The Final Measurement of $Re(\epsilon'/\epsilon)$ by KTeV Collaboration

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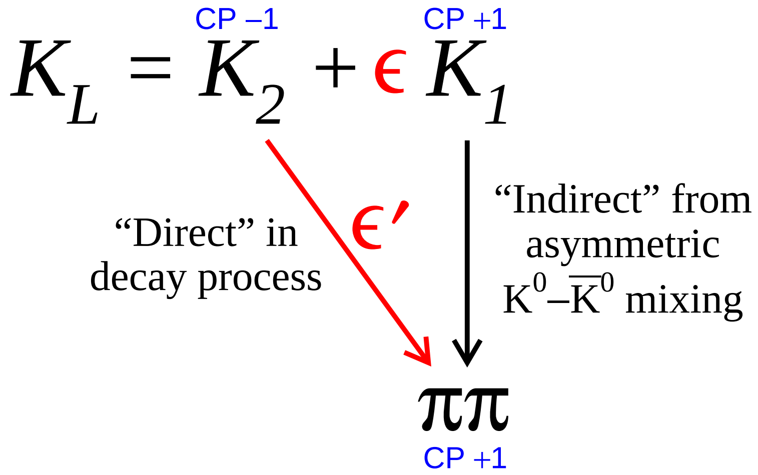
for KTeV collaboration

Introduction to ϵ'/ϵ

- Weak eigenstates contain 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 measurable quantities

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

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

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

Introduction to ϵ'/ϵ II

Define amplitudes to $\pi\pi$ states of a definite isospin:

$$
\begin{aligned}
< I|T|K^0 > &= (A_I + B_I)\, e^{i\delta_I} \\
< I|T|\overline{K}^0 > &= (A_I^* - B_I^*)\, e^{i\delta_I}
\end{aligned}
$$

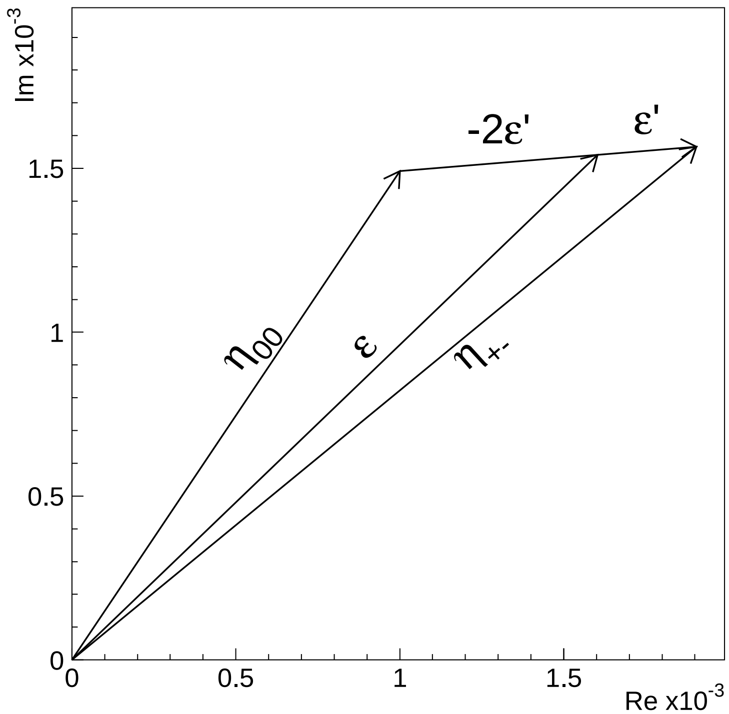
$Im(A_I)$ — CP violation
$Re(B_I)$ — CP & CPT violation
δ_I – final state interaction phase shifts, $\delta_2 - \delta_0 = (-42 \pm 4)^o$.

$$
\begin{aligned}
\epsilon'_{CP} &\approx \frac{i}{\sqrt{2}} \frac{Re(A_2)}{Re(A_0)} \left[\frac{Im(A_2)}{Re(A_2)} - \frac{Im(A_0)}{Re(A_0)} \right] e^{i(\delta_2 - \delta_0)} \\
\epsilon'_{CPT} &\approx \frac{1}{\sqrt{2}} \frac{Re(A_2)}{Re(A_0)} \left[\frac{Re(B_2)}{Re(A_2)} - \frac{Re(B_0)}{Re(A_0)} \right] e^{i(\delta_2 - \delta_0)}
\end{aligned}
$$

As numerically ϵ is almost parallel to ϵ'_{CP},

- $Re(\epsilon'/\epsilon)$ – Measure of direct CP violation.
- $Im(\epsilon'/\epsilon)$ – Measure of CPT violation.

Kaon Sector Parameters Measurements



Kaon parameters:

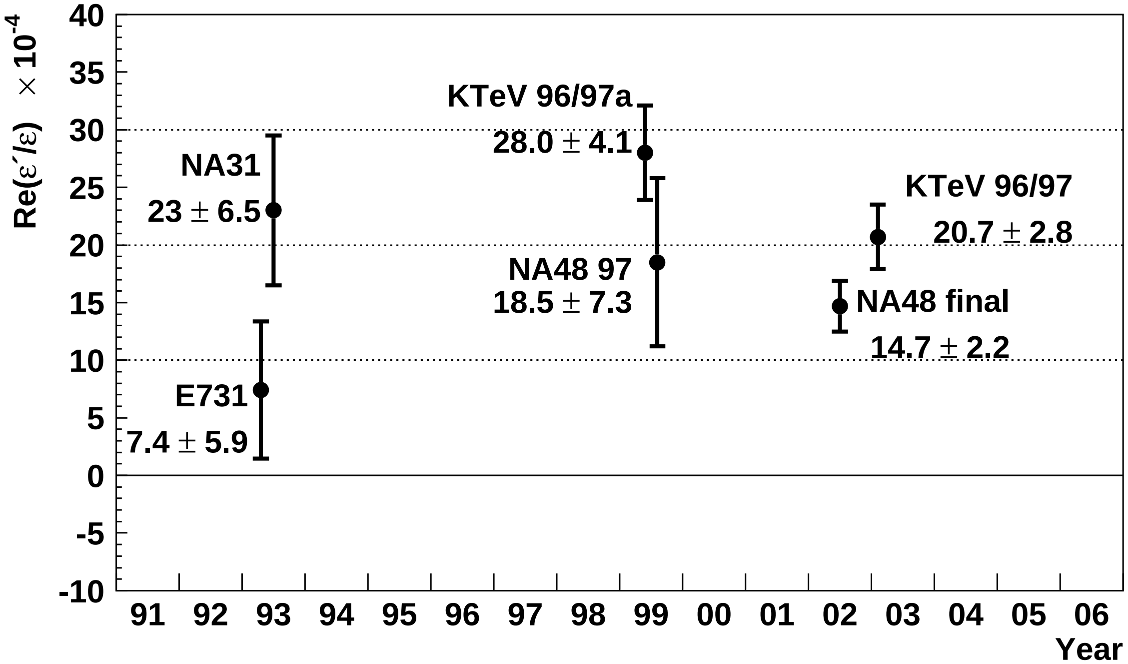
- $\Delta m = m_{K_L} - m_{K_S}$
- $\tau_S,\ \phi_\epsilon$
- $\phi_{+-} \approx \phi_\epsilon + Im(\epsilon'/\epsilon)$, $\phi_{00} \approx \phi_\epsilon - 2Im(\epsilon'/\epsilon)$, $\Delta\phi = \phi_{00} - \phi_{+-}$
- $Im(\epsilon'/\epsilon) \approx -\frac{1}{3}\Delta\phi$

Using interference in the regenerator beam, KTeV can measure not only decay rates but also phases as well as other kaon parameters.

CPT requires:

$$\phi_\epsilon = \phi_{SW} \equiv \arctan \frac{2\Delta m}{1/\tau_S - 1/\tau_L}$$

History of $Re(\epsilon'/\epsilon)$ measurements

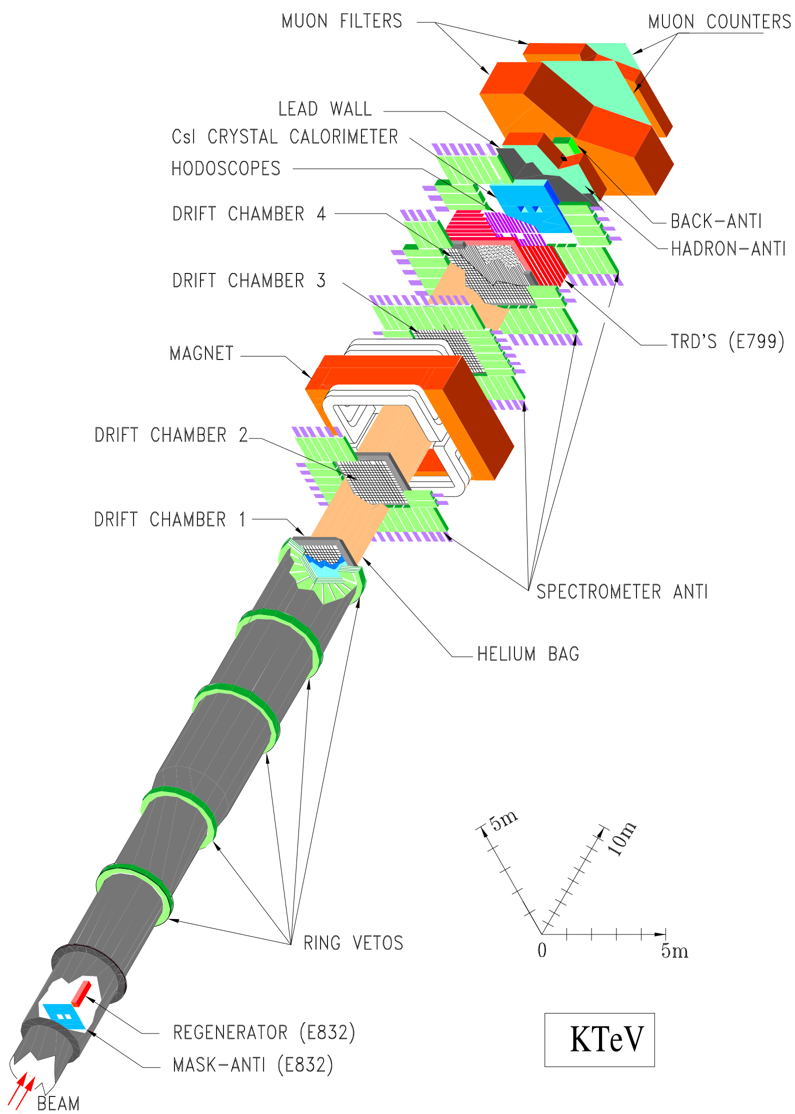


KTeV Data yields of $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^0\pi^0$ events:

Year	$K \rightarrow \pi^+\pi^-$	$K \rightarrow \pi^0\pi^0$
96	–	0.8×10^6
97	8.6×10^6	2.1×10^6
99	14.9×10^6	3.1×10^6

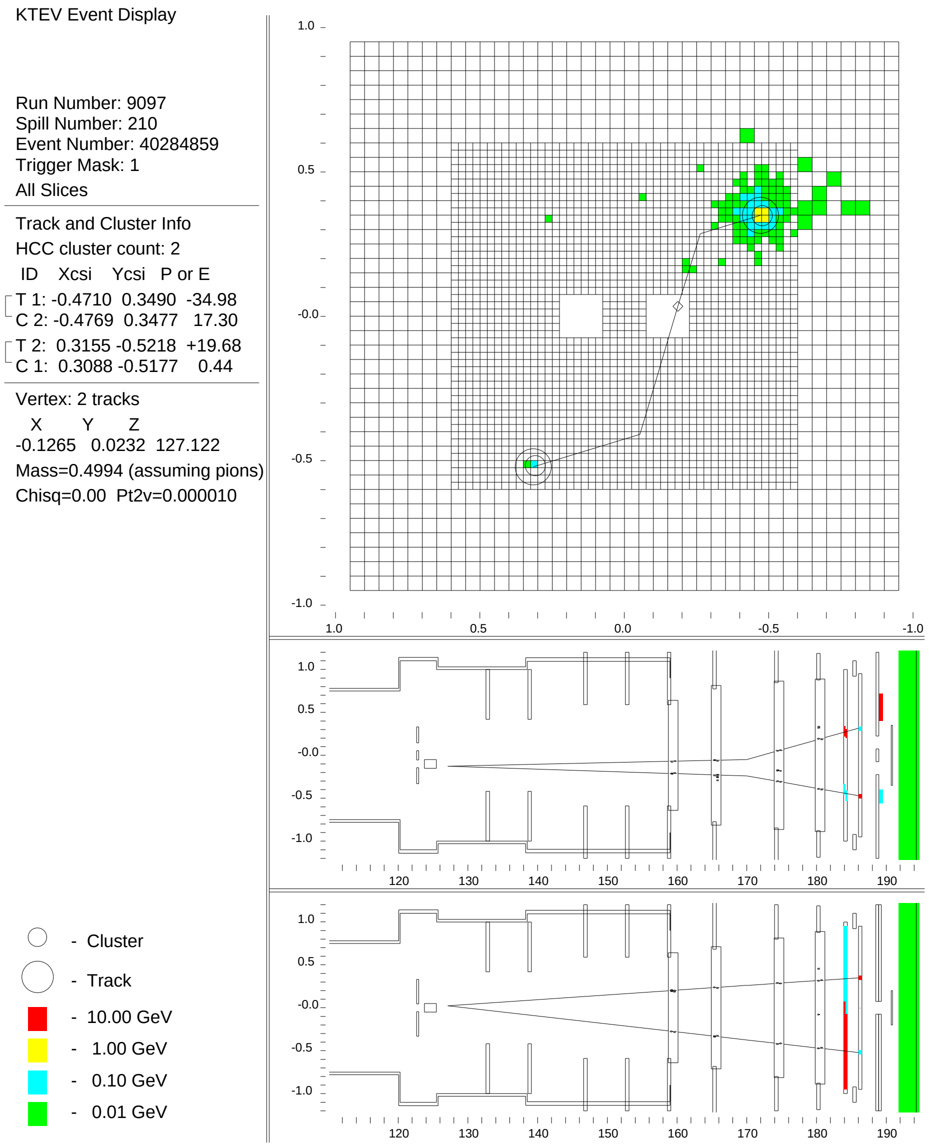
Today: analysis of the complete KTeV data set.

The KTeV Detector



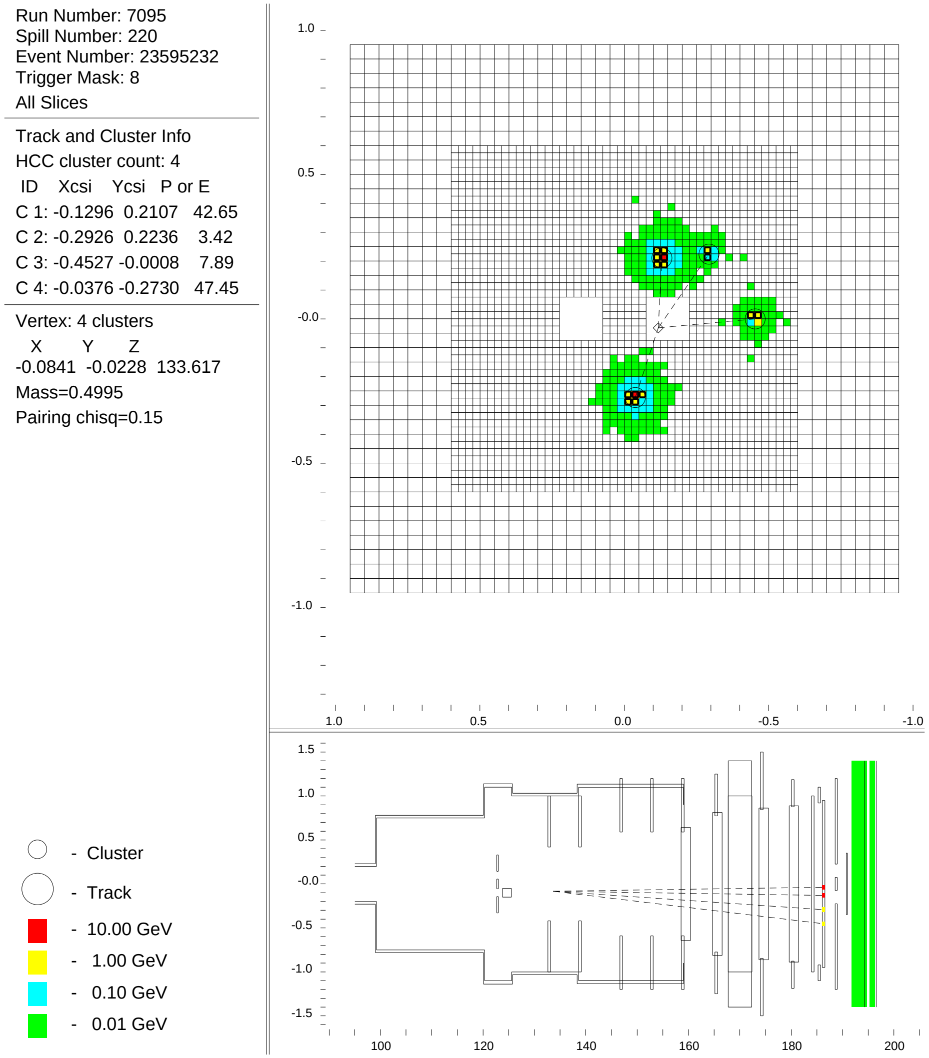
- Two almost parallel neutral beams, $K_L/n \sim 1/1$.
- Movable Regenerator to create K_S beam.
- Large Vacuum decay volume.
- Low material drift chamber spectrometer, high precision CsI calorimeter

Charged Mode Reconstruction



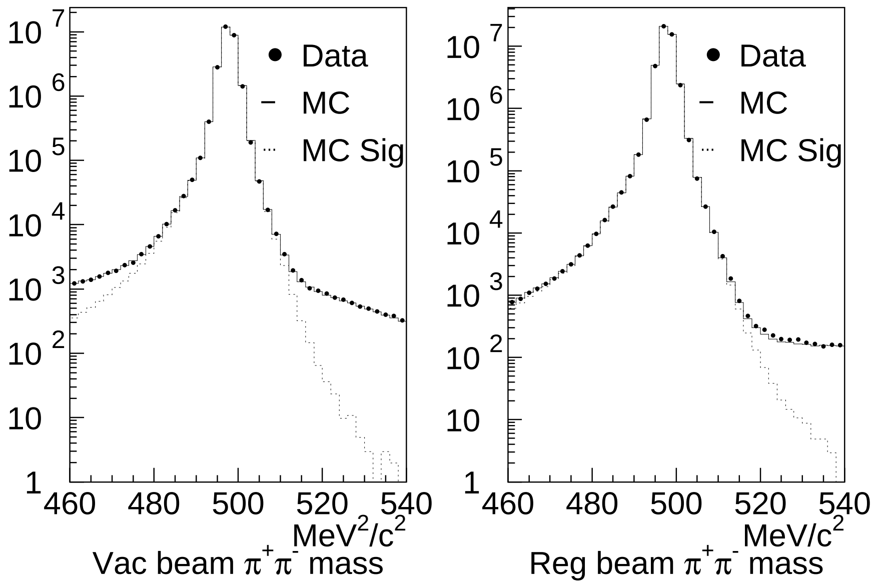
- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using X-vertex position
- Clearance cuts to define detector volume.

Neutral Mode Reconstruction



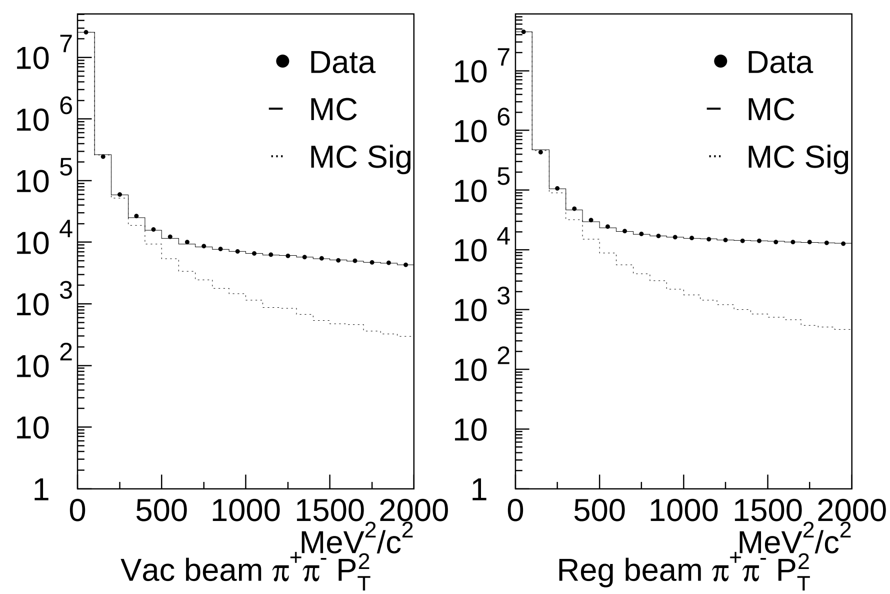
- CsI calorimeter to reconstruct photons energies and positions
- Z_v determined as average of $Z_{\pi^0} = \sqrt{E_1 E_2} R_{12} / m_{\pi^0}$
- Regenerator/Vacuum beam identification using X-center of energy
- Detector volume defined by veto detectors and Z_v

Charged Mode Improvements

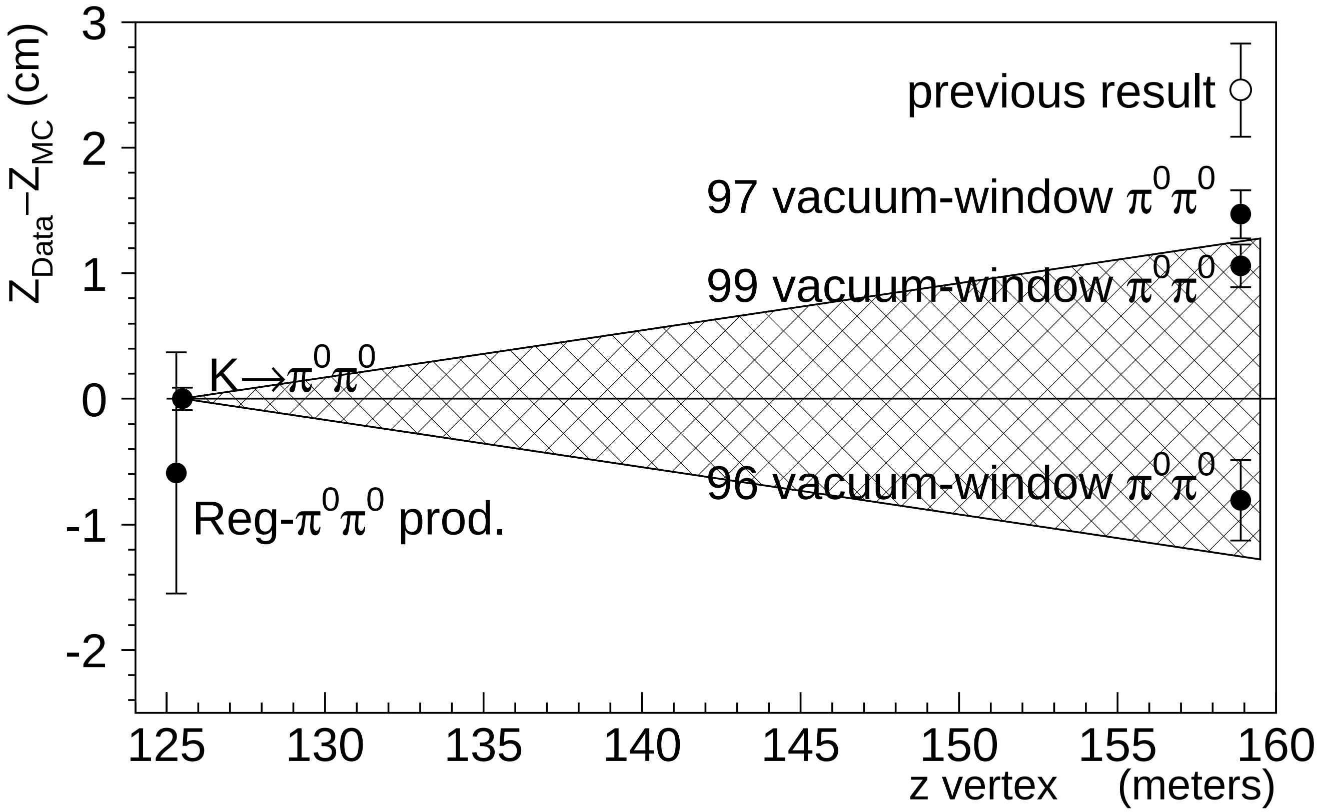


← Improvements in reconstruction and simulation of backgrounds, veto detectors thresholds. Mass resolution is 1.4 MeV/c^2, 15% better vs KTeV03.

Better description of detector material, scattering and δ-rays.
Good description of tails in mass and p_t^2 distributions.



Neutral Mode Improvements



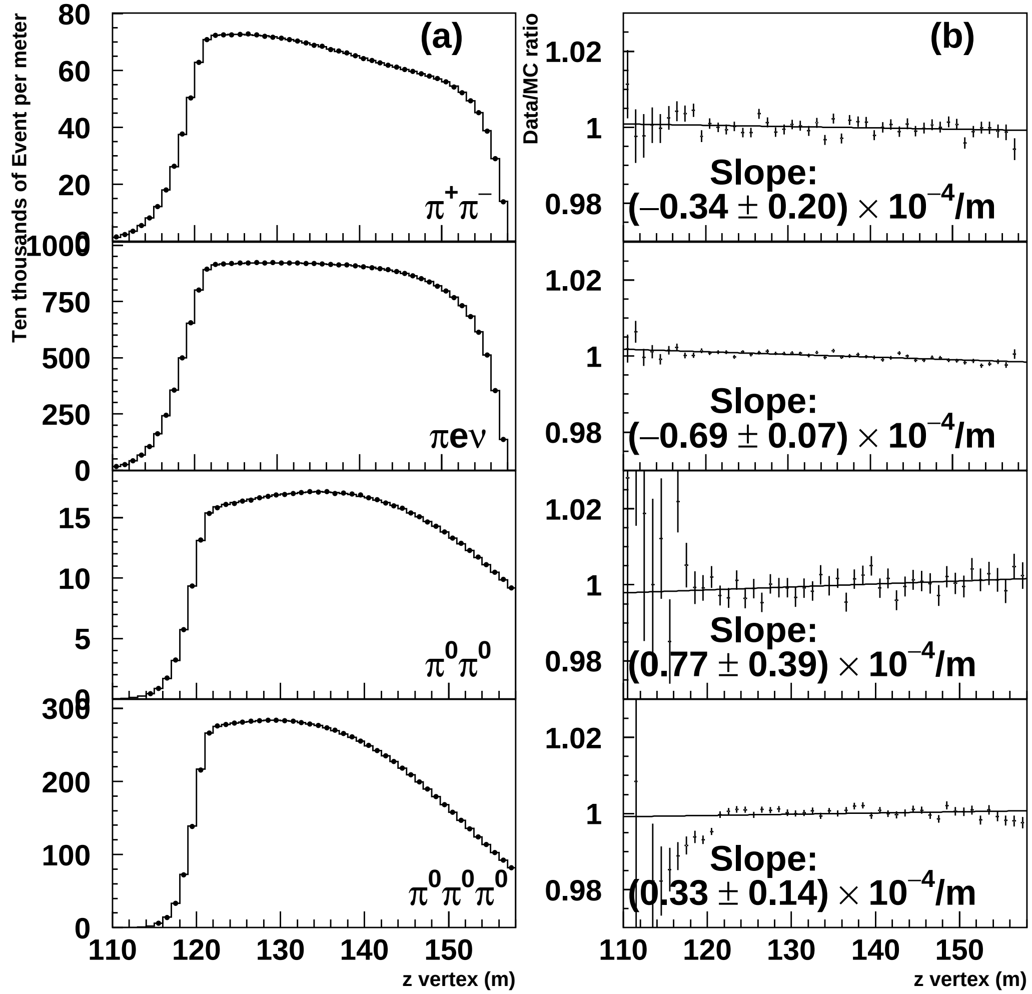
- Major improvements in CsI calorimeter simulation.
- Better description of the calorimeter nonlinearities.

Leading systematics for $Re(\epsilon'/\epsilon)$ from energy scale uncertainty reduced by factor of ~ 2.

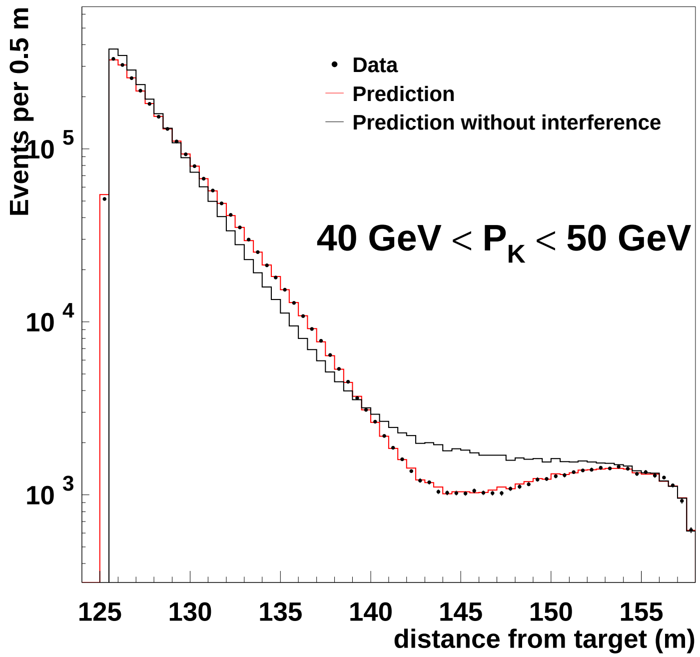
Acceptance Check

The measurement of $Re(\epsilon'/\epsilon)$ depends on how well MC describes decay vertex distribution for K_L decays. Difference of an average vertex between Reg. and Vac. beam is about 6 m.

$$\delta Re(\epsilon'/\epsilon) \approx \text{slope}$$



Fitting Kaon Parameters



Regenerator Vertex Z distribution

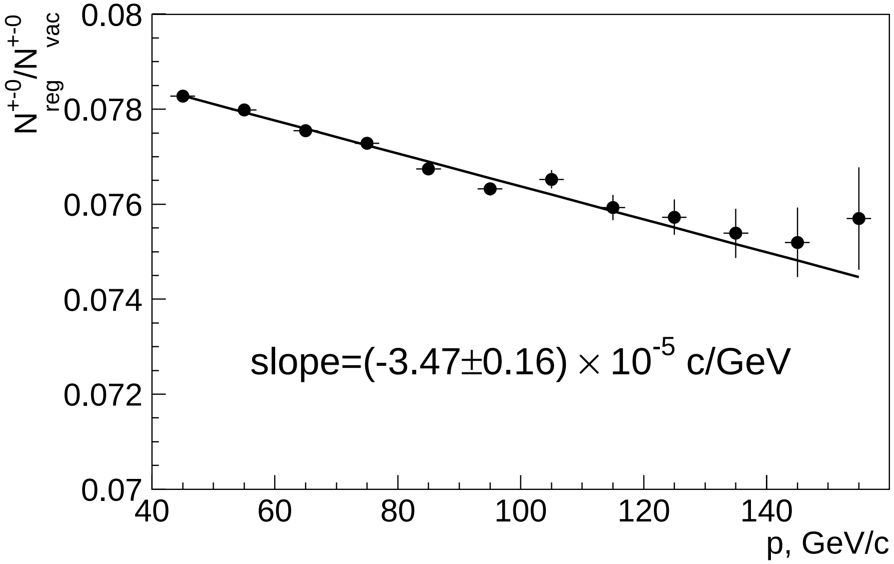
$K \to \pi\pi$ decay rate in Regenerator beam:

$$N(p,z) \sim |\rho|^2 e^{-\Gamma_S t} + |\eta|^2 e^{-\Gamma_L t}$$
$$+|\rho||\eta| cos(\Delta m t + \phi_\rho - \phi_\eta) e^{-\overline{\Gamma} t}$$

Clear interference effect.

- Regeneration amplitude ρ cancels out for ϵ'/ϵ.
- For $\Re(\epsilon'/\epsilon)$ fit integrated yield in Regenerator beam. Assume CPT, fix Δm, τ_S, $\Im(\epsilon'/\epsilon) = 0$.
- For $\Im(\epsilon'/\epsilon)$ fit shape in Regenerator beam. Float Δm, τ_S, ϵ'/ϵ, ϕ_ϵ

Regenerator Properties

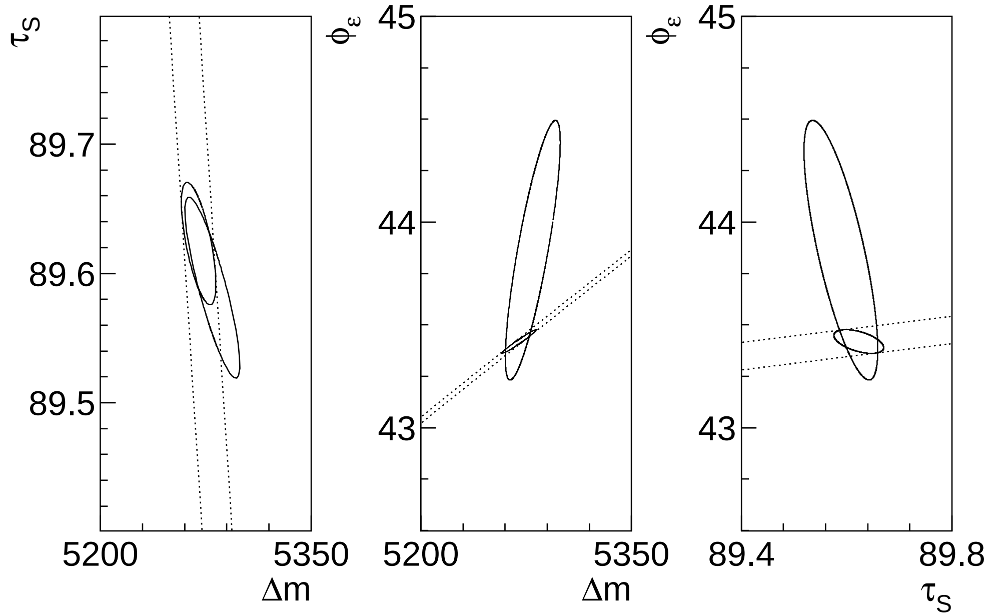


← Raw regenerator beam transmission as a function of kaon momentum.

- Measurements of $Re(\epsilon'/\epsilon)$ and $Im(\epsilon'/\epsilon)$ are weakly sensitive to regenerator parameters ρ and transmission.
- For Δm, τ_S and ϕ_ϵ regenerator beam transmission and screening corrections are dominant systematic sources.
- Measure transmission directly from data ($K_L \to \pi^+\pi^-\pi^0$ decays — nine fold increase, special trigger in 99).
- Compare screening corrections directly with $K_L \to \pi\pi$ data.

→Total ϕ_ϵ error reduced by factor 2.

τ_S, Δm and ϕ_ϵ results



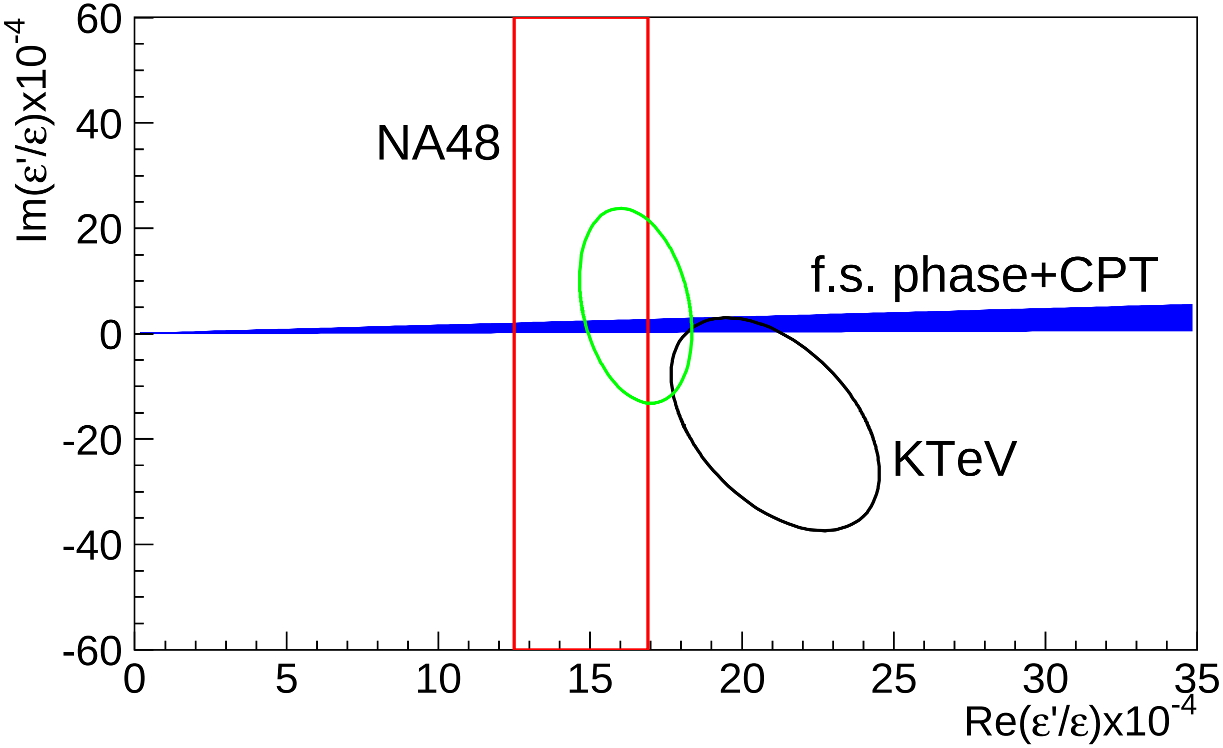
← Fit is performed without CPT assumption. Band indicate CPT constraint $\phi_\epsilon = \phi_{SW}$ applied a posteriori to obtain $\Delta m|_{CPT}$ and $\tau_S|_{CPT}$.

	KTeV03	PDG08	KTeV08
$\Delta m\|_{CPT} \times 10^6 \hbar s^{-1}$	5261 ± 15	5292 ± 9	5270 ± 12
$\tau_S\|_{CPT} \times 10^{-12}$s	89.65 ± 0.07	89.53 ± 0.05	89.62 ± 0.05
ϕ_{+-}, degrees	44.12 ± 1.40	43.4 ± 0.7	43.76 ± 0.64

CPT test:

$$\delta\phi = \phi_\epsilon - \phi_{SW} = [0.40 \pm 0.56]^\circ$$

$Im(\epsilon'/\epsilon)$ result



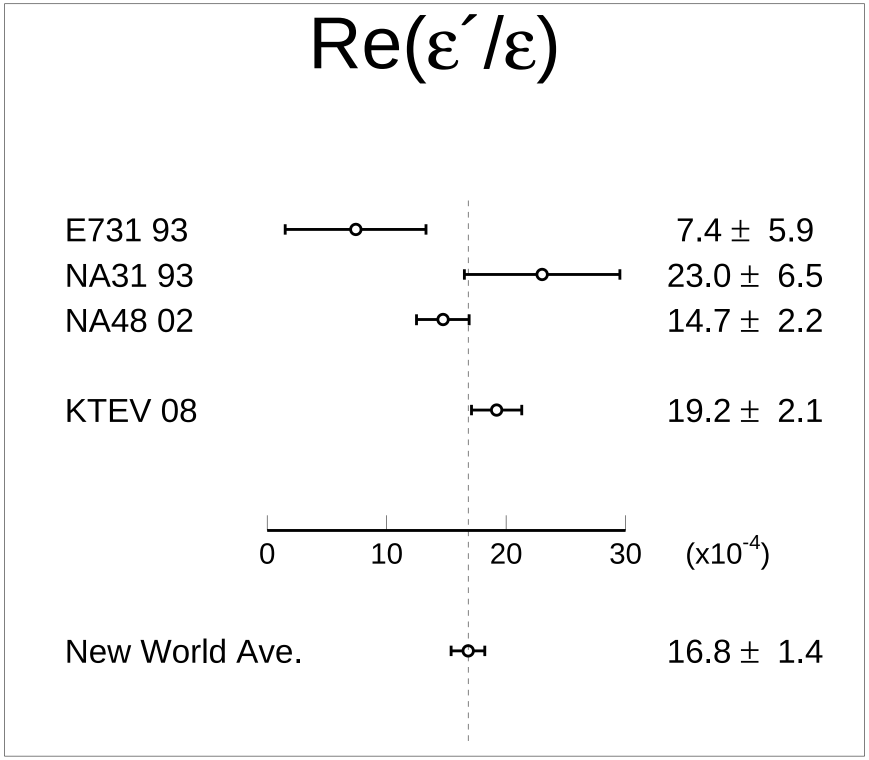
New result for $Im(\epsilon'/\epsilon)$:

$$Im(\epsilon'/\epsilon) = [-17.2 \pm 9.0_{\rm stat} \pm 18.1_{\rm syst}] \times 10^{-4} = [-17.2 \pm 20.2] \times 10^{-4}.$$

or $\Delta\phi = [0.30 \pm 0.35]^\circ$, improved vs $[0.39 \pm 0.50]^\circ$ (KTeV03) mostly due to energy scale improvement.

$Re(\epsilon'/\epsilon)$ results

$$Re(\epsilon'/\epsilon) = [19.2 \pm 1.1_{\rm stat} \pm 1.8_{\rm syst}] \times 10^{-4} = [19.2 \pm 2.1] \times 10^{-4}$$
$$(\chi^2/dof = 22.8/21)$$



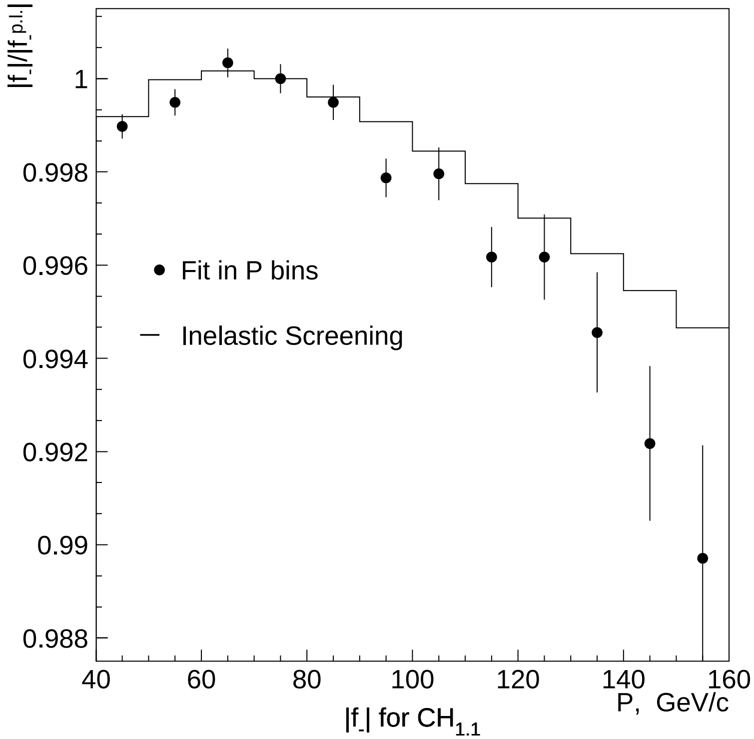
KTeV03: $Re(\epsilon'/\epsilon) = [20.7 \pm 1.5_{\rm stat} \pm 2.4_{\rm syst}] \times 10^{-4}$

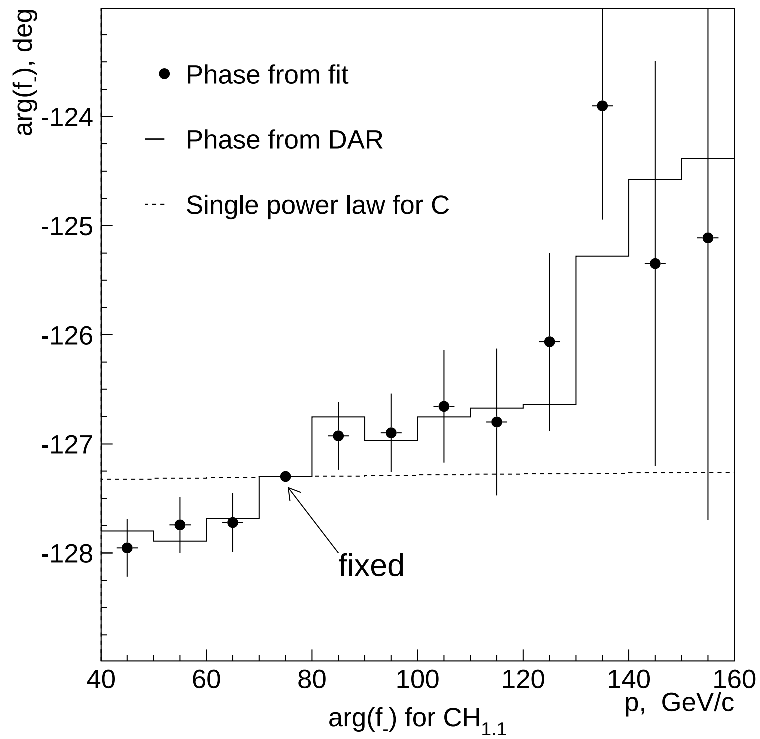
Conclusions

- Final Result from KTeV collaboration on $Re(\epsilon'/\epsilon)$, based on entire data set: $Re(\epsilon'/\epsilon) = [19.2 \pm 2.1] \times 10^{-4}$
- NA48 and KTeV results are consistent with each other, precise value of Direct CP violation parameter $\overline{Re(\epsilon'/\epsilon)} = [16.8 \pm 1.4] \times 10^{-4}$ is established.
- KTeV data is consistent with no CPT violation:
  - $\phi_\epsilon - \phi_{SW} = [0.40 \pm 0.56]^\circ$
  - $Im(\epsilon'/\epsilon) = [-17.2 \pm 20.2] \times 10^{-4}$

Extras

Screening Corrections





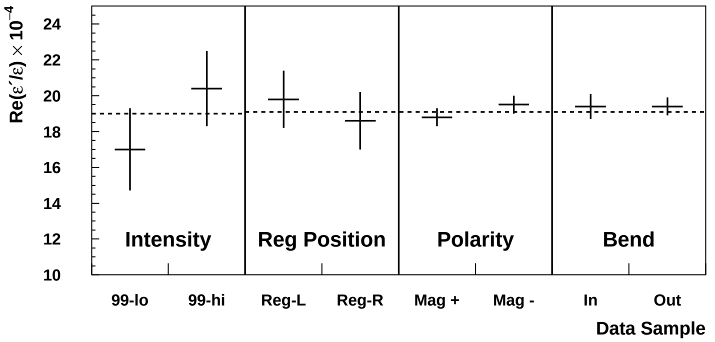
- Determine regeneration amplitude in 10 GeV kaon momentum bins. Agrees with screening corrections calculations for low P.
- Calculate phase at a given P using Derivative Analyticity Relation, using the 12 amplitudes.
- Compare variation of the phase vs P from DAR to direct fit to the data — good agreement.

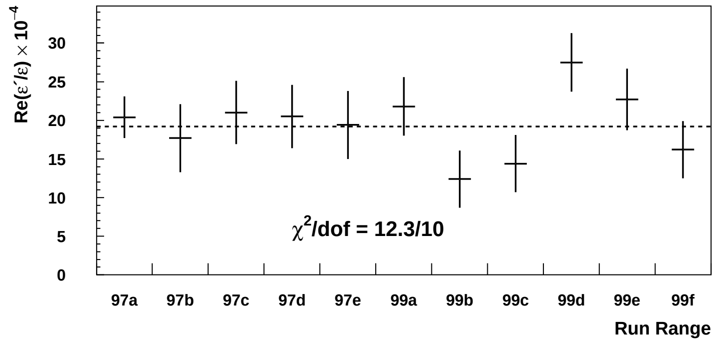
Systematic uncertainties in $Re(\epsilon'/\epsilon)$

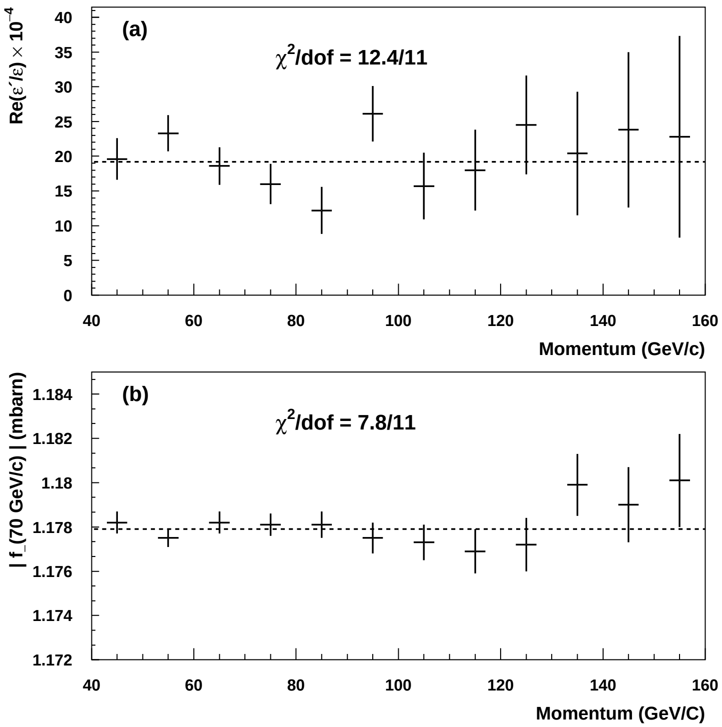
Source	$K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.23	0.20
CsI reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Background	0.20	1.07
MC statistics	0.20	0.25
Total	0.81	1.55
Fitting	0.31	
Total	1.78	

CsI reconstruction error is reduced from 1.47×10^{-4}.

$Re(\epsilon'/\epsilon)$ cross checks







Stability of $Re(\epsilon'/\epsilon)$ is studied for various data sub-samples as a function on run period, and as a function of kaon momentum. No systematic trends are observed.