureable quantities

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

- $\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \simeq 1 + 6\mathrm{Re}(\epsilon'/\epsilon)$
- SM predicts *both* indirect and direct $\not{CP}$.
- Theoretical calculations range 4–30 $\times 10^{-4}$.

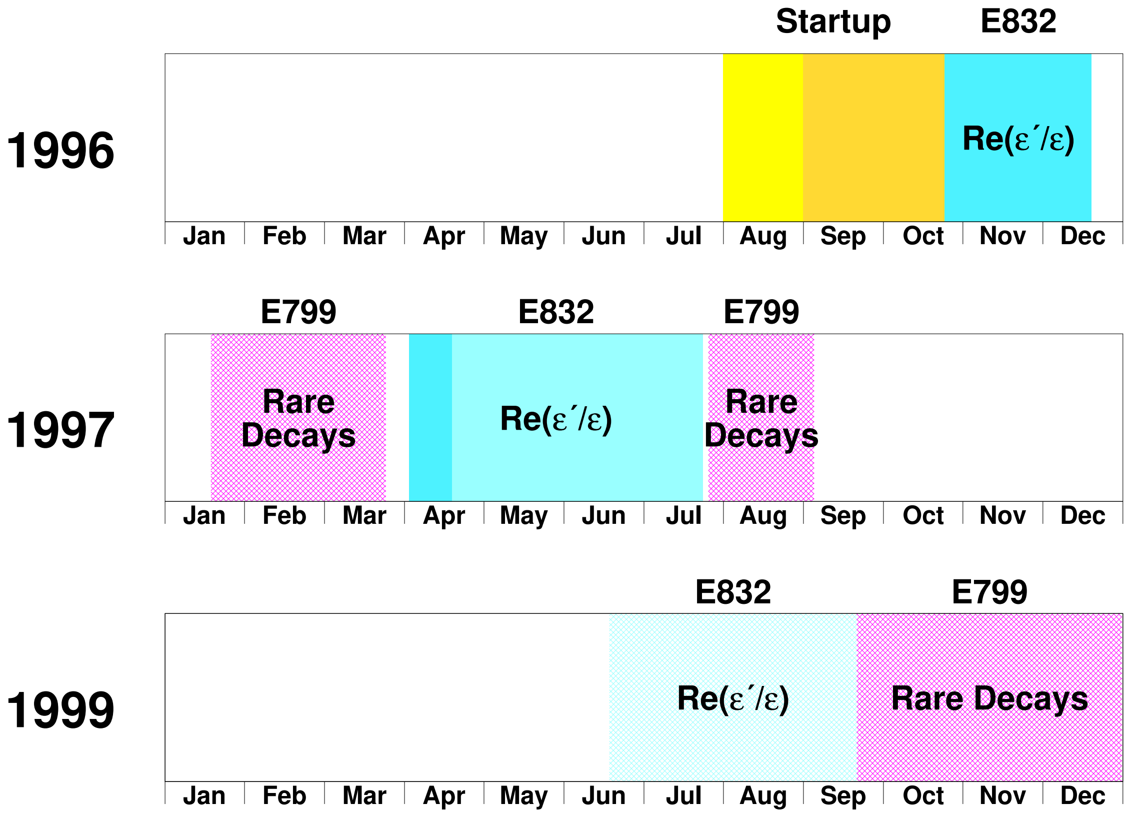
Experimental Status



+ The data establishes presence of the direct CP violation

– Large scatter of the values (probability = 1%)

The Fixed Target Run



Data sets used for new analysis (1997):

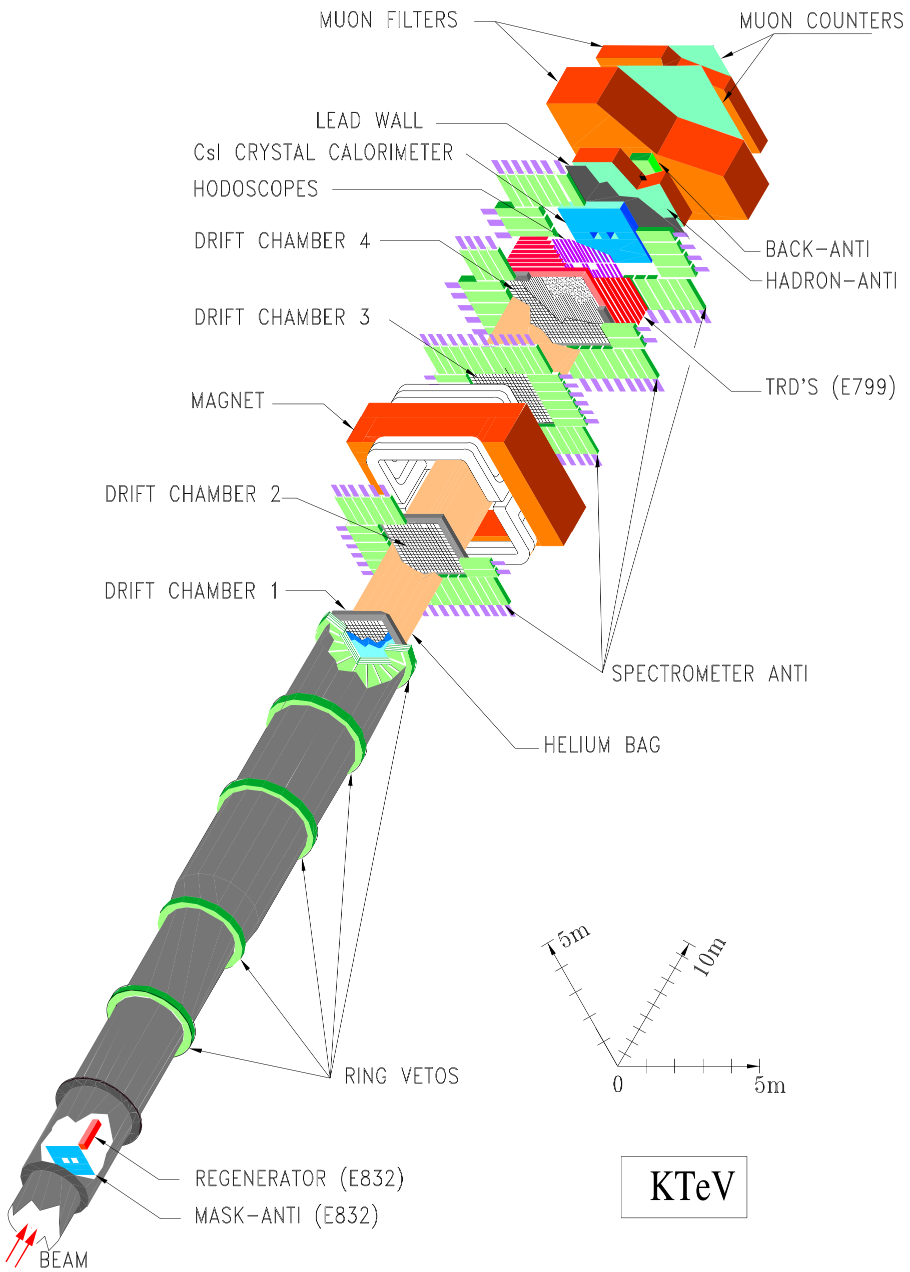
- $K \to \pi^0\pi^0$ and $K \to \pi^+\pi^-$ from 1997.

Published result (PRL 83, 22 (1999)):

- $K \to \pi^0\pi^0$ data from 1996.
- $K \to \pi^+\pi^-$ data from first 18 days of 1997.

Will present a combined result today.

The KTeV Detector



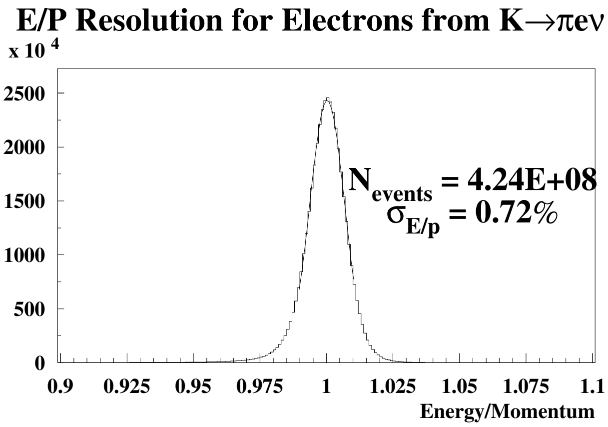
"Vacuum" beam $\rightarrow K_L$ beam

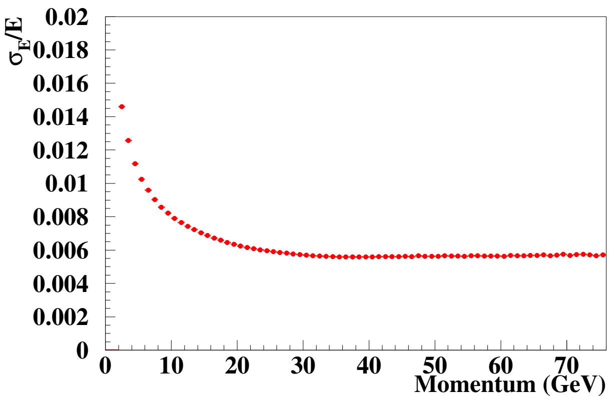
"Regenerator" beam $\rightarrow K_L + \rho K_S$ beam

The KTeV Detector Performance

NEUTRAL:

- CsI energy res: 0.7% at 15 GeV (1.3% at 3 GeV)
- CsI position res: $\sim$ 1 mm





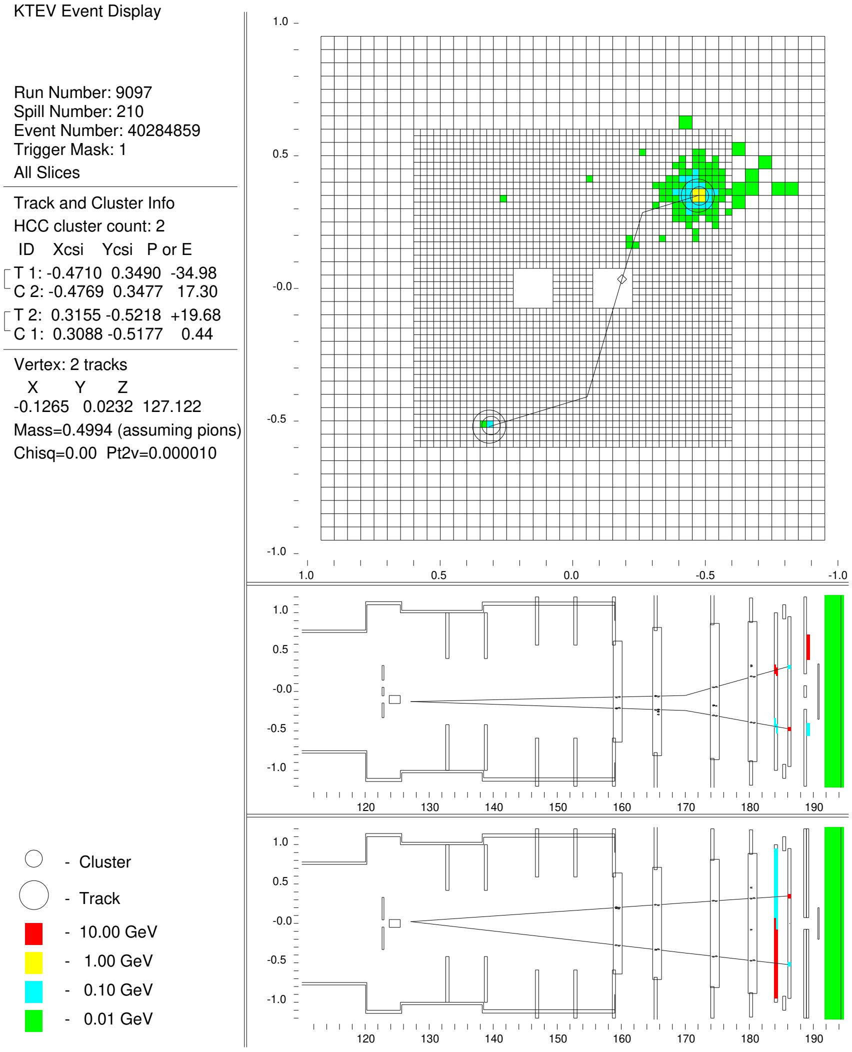
CHARGED:

- Drift Chamber resolution: 100 μm.
- Momentum resolution:

$$\frac{\sigma_p}{p} = 0.17\% \oplus 0.0071\% \cdot p \ [\mathrm{GeV}]$$

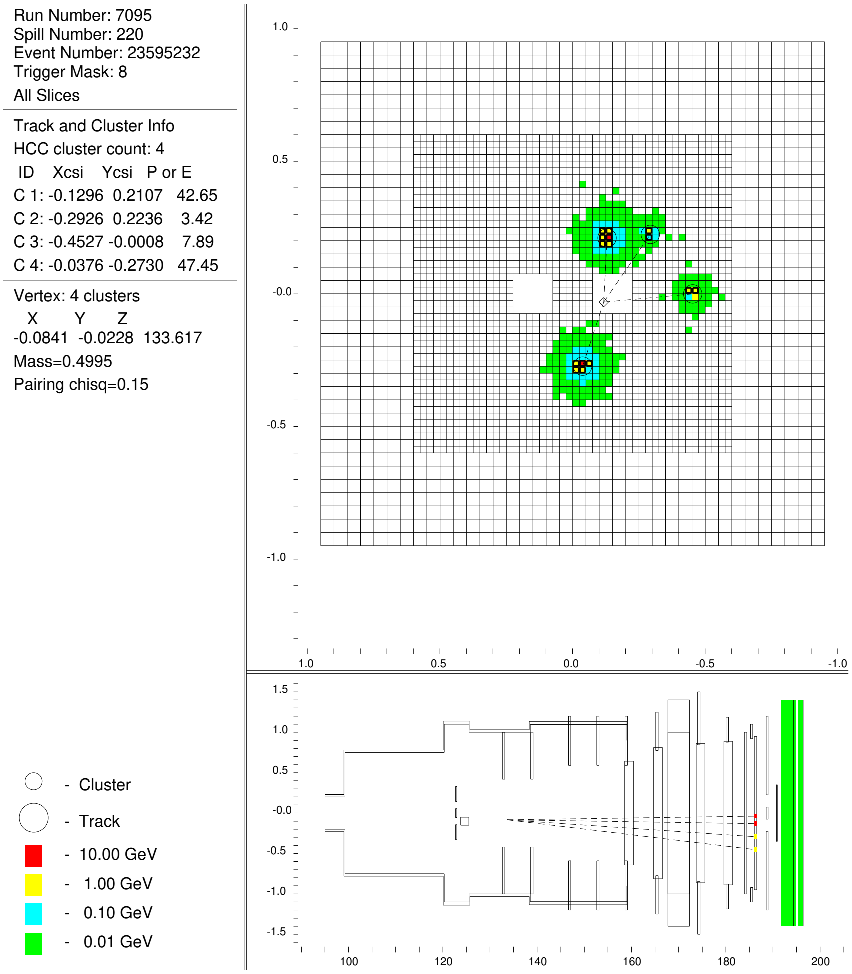
$$\sigma(M_{\pi^+\pi^-}) \sim \sigma(M_{\pi^0\pi^0}) \sim 1.5 \ \mathrm{MeV}$$

Sample $K \to \pi^+\pi^-$ Event



- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using x-vertex position
- Clearance cuts define fiducial volume.

Sample $K \to \pi^0\pi^0$ Event



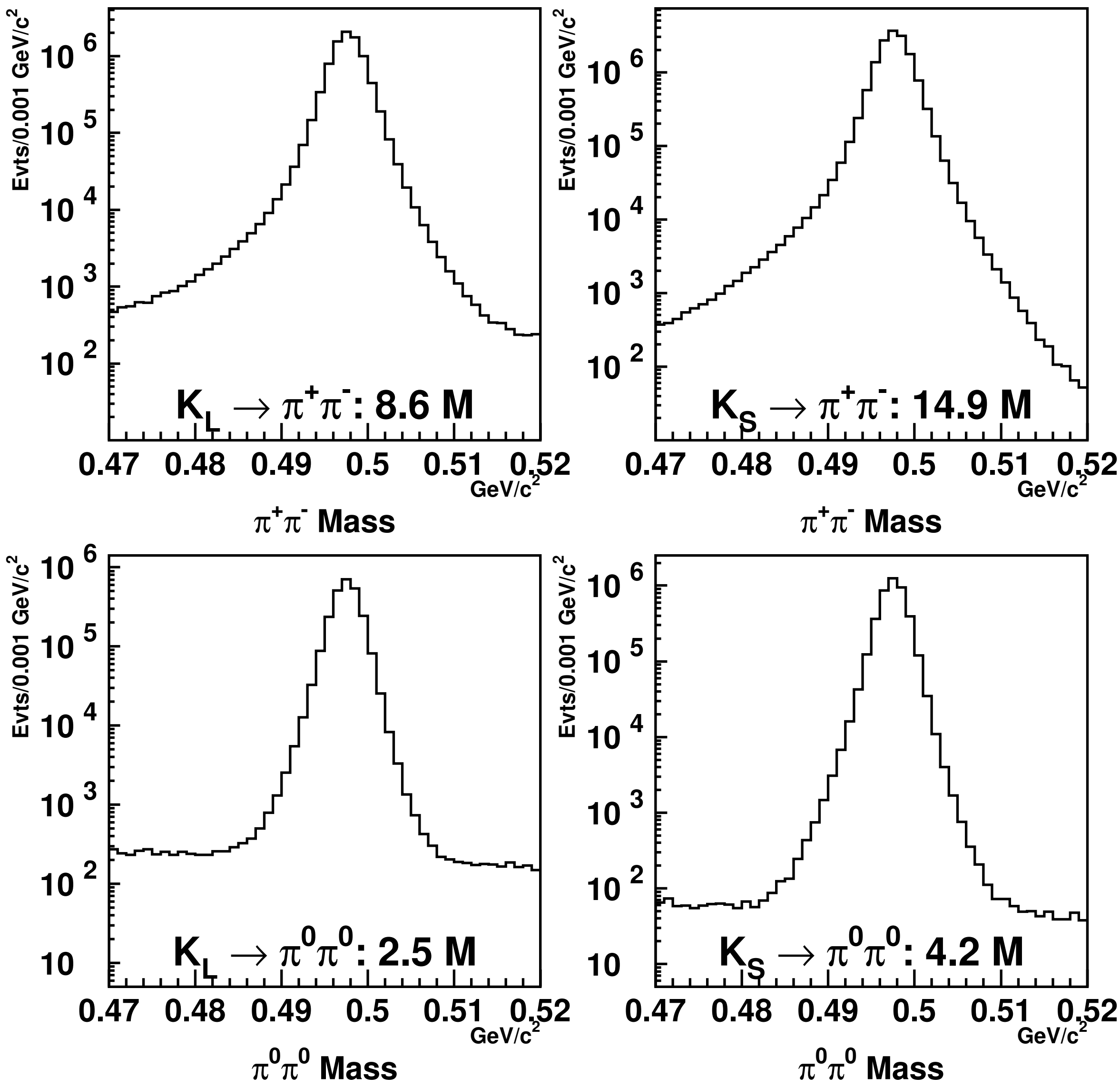
- CsI calorimeter to reconstruct photons energies and positions
- z_v determined as average of

$$z_{\pi^0} = \sqrt{E_1 E_2} R_{12} / m_{\pi^0}$$

- Regenerator/Vacuum beam identification using x-center of enegy
- Fiducial volume defind by veto detectors & z_v

Raw Reconstructed Mass Distributions

No background subtraction



Backgrounds to $K \to \pi\pi$

Backgrounds are different for charged-modes and neutral-modes

Charged-mode backgrounds:

- Semi-leptonic $K_L \to \pi^\pm e^\mp \nu_e$ ("K_{e3}")
- Semi-leptonic $K_L \to \pi^\pm \mu^\mp \nu_\mu$ ("$K_{\mu 3}$")

Neutral-mode backgrounds:

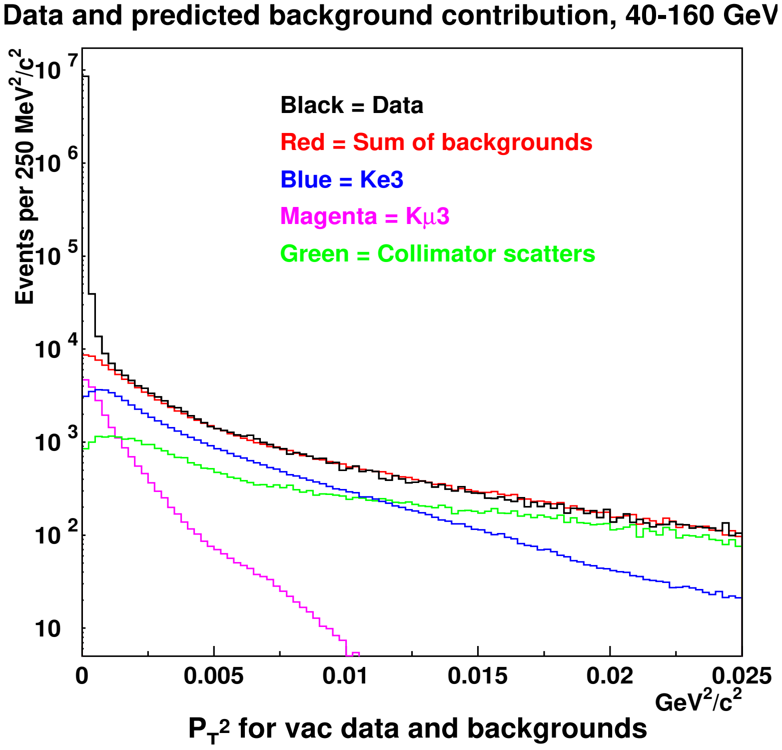
- $K_L \to 3\pi^0$

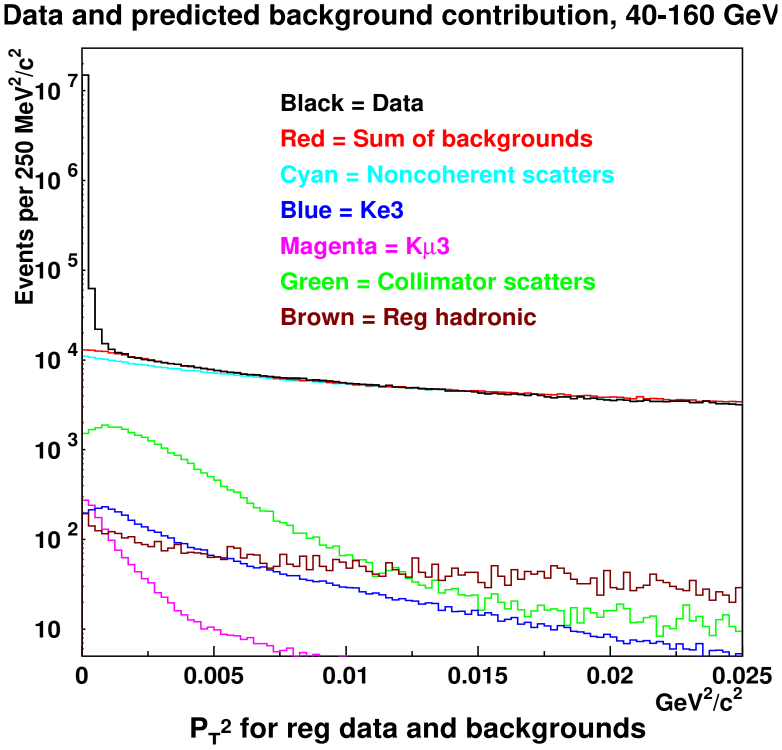
Common backgrounds:

- $K \to \pi\pi$ scattering in the final defining collimator.
- $K \to \pi\pi$ scattering in the regenerator.

The common backgrounds have different effects due to ability in separate modes to cut on P_T^2.

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

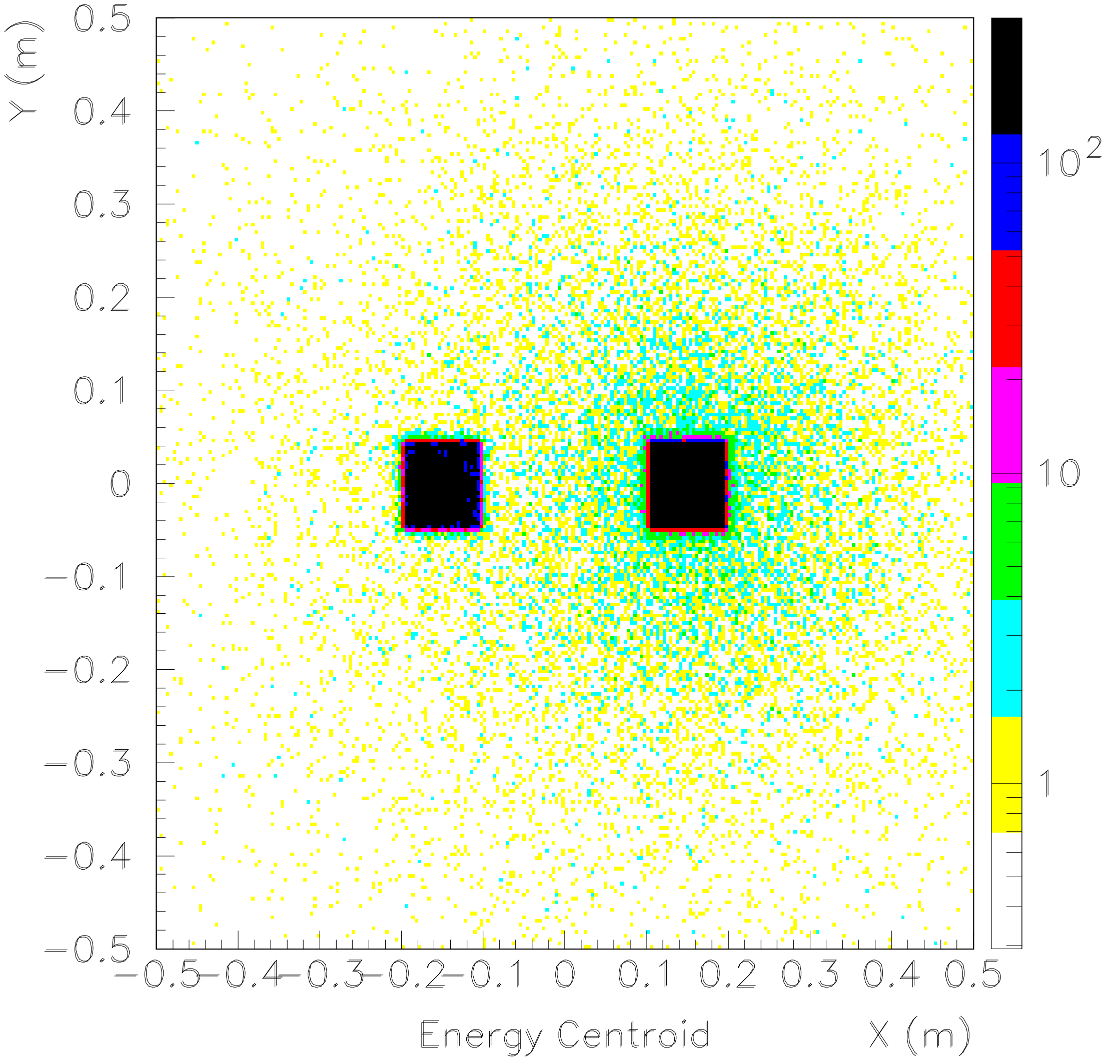




$\text{Back/Sign(Vac)} \approx 0.10\%$ $\text{Back/Sign(Reg)} \approx 0.09\ \%$

Good PID in calorimeter, μ-veto system suppresses semi-leptonic decays. Good resolution allows for tight P_T^2 cut against scatter backgrounds.

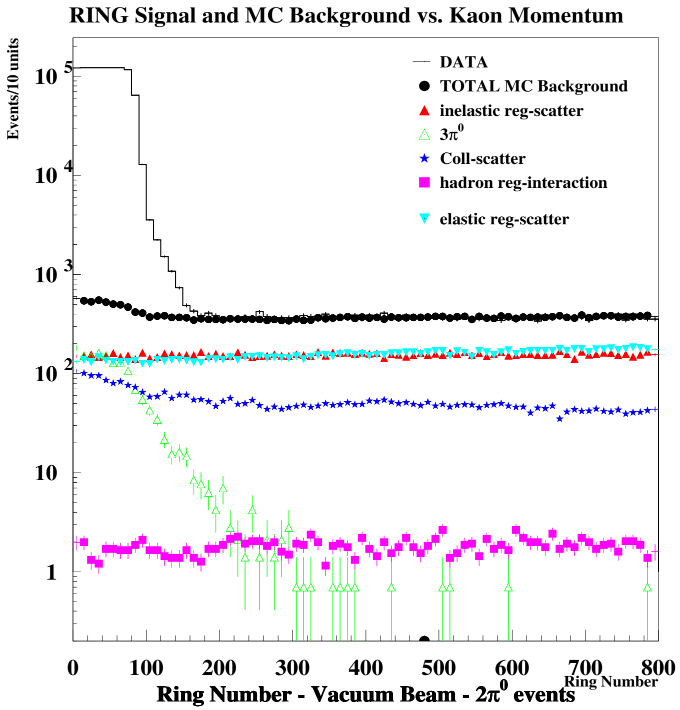
Kaon Center-of-Energy for $K \to \pi^0\pi^0$ Decays

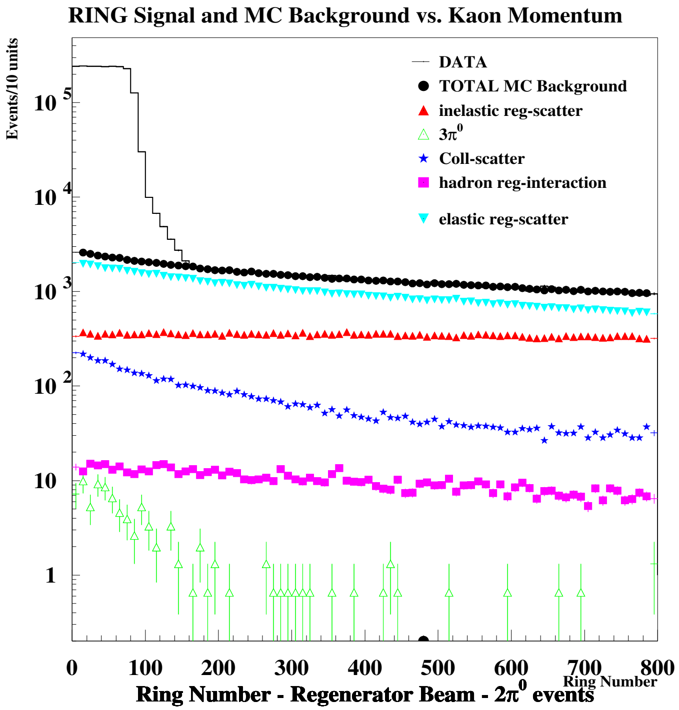


The two KTeV beams are shown: Vacuum on left, Regenerator on right.

Neutral-Mode Backgrounds

"Ring Number" is a scaled Center of Energy. Cut at $R = 110$ is the edge of the beam. Scattered events appear outside beam, $R > 110$. $K_L \to 3\pi^0$ events are inside beam, but identifiable from mass sidebands.





Back/Sign(Vac) $\approx$ 0.5% Back/Sign(Reg) $\approx$ 1.2 %

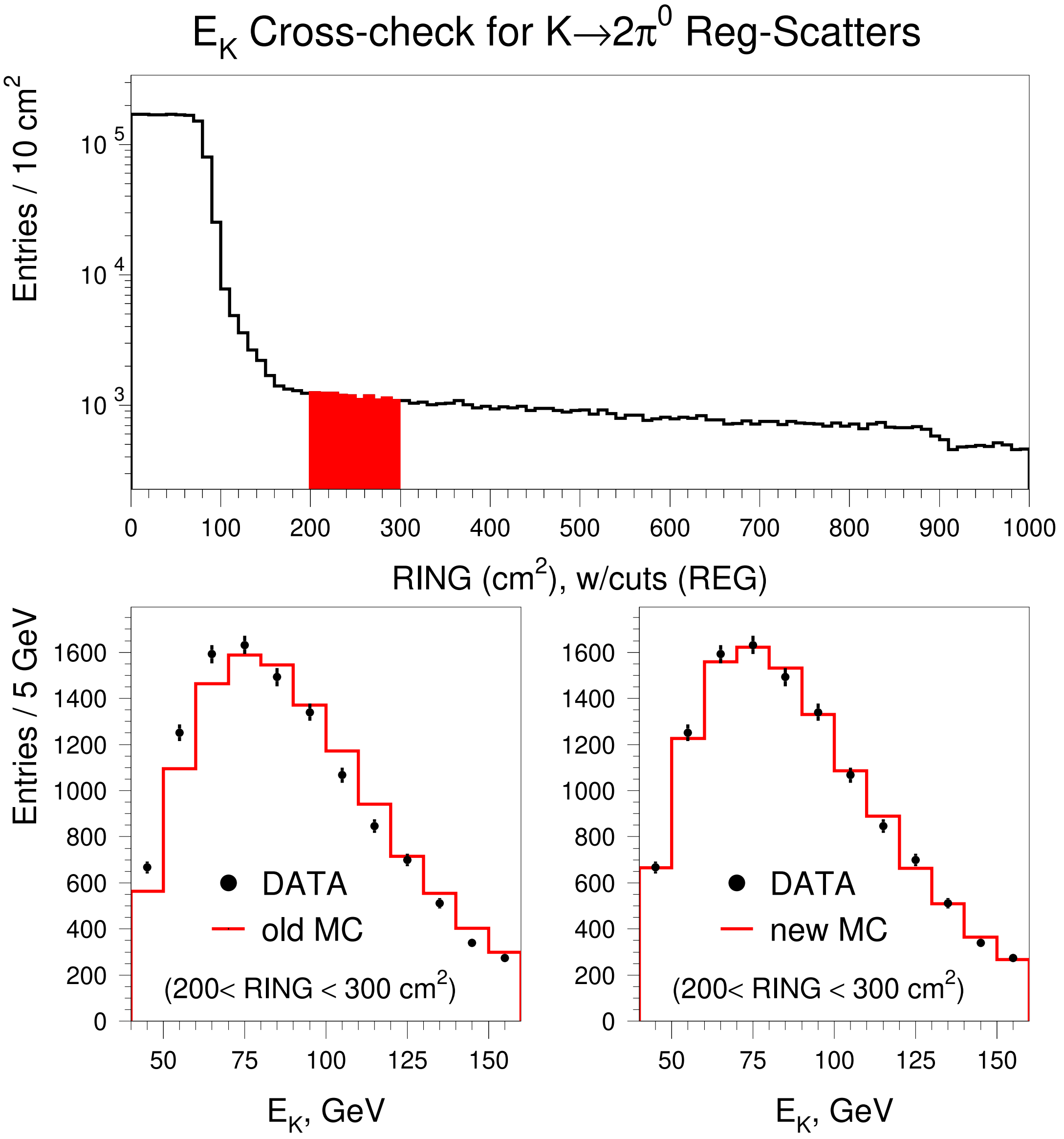
Regenerator Scattering Background

Scattering in the background is predicted from a Monte Carlo simulation that is *tuned to data*.

- The $K_S \to \pi^+\pi^-$ P_T^2 spectrum is acceptance-corrected and then fit to a 3D function of P_K, P_T^2 and t/τ_S.
- With the reg-scat function, we generate MC scattered $K \to \pi^0\pi^0$ decays to determine neutral background.
- Improvements since PRL result give better data/fit-function agreement for $K_S \to \pi^+\pi^-$ regenerator-scattered events.

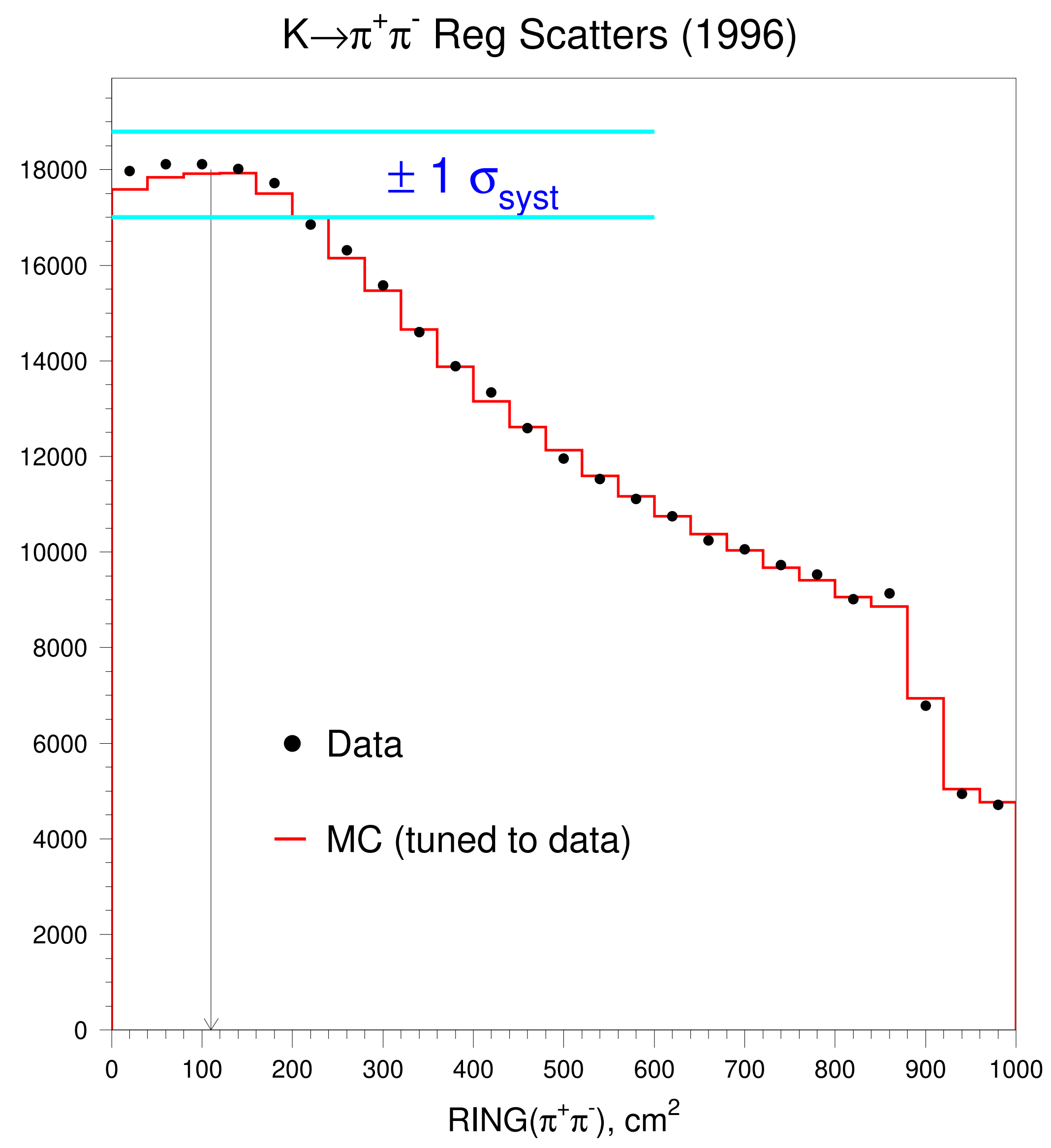
Investigating the fit function revealed a mistake in the background estimation for the published result $\Delta\mathrm{Re}(\epsilon'/\epsilon) = -1.7 \times 10^{-4}$.

Fixed P_K Dependence of Background



New regenerator scattering Monte Carlo improves P_K dependence of background.

Check Scatter Model in $K \to \pi^+\pi^-$



Background/Signal Levels for KTeV

Background Source	KTeV Vac Beam ($\times 10^{-3}$)	KTeV Reg Beam ($\times 10^{-3}$)
Charged $K \to \pi l \nu$	0.90	0.03
Charged Scattering in Coll	0.10	0.10
Charged Scattering in Reg	—	0.73
Total	1.00	0.87
$K_L \to 3\pi^0$	1.1	0.3
Neutral Scattering in Coll	1.2	0.9
Neutral Scattering in Reg	2.5	11.3
Reg Hadronic Int.	—	0.1
Total	4.8	12.4

If we ignored backgrounds: $\Delta \mathrm{Re}(\epsilon'/\epsilon) \approx 13 \times 10^{-4}$.

Systematic for background: $\sigma_{\mathrm{bkgd}} = 1.1 \times 10^{-4}$.

Number of Events and Statistical Precision

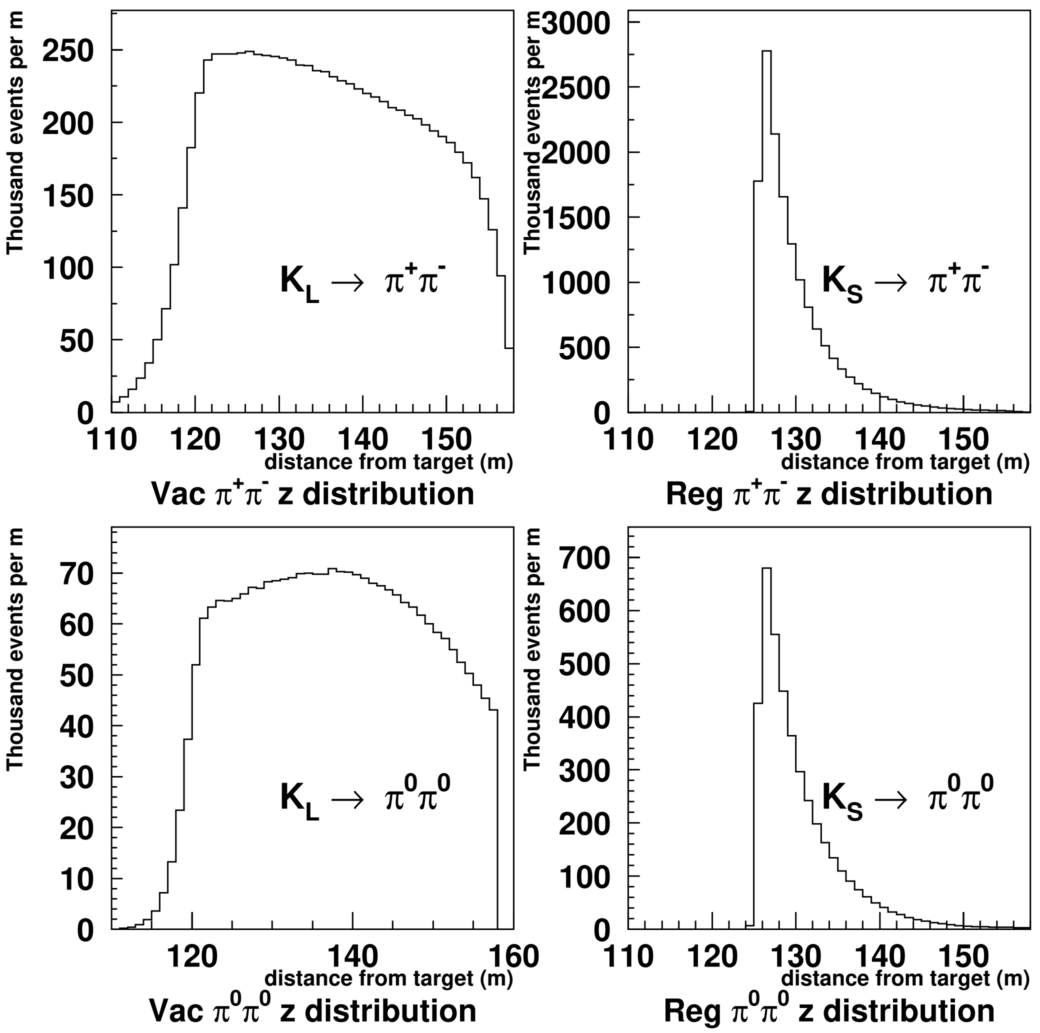
	$K_L \to$		$K_S \to$		
	$\pi^+\pi^-$ $(\times 10^6)$	$\pi^0\pi^0$ $(\times 10^6)$	$\pi^+\pi^-$ $(\times 10^6)$	$\pi^0\pi^0$ $(\times 10^6)$	σ(stat) $(\times 10^{-4})$
PRL	2.6	0.9	4.5	1.4	3.0
1997	8.6	2.5	14.9	4.2	1.73
Combined	11.2	3.4	19.4	5.6	~ 1.5

Have collected large statistics samples for $\mathrm{Re}(\epsilon'/\epsilon)$ analysis.

Not quite at $\sigma(\mathrm{stat}) = 1 \times 10^{-4}$ level.

Can achieve that level with addition of KTeV99 dataset.

Understanding the Acceptance



Due to the different lifetimes ($\tau_L \gg \tau_S$), the K_S beam reconstructs upstream of the K_L beam, and hence has a different *average* acceptance.

Need an analysis technique to put two beams on equal footing.

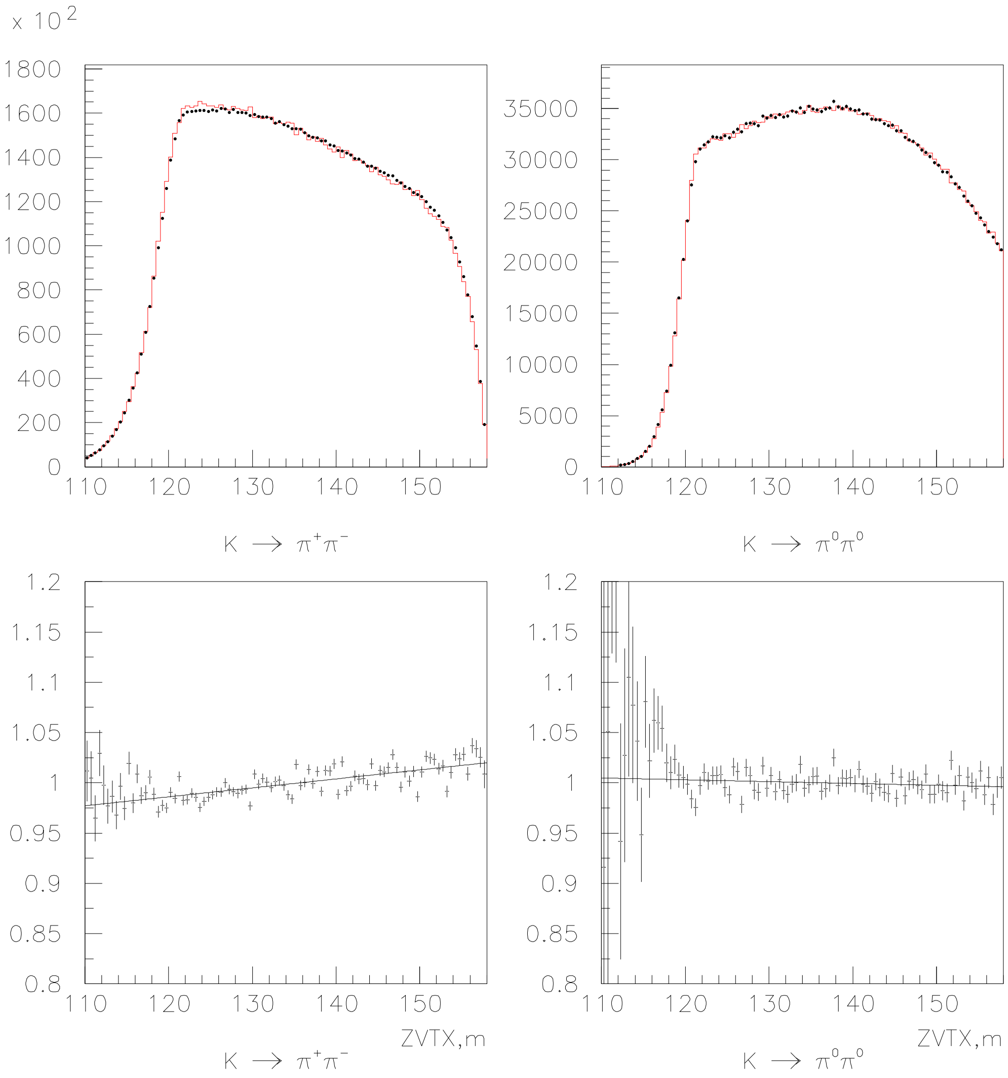
The Monte Carlo Acceptance Correction

We measure the detector geometry and response, and create a detailed MC prediction of the acceptance in each beam.

Correction to $\mathrm{Re}(\epsilon'/\epsilon)$ is large ($\sim 80 \times 10^{-4}$) $\rightarrow$ Systematics under control?

- Most of the correction is due to the geometry of the detector ($\sim 90\%$).
- Remaining effort for detailed understanding of detector response.
- Use large statistics modes (K_{e3}, $K_L \rightarrow 3\pi^0$) to cross-check performance of the Monte Carlo.
- Monte Carlo predicts slight acceptance differences between beams, due to accidental activity.
- Can measure kaon parameters ($\tau_S, \Delta m$)

Geometry-Only MC



Acceptance correction based on Monte Carlo with ideal detector response: $\Delta\mathrm{Re}(\epsilon'/\epsilon) \approx 12 \times 10^{-4}$, of which $\sim 10 \times 10^{-4}$ is seen as a z-slope.

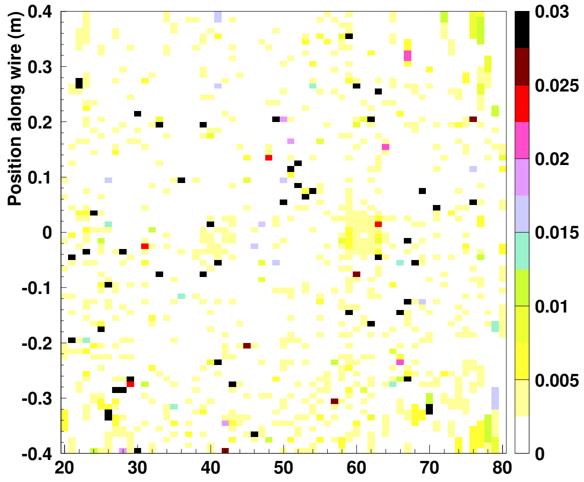
$\rightarrow$ corrections due to detector simulation $\sim 10 \times 10^{-4}$.

The Monte Carlo Acceptance Correction (cont)

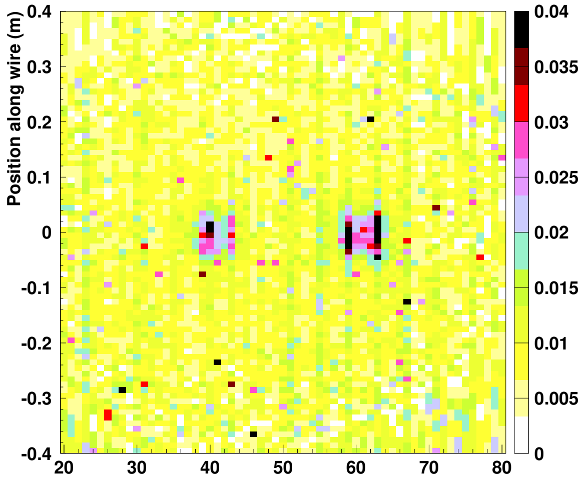
We measure the response of detector:

- Resolutions.
- Inefficiency profiles.
- DC "maps" of response.
- New DC delayed-hit model.
- GEANT showers in CsI.

For example, measure the inefficiency and delayed-hit probabilities across chamber face, use as input to MC.



Missing hit probability in DC1X plane 1



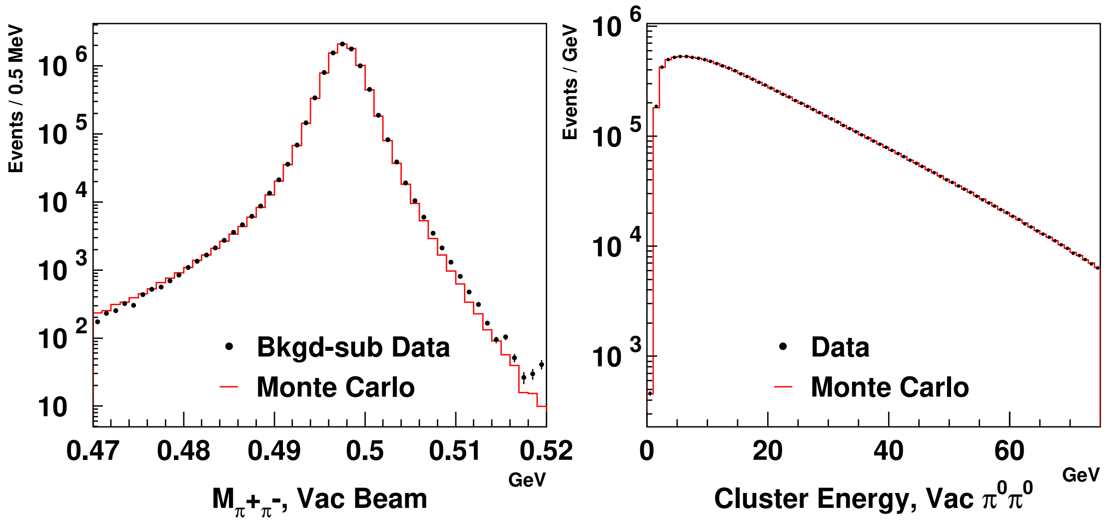
Delayed hit probability in DC1X plane 1

Tests of the Monte Carlo Acceptance Correction

Check Monte Carlo output with "higher level" distributions to insure MC is predicting acceptance correctly.

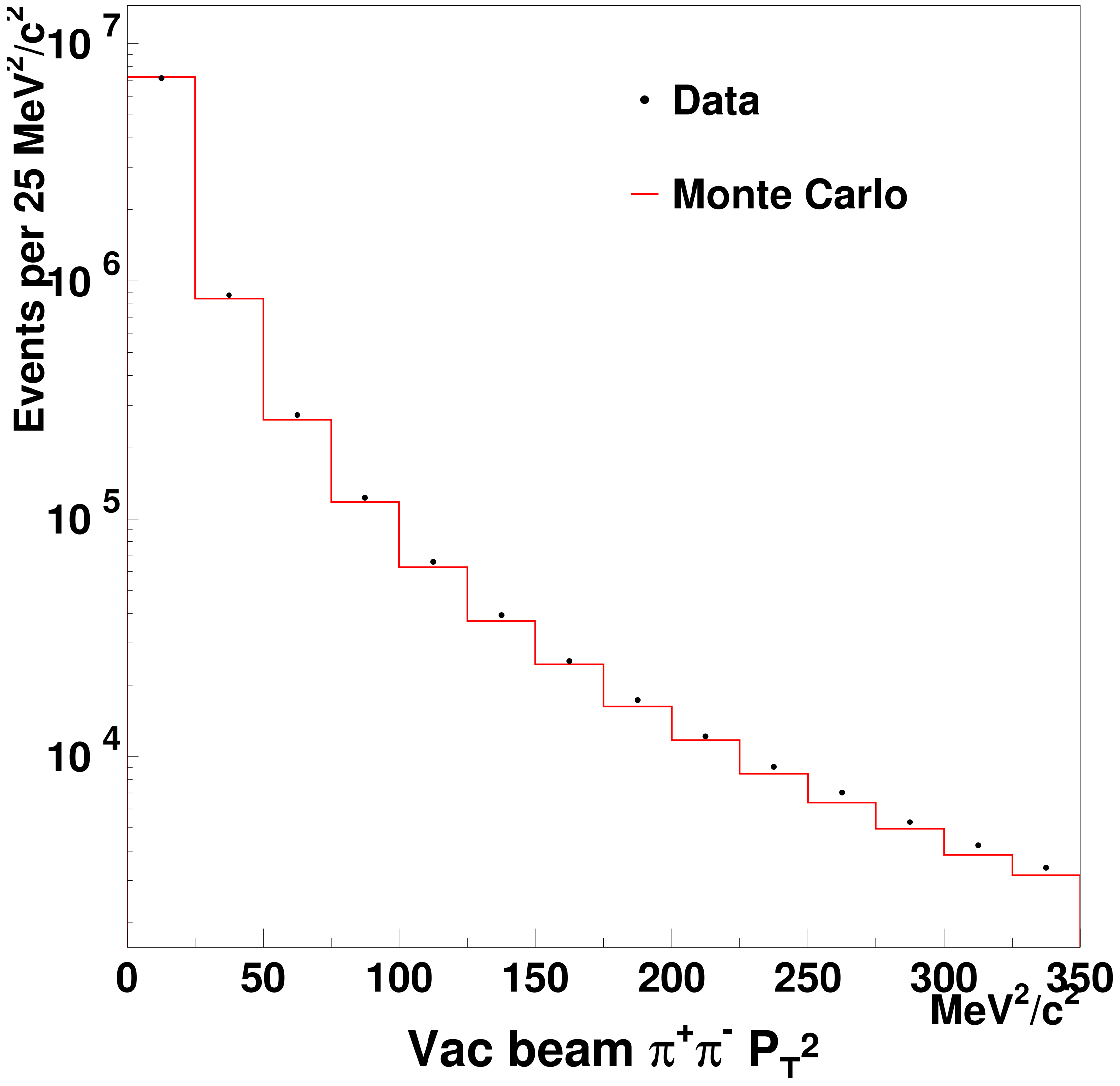
- P_T^2 distribution of $K \to \pi^+\pi^-$ (resolution/inefficiency/scattering).
- Mass resolutions.
- Cluster distributions ($K \to \pi^0\pi^0$).

Differences in the above (and others!) set scale of systematic uncertainties.



Tests of the Monte Carlo Acceptance Correction (cont)

E.g., compare P_T^2 from background-subtracted data to Monte Carlo prediction.

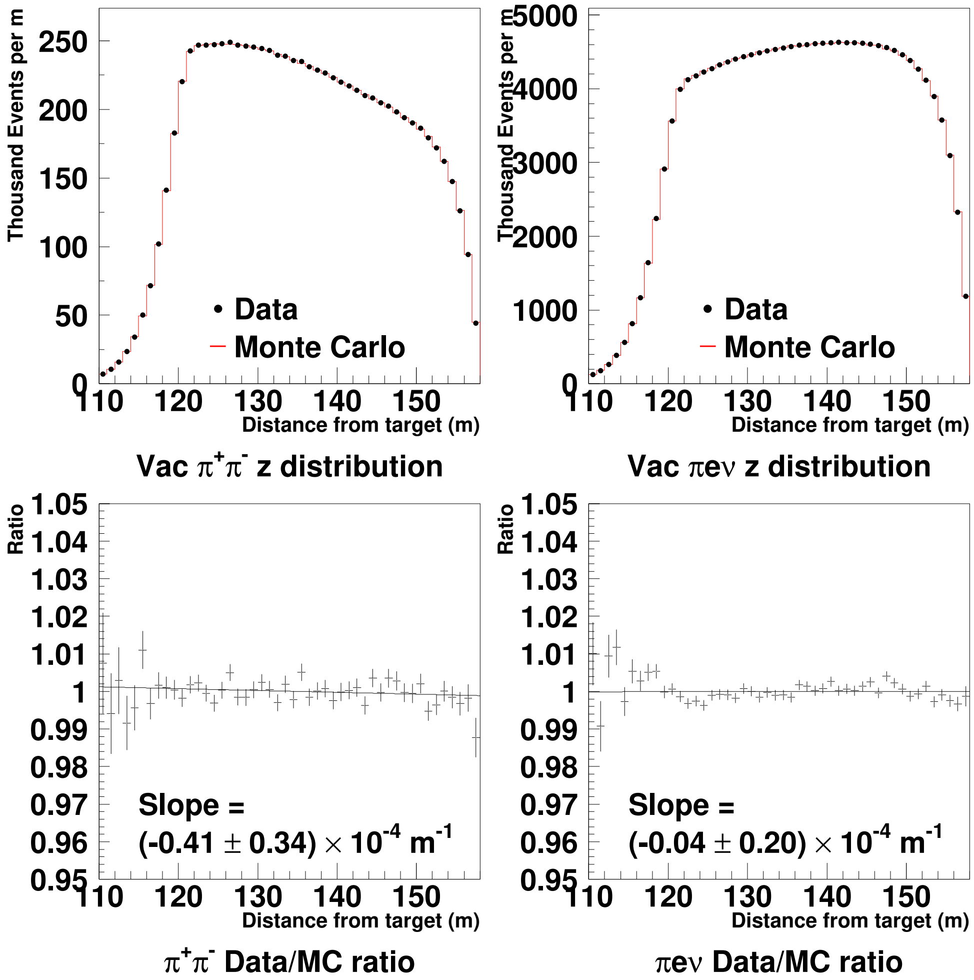


Final Test of MC Acceptance

The final check of the acceptance is the vertex z distribution in the vacuum beam.

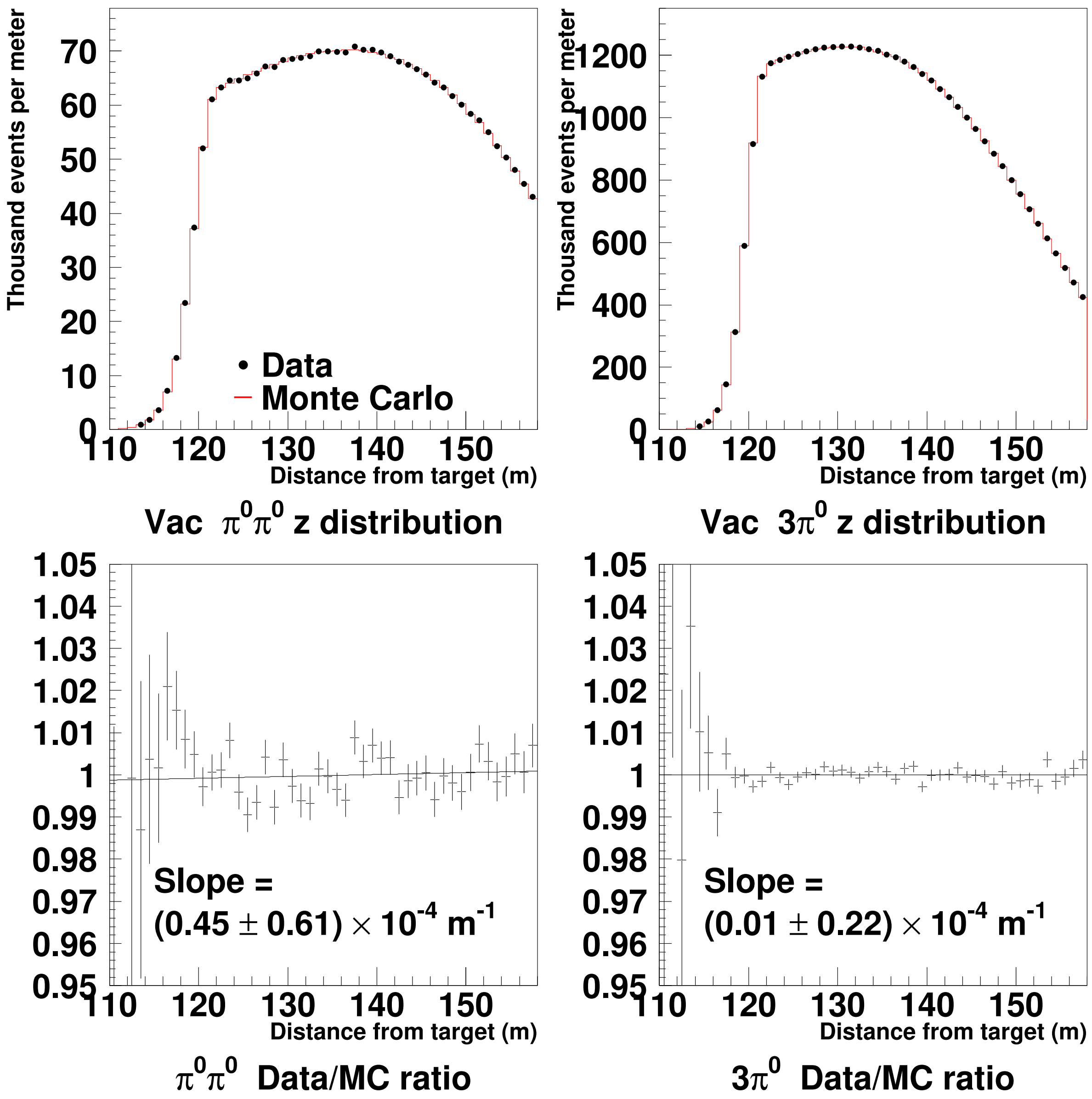
Acceptance bias on $\mathrm{Re}(\epsilon'/\epsilon) \leftrightarrow$ slope in plot, due to different vertex z distributions in vac/reg beams.

<u>1997 $K \to \pi^+\pi^-$ & K_{e3}</u>

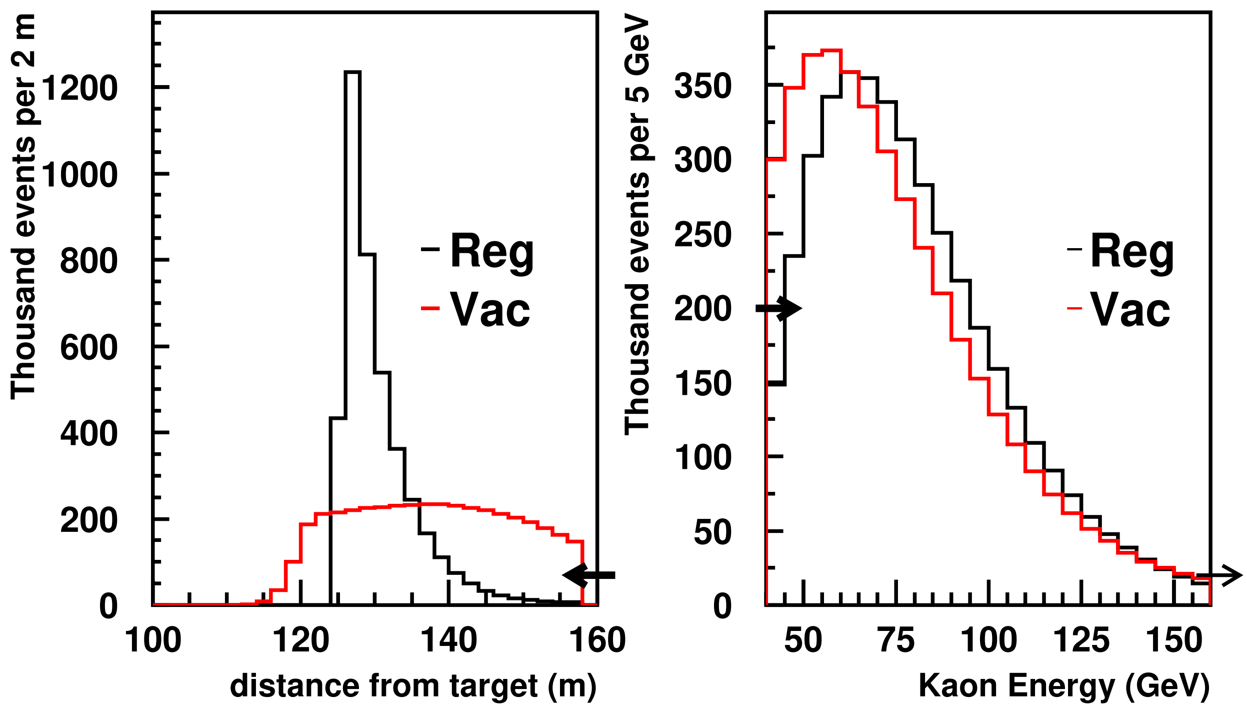


Final Test of MC Acceptance (cont)

1997 $K \to \pi^0\pi^0$ & $K_L \to 3\pi^0$

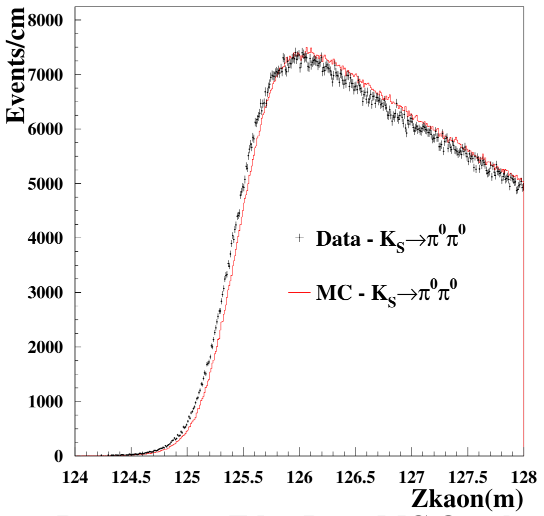


Effect of the Energy Scale Misreconstruction

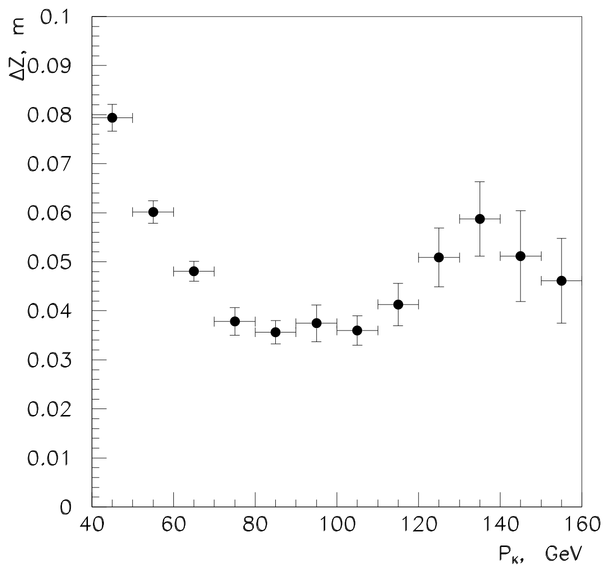


- Energy scale misreconstruction α affects both E_K and z: $\Delta E_K/E_K \sim \alpha$, $\Delta z/z \sim -\alpha$.
- Event migration is larger in Vacuum beam vs Regenerator beam.

The Energy Scale Systematics I

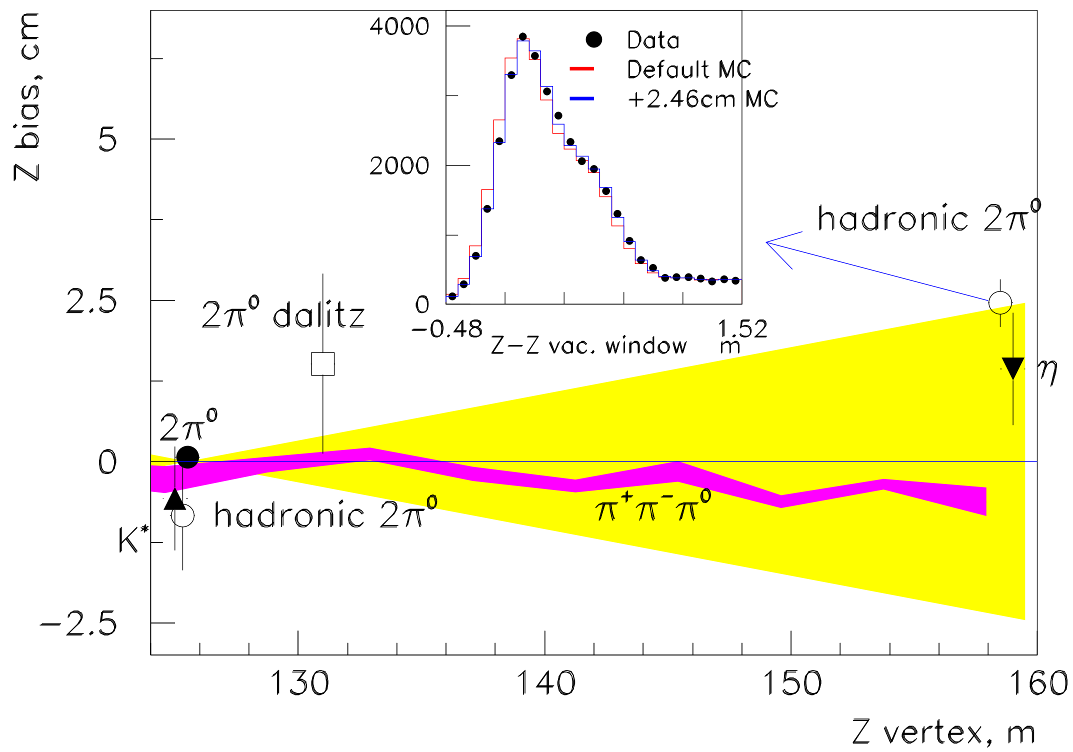


Regenerator Edge Data-MC Overlay



- Perform final correction using sharp edge of the distribution in the regenerator beam $\Delta \mathrm{Re}(\epsilon'/\epsilon) = +2.1 \times 10^{-4}$
- Use P_K dependent correction.
- Applying of a flat scale is different by $\Delta \mathrm{Re}(\epsilon'/\epsilon) = 0.6 \times 10^{-4}$, covered by our systematic.

Cross Checks of the Energy Scale



- Use different methods to cross-check energy calibration: $K \to \pi^+\pi^-\pi^0$, $K_S^* \to \pi^0 K_S$, $K \to 2\pi^0$ Dalitz, $\eta \to 3\pi^0$ hadronic production of $2\pi^0$.
- Use hadronic production of $2\pi^0$ at the Vacuum Window to set uncertainty in the energy scale.
- Assume linear scale variation from Regenerator edge. Use $\pi^+\pi^-\pi^0$ to cross-check.

Systematic Uncertainties for 1997

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 calib, aligned	**0.28**	**0.38**
Analysis cut variations, Reconstruction	**0.25**	**0.37**
Background subtraction	**0.20**	**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**
Class 4: Kaon flux and physics parameters		
Reg-beam attenuation	**0.19**	
Δm, τ_S	**0.24**	
Reg phase screening	**0.31**	
TOTAL	**2.32**	

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**	

From Counting to Re(ϵ'/ϵ)

Naïvely, could take global acceptance, raw number of events, and calculate Re(ϵ'/ϵ).

$$\mathrm{Re}(\epsilon'/\epsilon) \stackrel{?}{\approx} \frac{1}{6}\left[\frac{\frac{N(\mathrm{Vac}\ \pi^+\pi^-)}{A(\mathrm{Vac}\ \pi^+\pi^-)} \Big/ \frac{N(\mathrm{Reg}\ \pi^+\pi^-)}{A(\mathrm{Reg}\ \pi^+\pi^-)}}{\frac{N(\mathrm{Vac}\ \pi^0\pi^0)}{A(\mathrm{Vac}\ \pi^0\pi^0)} \Big/ \frac{N(\mathrm{Reg}\ \pi^0\pi^0)}{A(\mathrm{Reg}\ \pi^0\pi^0)}} - 1\right]$$

Problems:

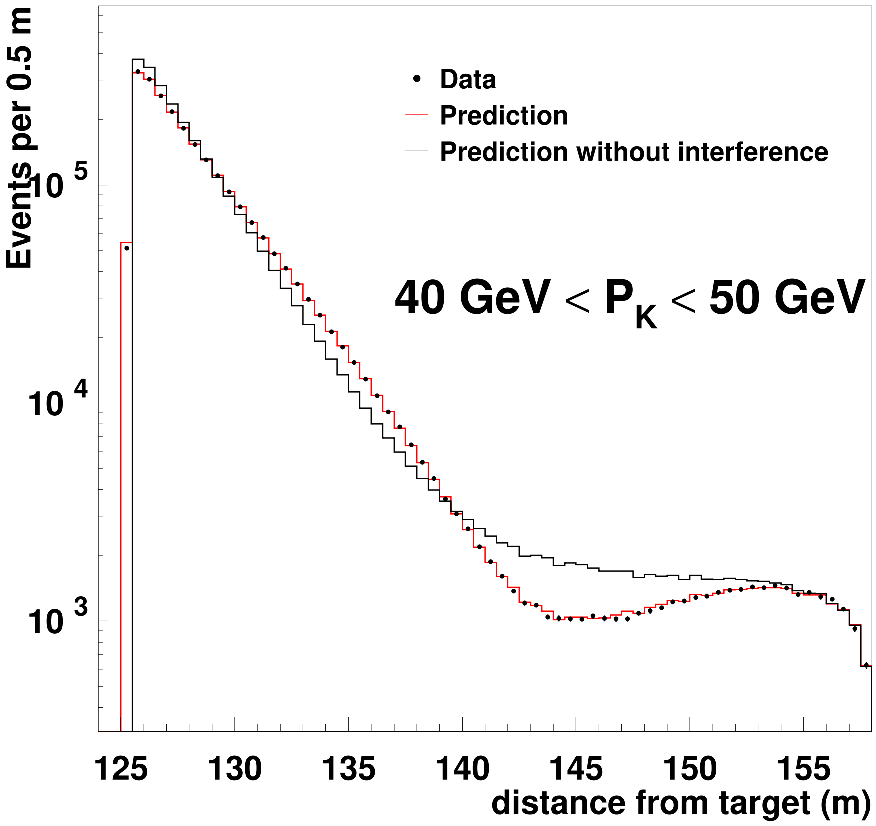
- Regenerator beam not pure K_S.
  $K_{\mathrm{reg}} = K_L + \rho K_S$
  Interference
- Requires precise determination of *average* acceptance.

K_S and K_L in the Regenerator Beam

The regenerator beam is a coherent super-position of K_S and K_L. Must account for K_L component to extract correct value of $\mathrm{Re}(\epsilon'/\epsilon)$.

K_{Reg} shape depends on:

- τ_S, Δm, ϕ_η.
- Attenuation in the regenerator.

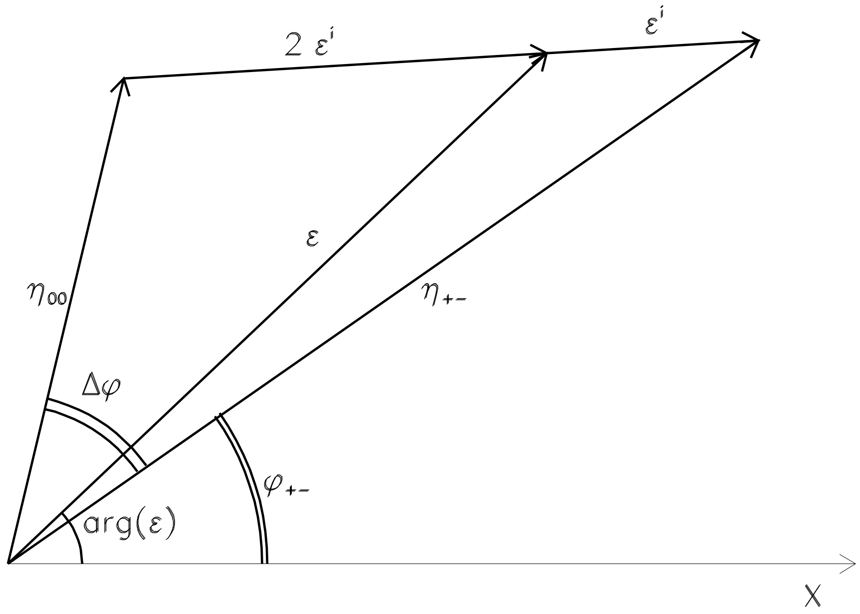


Regenerator Vertex Z distribution

Δm, τ_S, ϕ_{+-}, $\Delta\phi$

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_{+-}
- $\Delta\phi = \phi_{00} - \phi_{+-}$ $[\cancel{CPT}]$



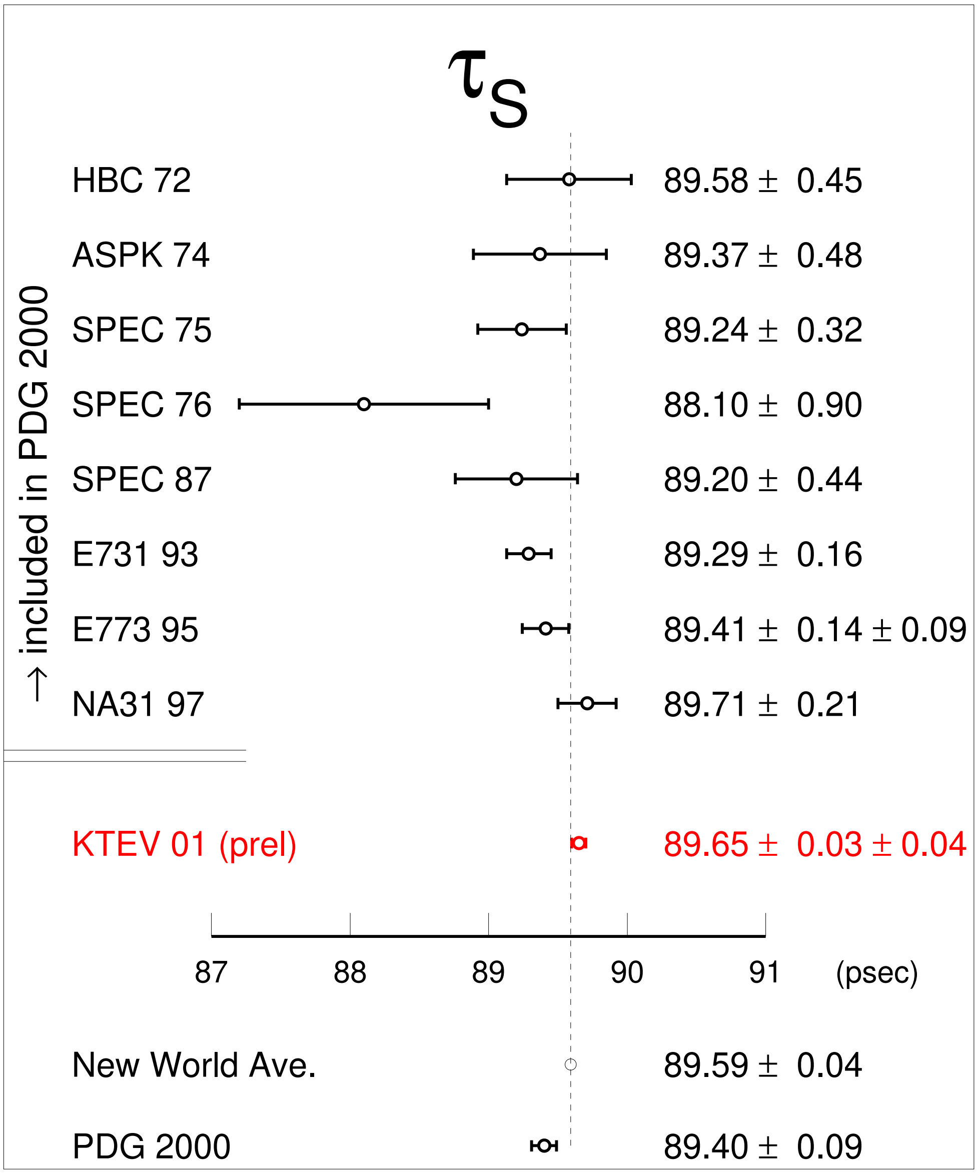
$\mathrm{Im}(\epsilon'/\epsilon) = -\frac{1}{3}\Delta\phi$ $[\cancel{CPT}]$

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

Kaon Sector Parameters as Measured in KTeV

PRELIMINARY:

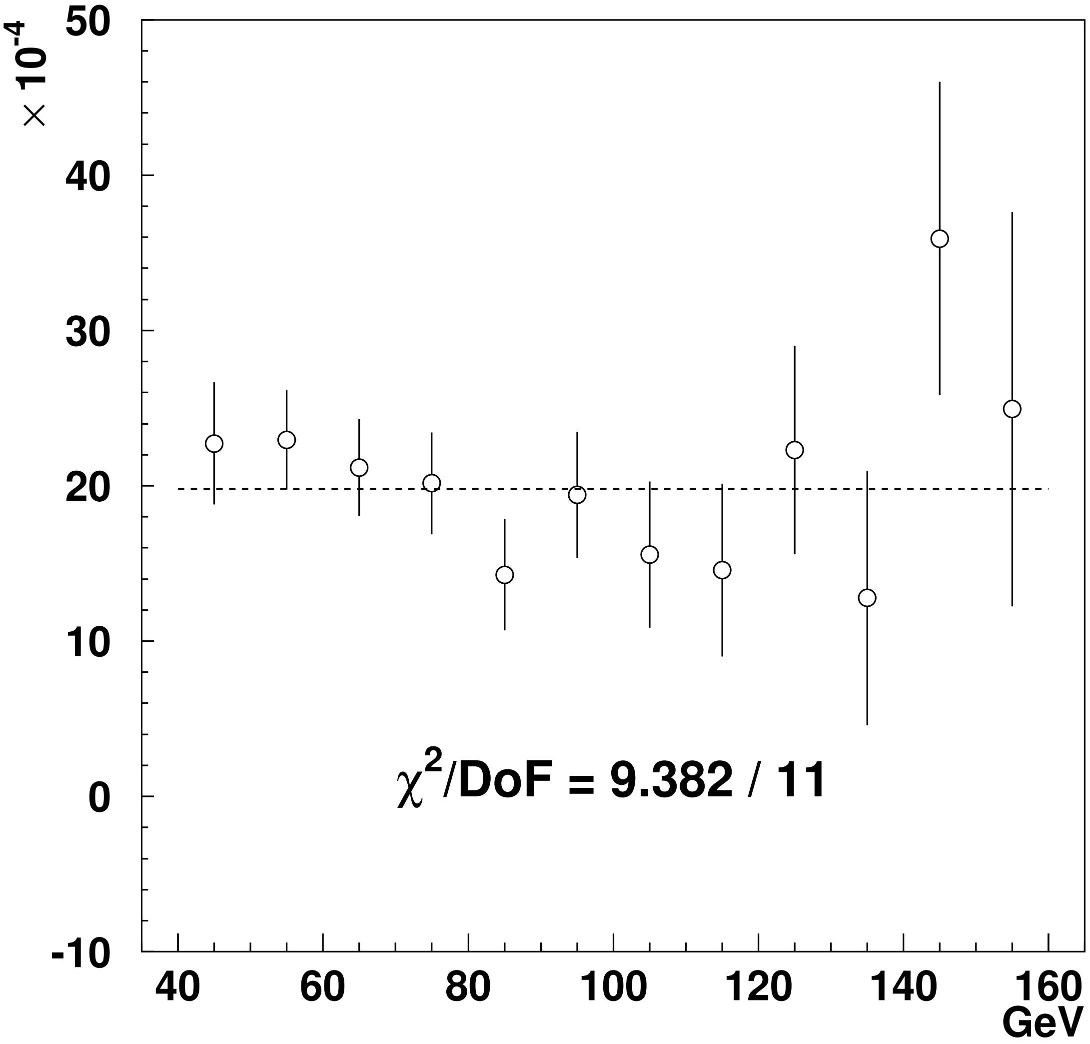
$$\Delta m = (5262 \pm 7.7\ (\text{exp}) \pm 13\ (\text{th.})) \times 10^6 \hbar s^{-1}$$
$$\tau_S = (8967.1 \pm 3.5\ (\text{exp}) \pm 4\ (\text{th.})) \times 10^{-14} s$$
$$\phi_{+-} = 44.11 \pm 0.72\ (\text{stat}) \pm 1.1\ (\text{syst})$$
$$\Delta\phi = 0.41^\circ \pm 0.22^\circ(\text{stat}) \pm 0.53^\circ(\text{syst})$$



Result From 1997 Data Set

Result from data set statistically *independent* of PRL published result.

$$\mathrm{Re}(\epsilon'/\epsilon) = (\mathbf{19.8} \pm \mathbf{1.7}\ (\mathrm{stat}) \pm \mathbf{2.3}\ (\mathrm{syst}) \pm \mathbf{0.6}\ (\mathrm{MC\ stat})) \times \mathbf{10^{-4}}$$



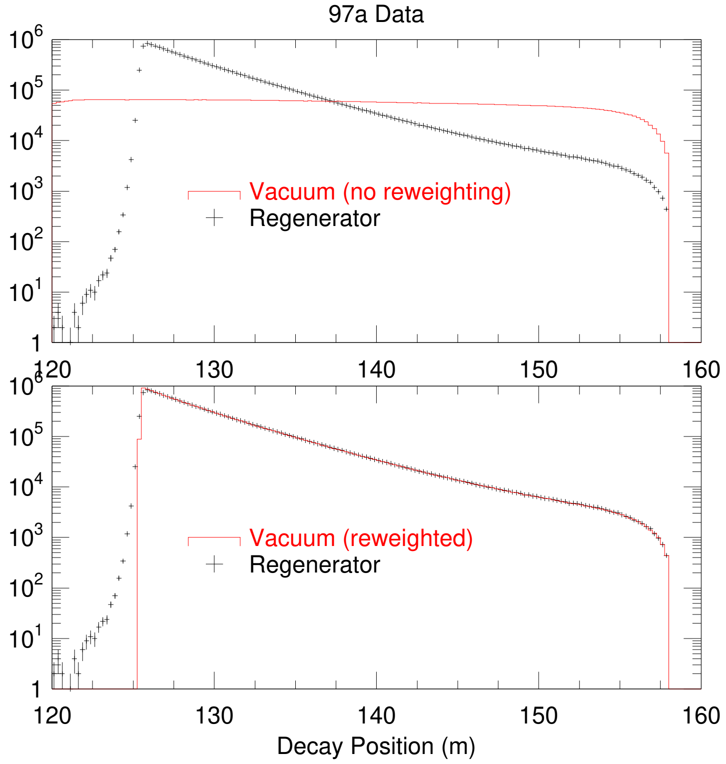
Re(ε′/ε) versus Kaon Energy

Cross-Check: Reweighting Technique to Measure Re(ϵ'/ϵ)

KTeV can measure Re(ϵ'/ϵ) without a Monte Carlo acceptance correction.

Due to KTeV geometry, acceptance at a given (E, z) is the $\approx$ same between the vac and reg beams.

We *reweight* vacuum beam events to have same (E, z) distribution as regenerator beam

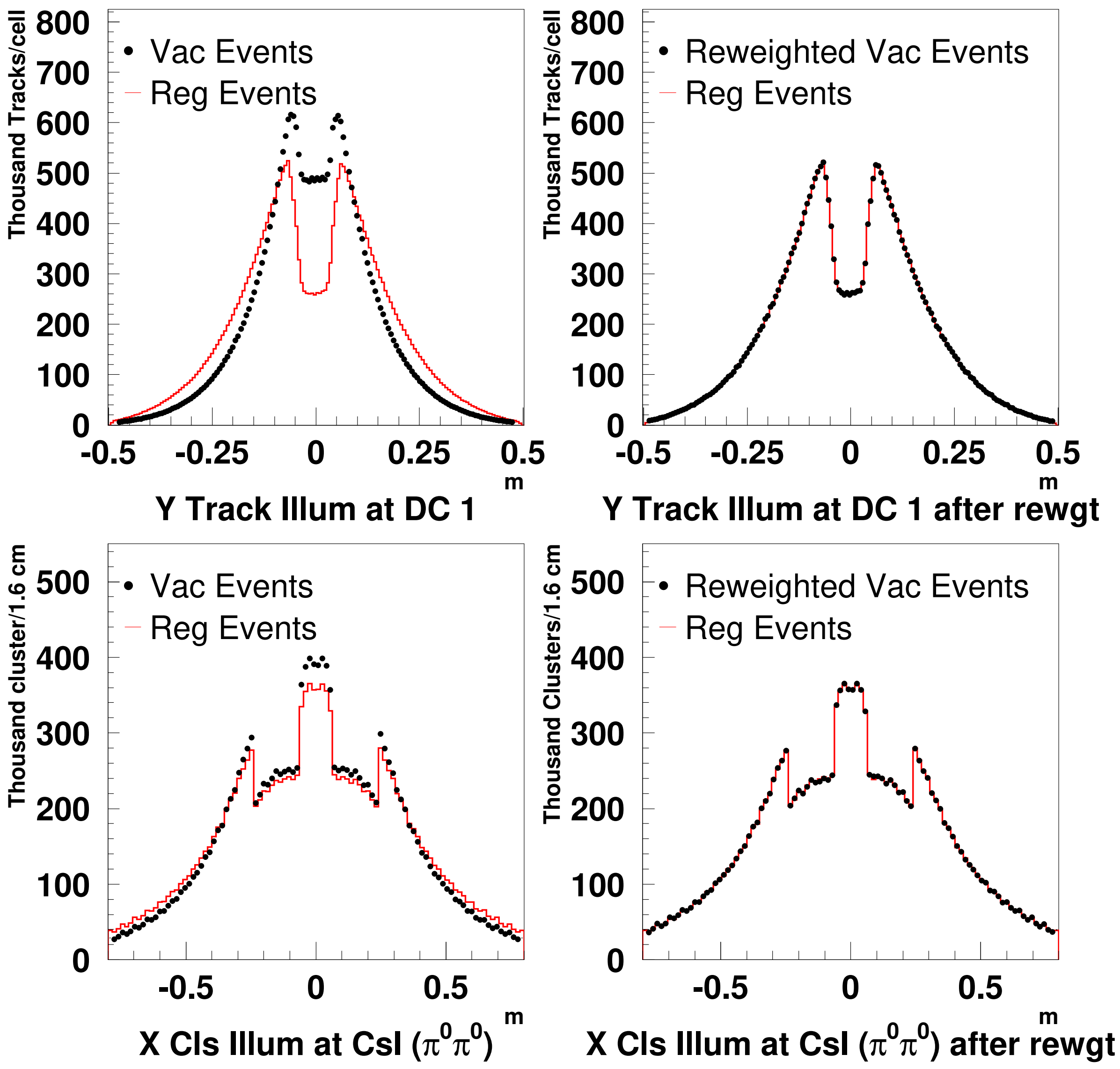


Check of Monte Carlo method.

Statistically less significant than Monte Carlo method ($\sigma = 1.7\times$).

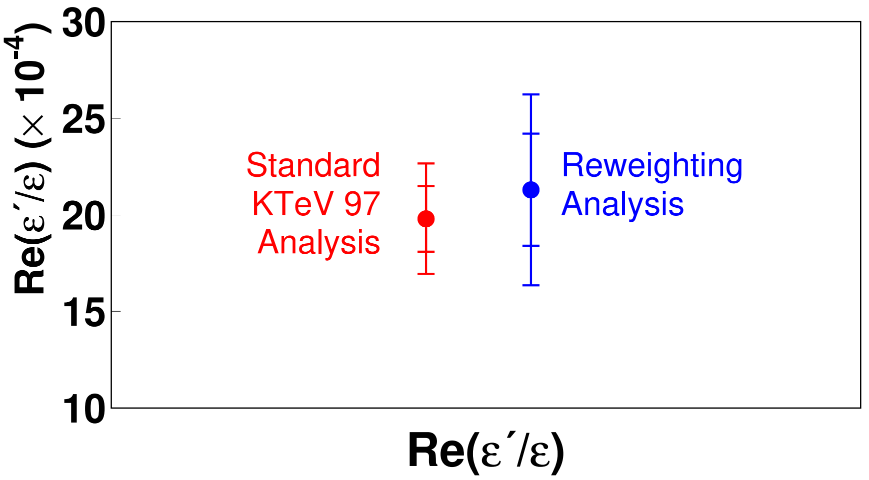
Different systematics.

Illuminations in the Reweighting Method



Reweighting Method Result

The preliminary result from the reweighting analysis for the 1997 dataset:



This result compares well to our main result.

We have attempted to understand the uncorrelated parts of the statistical and systematic error. With a *preliminary* understanding of the correlated parts of the systematic uncertainty,

$$\Delta\text{Re}(\epsilon'/\epsilon) = 1.5 \pm 2.1\ (\text{stat}) \pm 3\ (\text{syst}) \times 10^{-4}$$

Update of Published Result with Improved Techniques

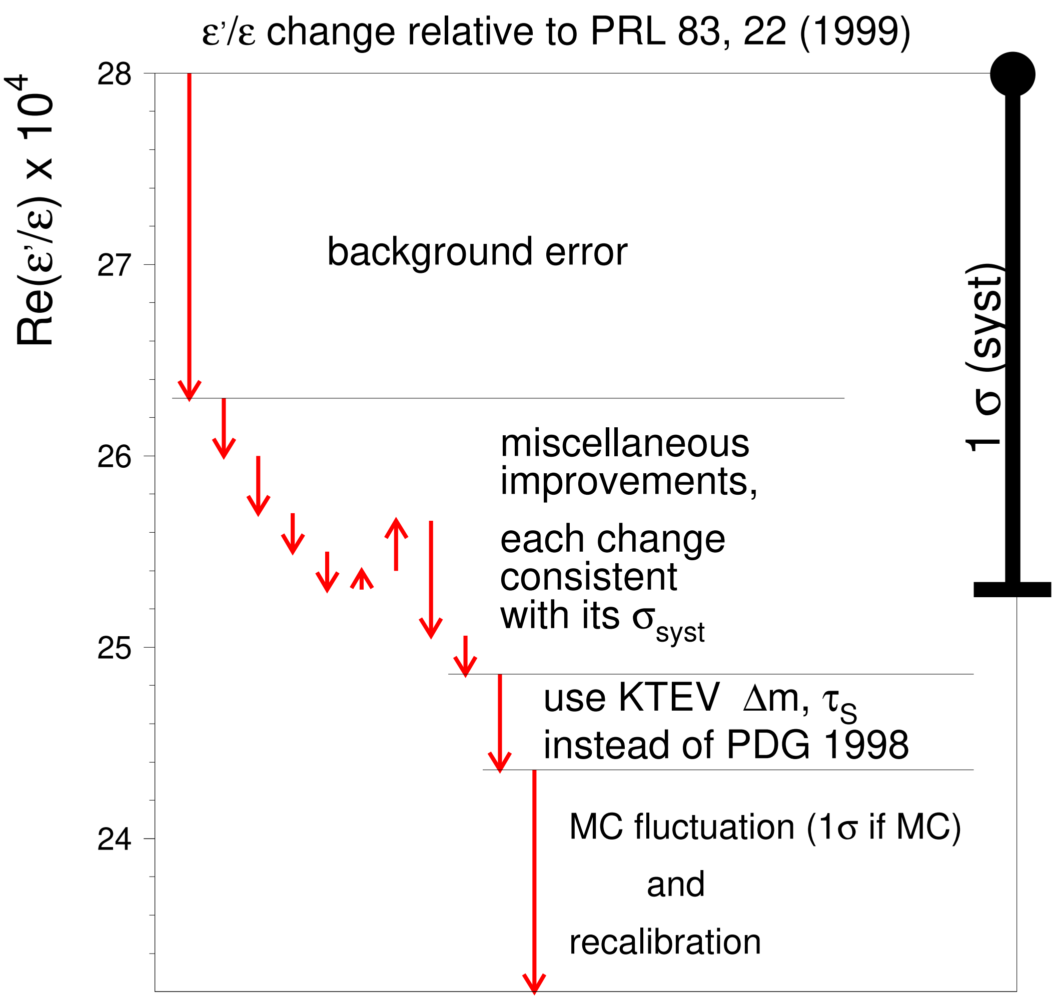
We have made several improvements to the analysis of $\mathrm{Re}(\epsilon'/\epsilon)$ for the new result:

- CsI calibration.
- DC calibration and alignment.
- Understanding of the neutral backgrounds.
- Apertures.
- Δm, τ_S.
- Inputs to the fitter.

Apply these to the analysis of published PRL sample.

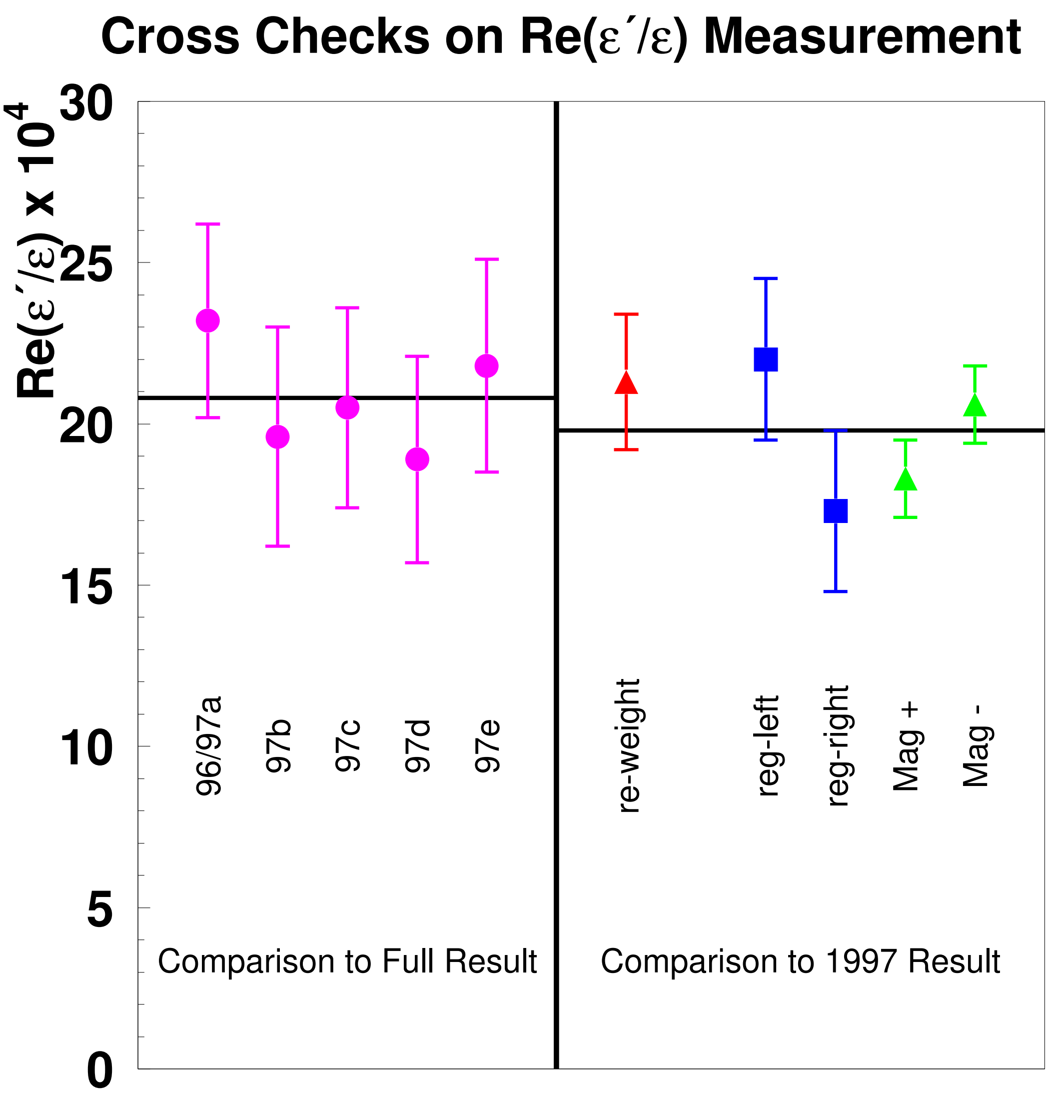
Update of Published Result with Improved Techniques (cont)

$$\mathrm{Re}(\epsilon'/\epsilon) = (\mathbf{23.2} \pm \mathbf{3.0}\ (\mathrm{stat}) \pm \mathbf{3.2}\ (\mathrm{syst}) \pm \mathbf{0.7}\ (\mathrm{MC\ stat})) \times \mathbf{10^{-4}}$$



Note: sources of shifts are not correlated

Cross-Checks of Re(ϵ'/ϵ) Measurement



The Result, Restated

KTeV has a new measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ from a dataset that is statistically independent from our published result.

$$\begin{array}{ccl} \mathrm{Re}(\epsilon'/\epsilon) & = & (\mathbf{19.8} \pm \mathbf{1.7}\ (\mathrm{stat}) \pm \mathbf{2.3}\ (\mathrm{syst}) \\ (1997) & & \quad \pm\, \mathbf{0.6}\ (\mathrm{MC\ stat})) \quad \times \mathbf{10^{-4}} \end{array}$$

Consistent with reanalysis of published result,

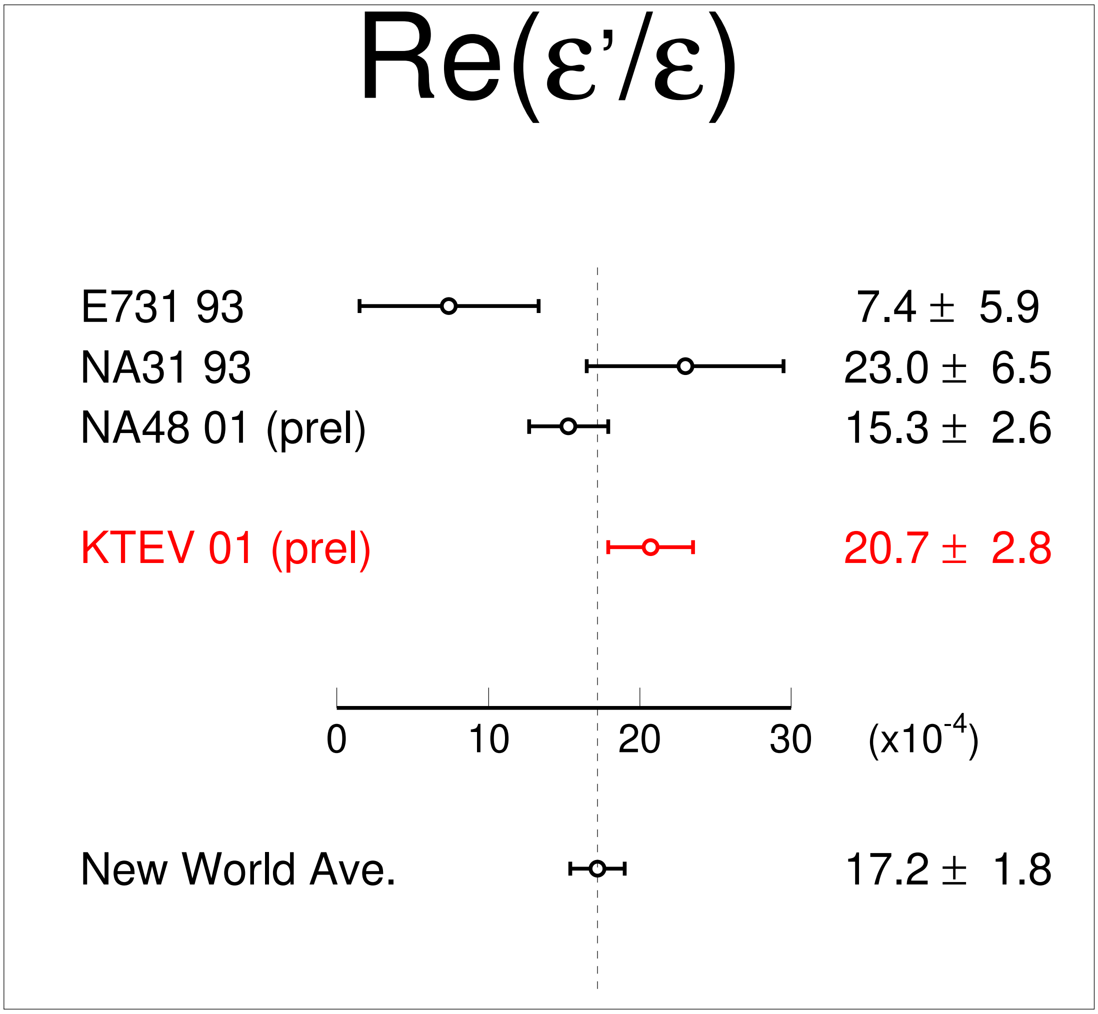
$$\begin{array}{ccl} \mathrm{Re}(\epsilon'/\epsilon) & = & (\mathbf{23.2} \pm \mathbf{3.0}\ (\mathrm{stat}) \pm \mathbf{3.2}\ (\mathrm{syst}) \\ (\mathrm{PRL}) & & \quad \pm\, \mathbf{0.7}\ (\mathrm{MC\ stat})) \quad \times \mathbf{10^{-4}} \end{array}$$

Combined result for the 1996-1997 dataset:

$$\begin{array}{ccl} \mathrm{Re}(\epsilon'/\epsilon) & = & (\mathbf{20.7} \pm \mathbf{1.5}\ (\mathrm{stat}) \pm \mathbf{2.4}\ (\mathrm{syst}) \\ (96+97) & & \quad \pm\, \mathbf{0.5}\ (\mathrm{MC\ stat})) \quad \times \mathbf{10^{-4}} \\ & = & (\mathbf{20.7} \pm \mathbf{2.8}) \times \mathbf{10^{-4}} \end{array}$$

Comparison to Other Measurements

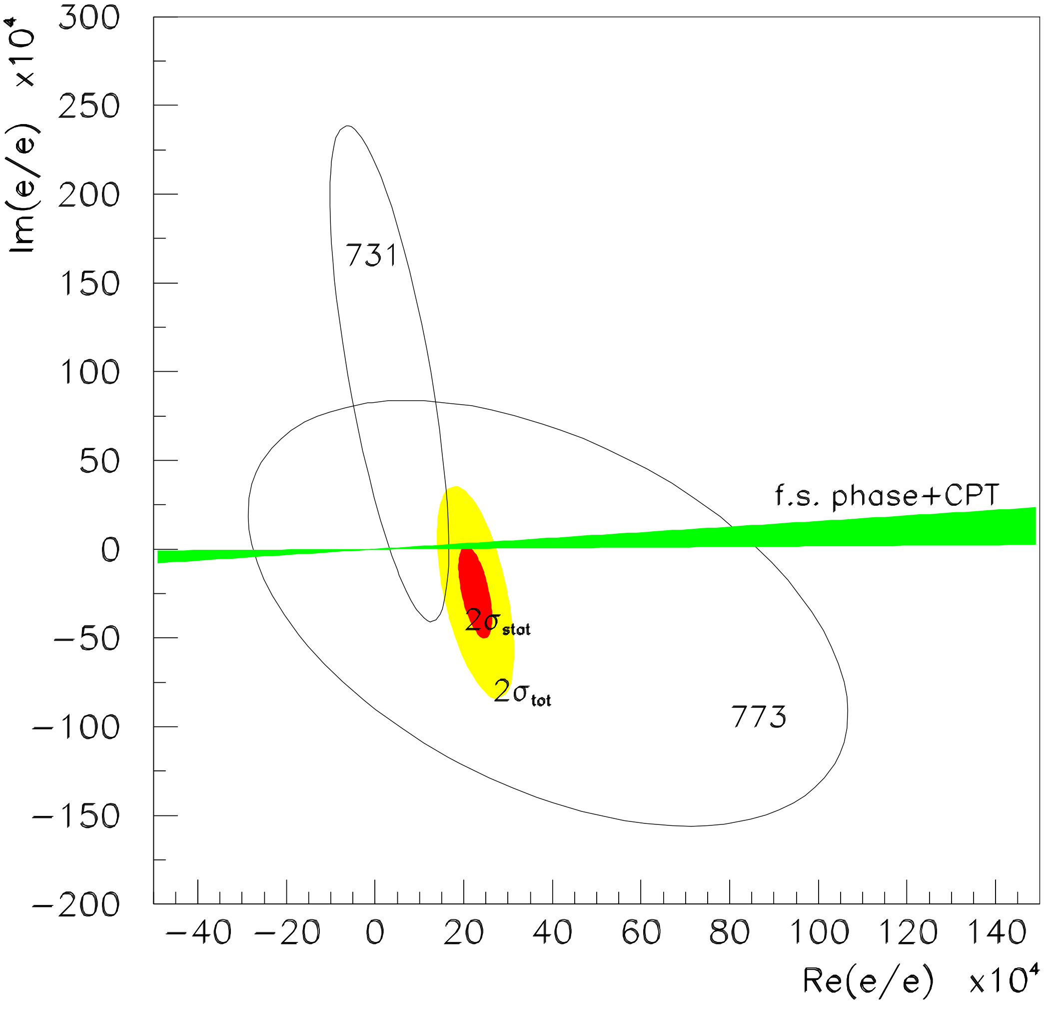
$$\mathrm{NA48}: \quad \mathrm{Re}(\epsilon'/\epsilon) = \quad (15.3 \pm 2.6) \times 10^{-4}$$
$$\mathrm{KTeV}: \quad \mathrm{Re}(\epsilon'/\epsilon) = \quad (20.7 \pm 2.8) \times 10^{-4}$$



$$\text{World Ave. Re}(\epsilon'/\epsilon) \quad = \quad 17.2 \pm 1.8 \times 10^{-4}$$
$$\text{Probability} \quad = \quad 13\%$$

History of FNAL Measurements

FNAL experiments can measure both Re(ϵ'/ϵ) and Im(ϵ'/ϵ) (with less precision).



Conclusions and Future Prospects

KTeV has measured the $\not{CP}$ parameter $\mathrm{Re}(\epsilon'/\epsilon)$:

$$\begin{aligned} \mathrm{Re}(\epsilon'/\epsilon) \quad &= \quad (\mathbf{20.7} \pm \mathbf{1.5}\ (\mathrm{stat}) \pm \mathbf{2.4}\ (\mathrm{syst}) \\ (96+97) \quad & \qquad \pm\, \mathbf{0.5}\ (\mathrm{MC\ stat})) \times \mathbf{10^{-4}} \\ &= \quad (\mathbf{20.7} \pm \mathbf{2.8}) \times \mathbf{10^{-4}} \end{aligned}$$

We have also made new measurements of the kaon sector parameters Δm, τ_S, ϕ_{+-} and $\Delta\phi$.

Combined with NA48, this result places tight limits on the value of $\mathrm{Re}(\epsilon'/\epsilon)$. The value of $\mathrm{Re}(\epsilon'/\epsilon)$ is known to roughly 10%.

Interpretation for Standard Model CKM parameters is confusing. These experimental results have higher precision than current calculations.

- Initial results from KTeV and NA48 spurred many new calculations.

Have an equal dataset (KTeV99) on tape — will reduce statistical error to $\sim 1 \times 10^{-4}$.