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

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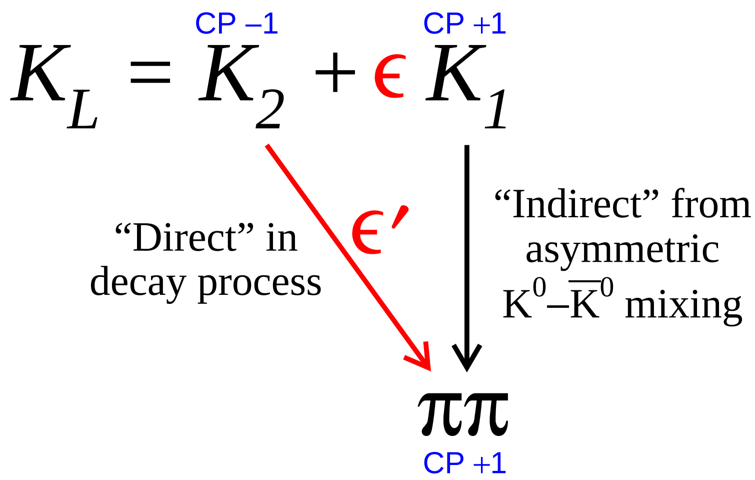
DESY

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

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

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

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

Introduction to ϵ'/ϵ II

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

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

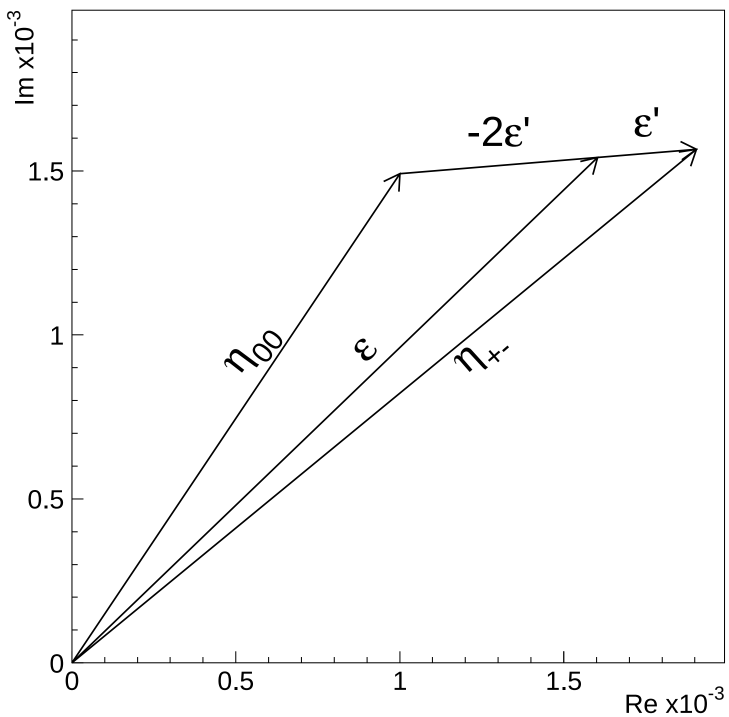
$Im(A_I)$ — CP violation
$Re(B_I)$ — CP & CPT violation
δ_I – final state interaction phase shifts, $\delta_2 - \delta_0 = (-42 \pm 4)^o$.

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

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:

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

CP symmetry violation and everyday life

CP violation $\leftrightarrow$ matter $\neq \overline{\text{matter}}$.

If **CPT** is conserved, then **CP** violation implies **T** violation.

Gross **CP** and **T** violation is observed in everyday life:

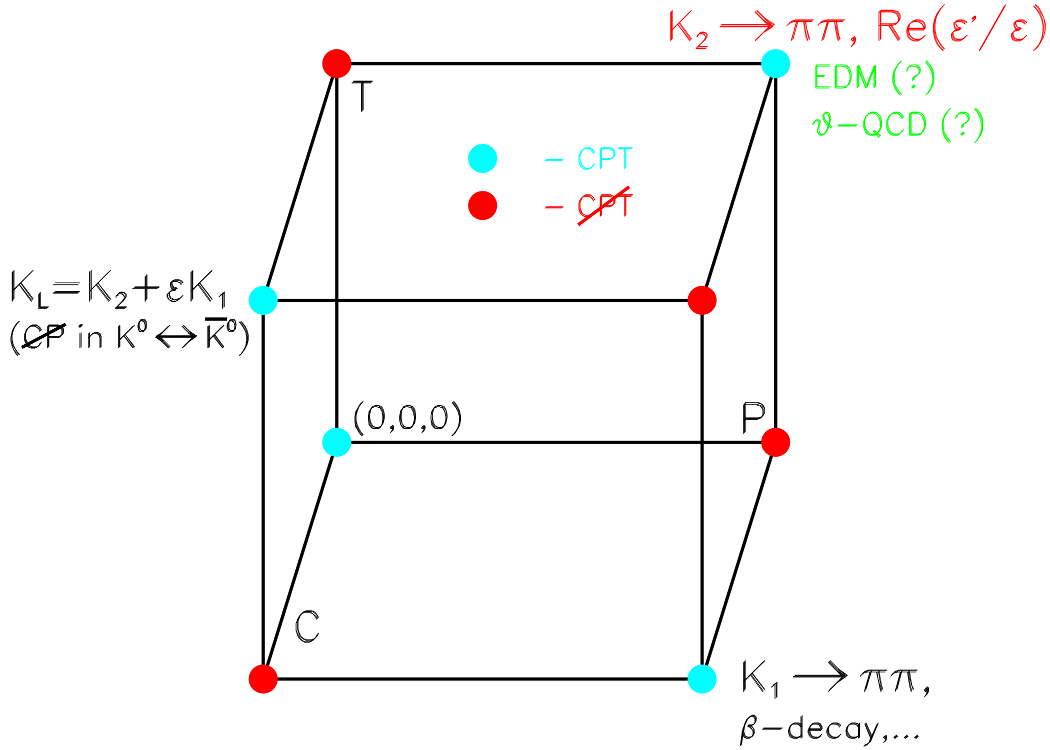
- There is no anti-matter around
- There is a clear "direction of time"

Do those facts arise due to fundamental laws of nature or due to very special initial conditions ?

Saharov's conditions to generate observed matter/anti-matter asymmetry dynamically:

1. Thermodynamic non-equilibrium
2. Baryon number non-conservation
3. Direct **CP** violation $(A(X) \to Y \neq A(\bar{X}) \to \bar{Y})$

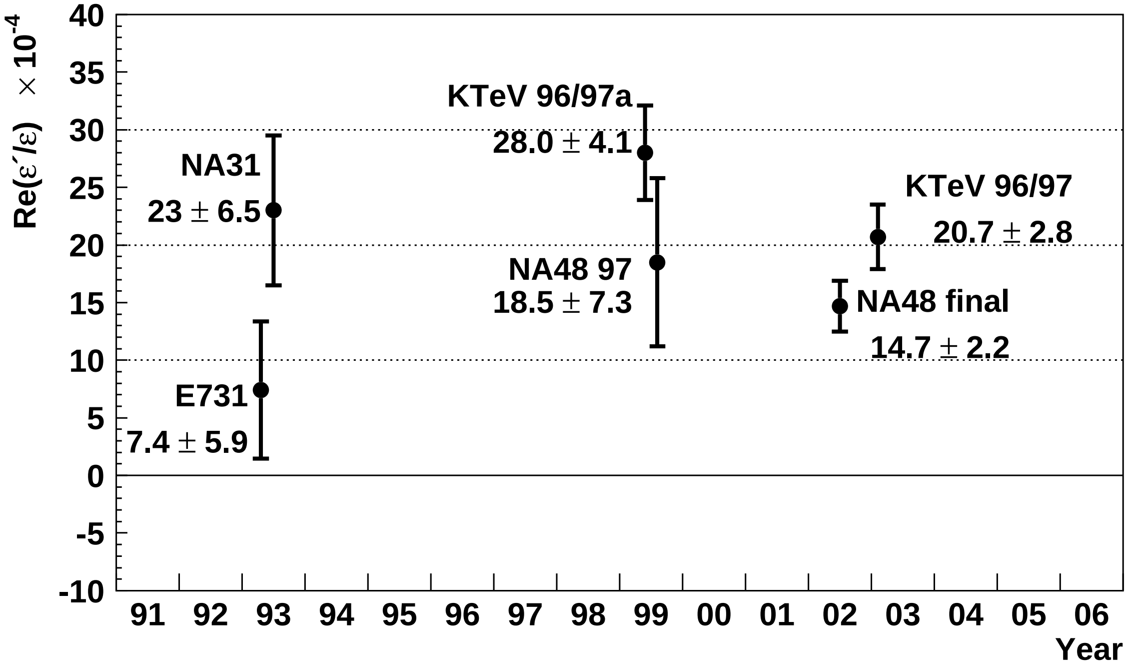
CPT cube



"CPT cube" illustrates CPT allowed/forbidden processes.

- All CPT allowed violations of discrete symmetries are observed in the neutral kaon system, including the measurement of direct CP violation.
- Observations in kaon sector are supported by B measurements
- Future: EDM, θ-QCD (...)

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

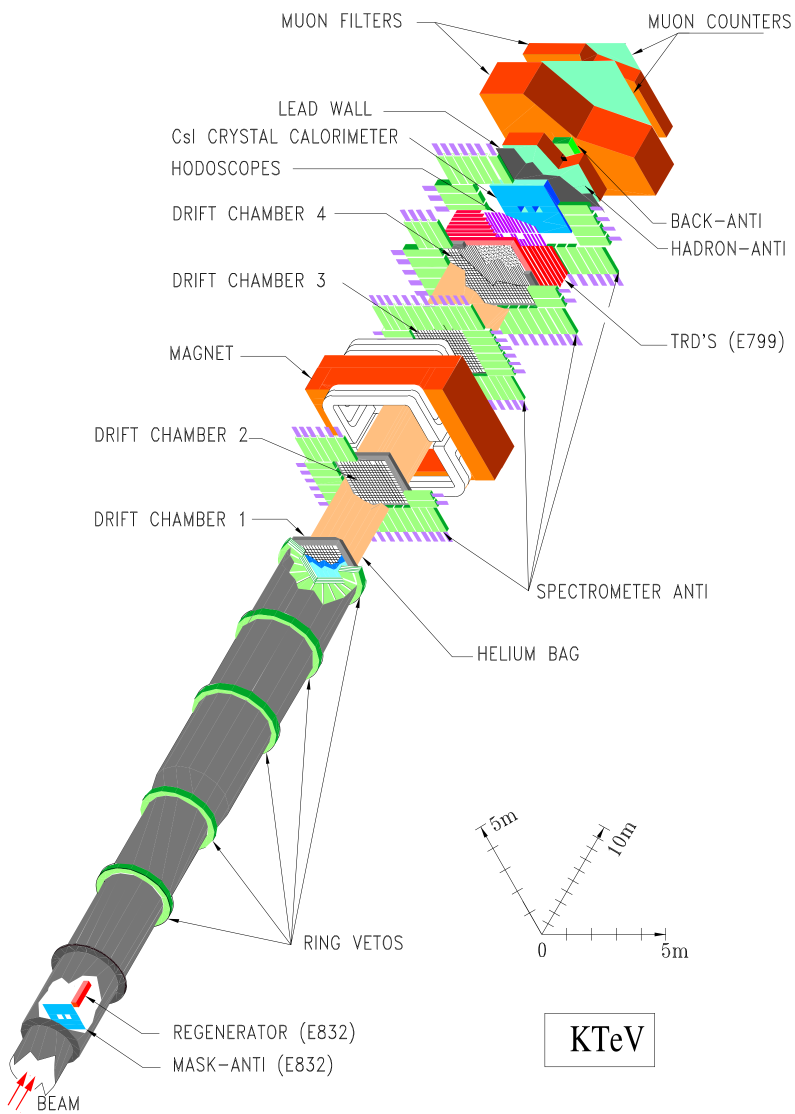


KTeV Data yields of $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ events:

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

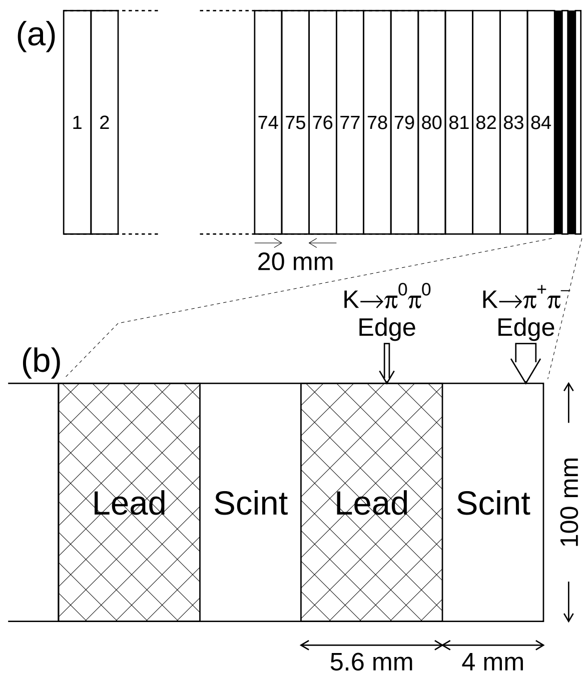
Today: analysis of the complete KTeV data set.

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

The Regenerator



Difference in K^0, $\overline{K^0}$ interactions lead to K_S **regeneration**:

$$f: \quad K^0 + C_{12} \rightarrow K^0 + C_{12}$$
$$\overline{f}: \quad \overline{K^0} + C_{12} \rightarrow \overline{K^0} + C_{12}$$
$$K_L + C_{12} \rightarrow (f + \overline{f})K_L + (f - \overline{f})K_S + C_{12}$$

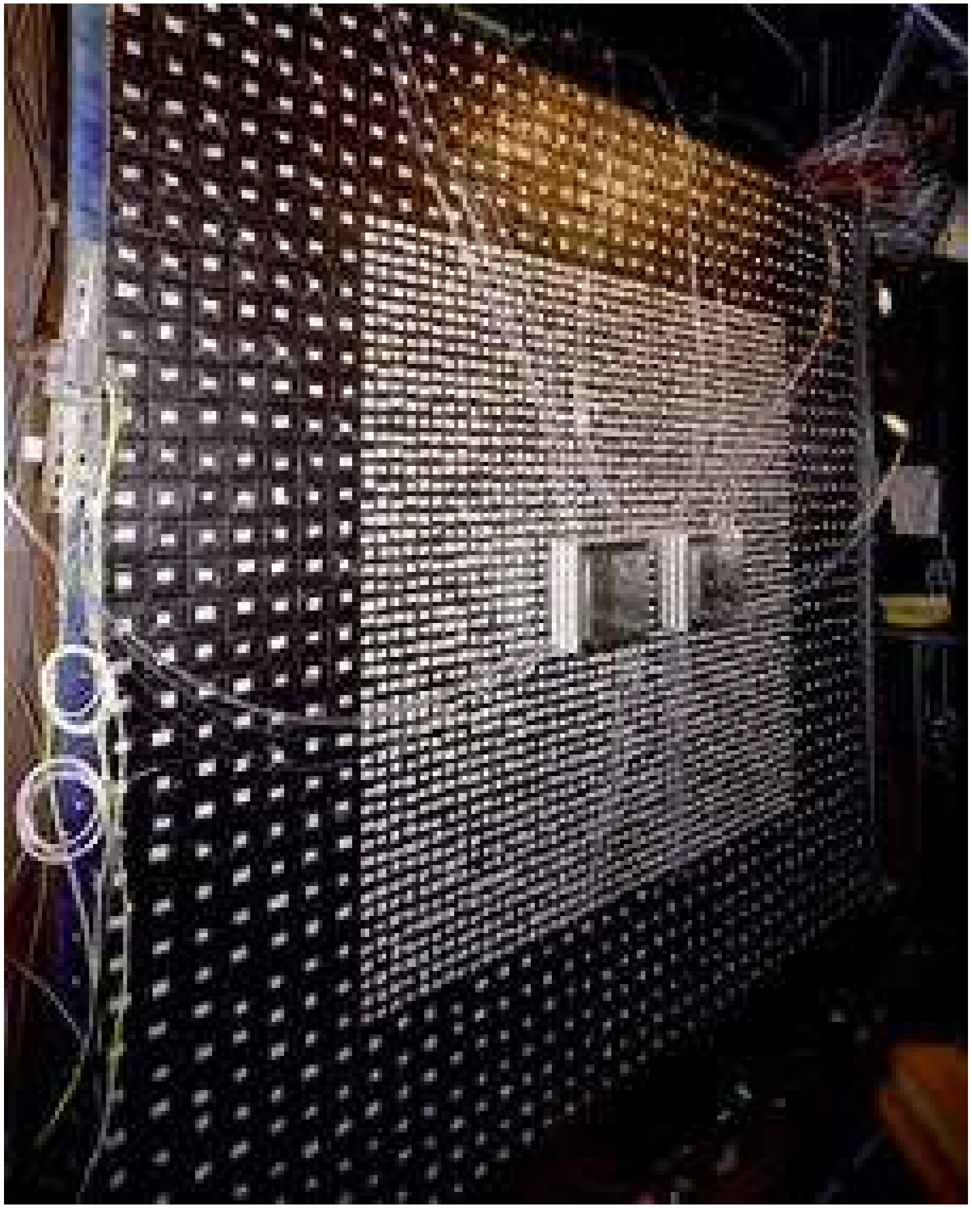
In Regge theory regeneration for isoscalar targets is explained as ω exchange.

- Output of regenerator is *coherent mixture* of $K_L + \rho K_S$
- Close to regenerator edge $K_S \rightarrow \pi\pi$ decays dominate.
- At larger proper time $K_L - K_S$ *interference* is important

\+ $\rightarrow$ sensitivity to $\Delta m, \phi_{+-}, \Im(\epsilon'/\epsilon)$

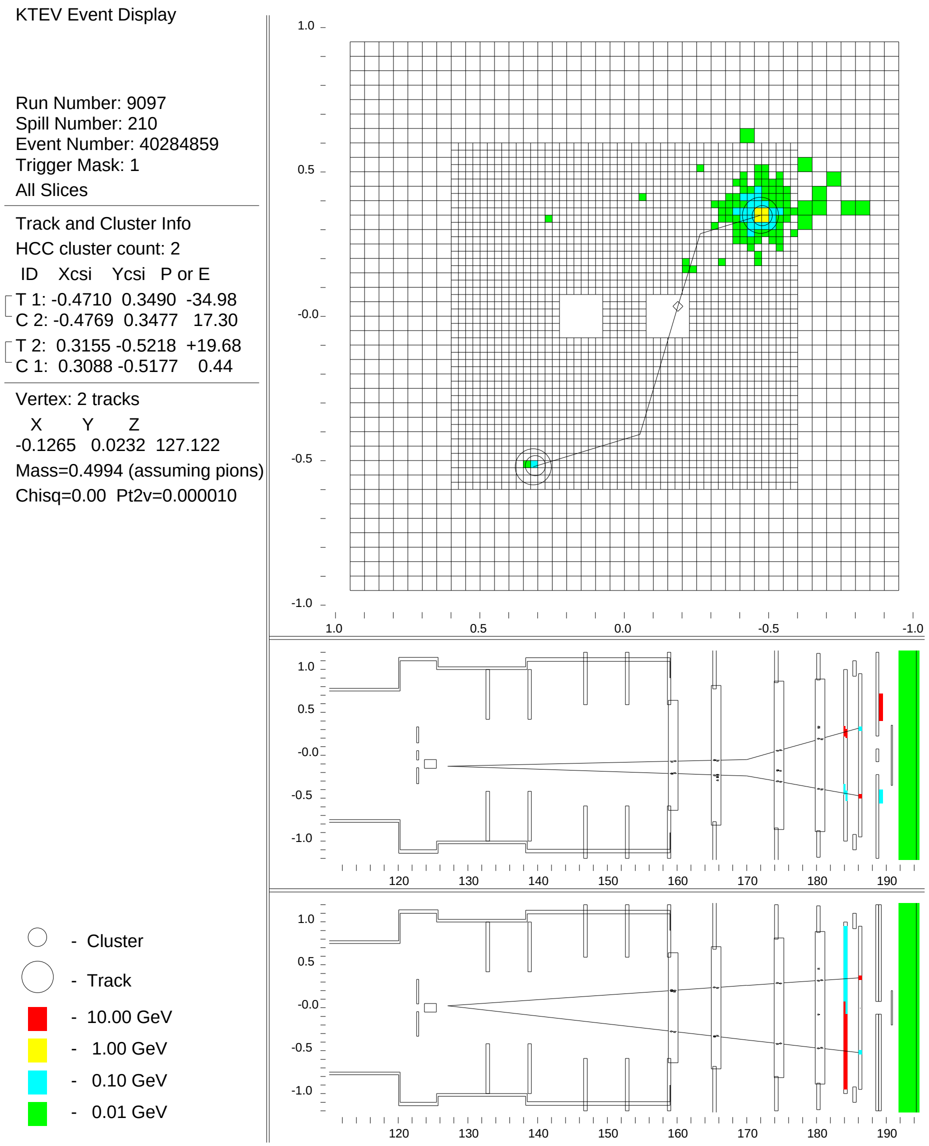
− regeneration in finite p_t^2 scattering processes creates additional **background**, large for neutral mode.

The CsI Calorimeter



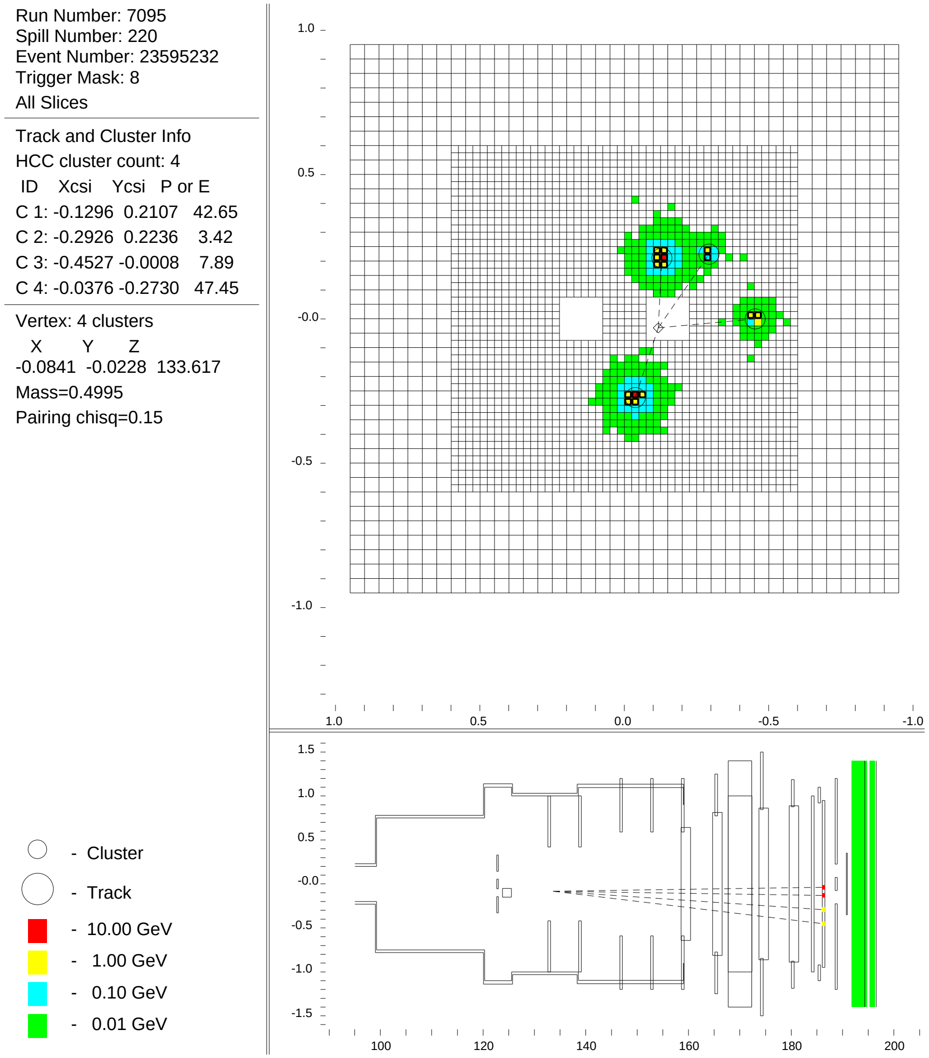
- 3100 CsI crystals, "small" ($2.5 \times 2.5 \times 50$ cm^3) and "large" ($5.0 \times 5.0 \times 50$ cm^3).
- Energy resolution $\sim 0.6\%$
- Absolute energy scale $\sim 0.05\%$

Charged Mode Reconstruction



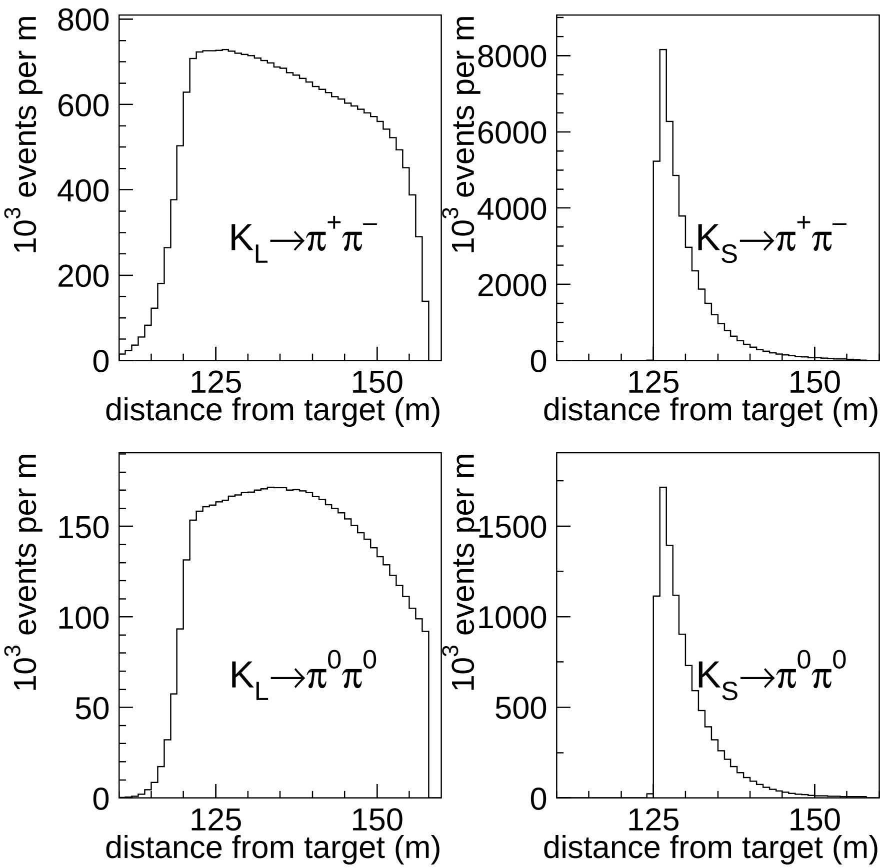
- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using X-vertex position
- Clearance cuts to define detector volume.

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 $Z_v < 158$ m cut to stay inside vacuum decay volume.

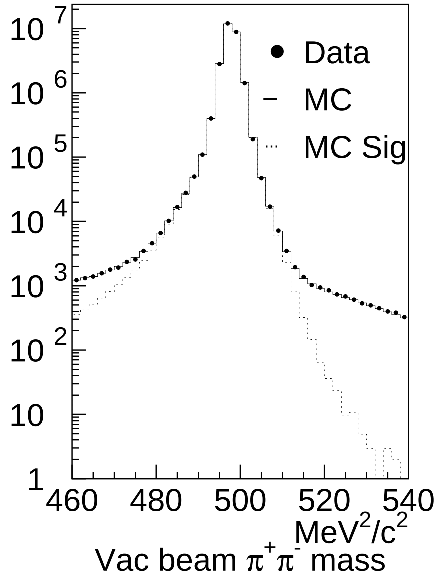
Understanding the Acceptance

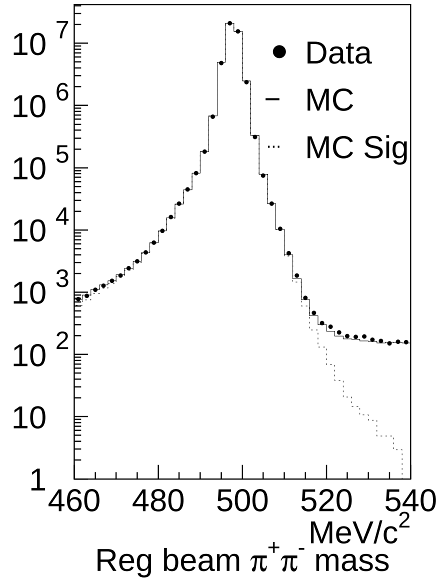


The K_S beam probes a different region of the detector that the K_L beam.

KTeV uses MC simulation to correct for acceptance difference.

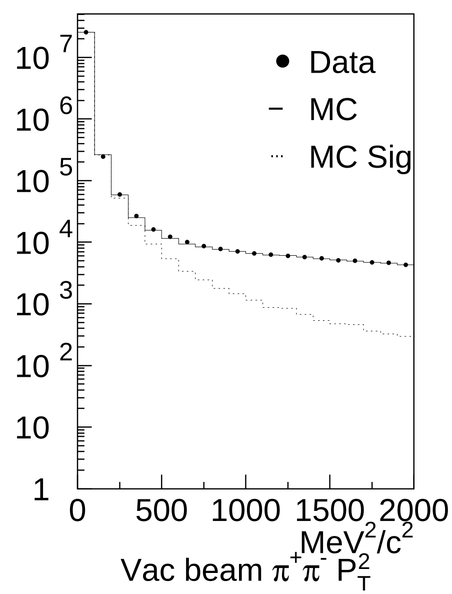
Charged Mode Improvements

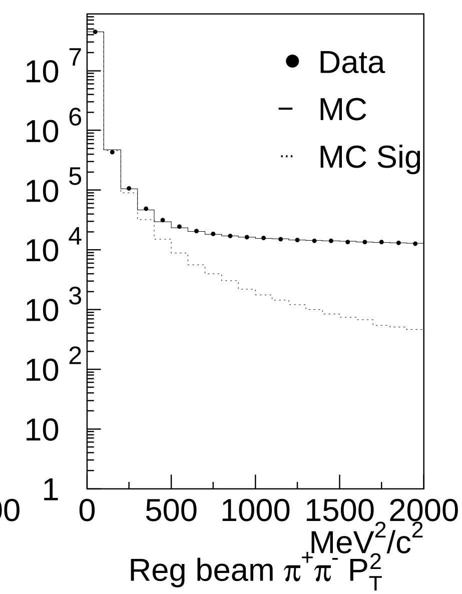




← Improvements in reconstruction and simulation of backgrounds, veto detectors thresholds. Mass resolution is 1.4 MeV/c^2, 15% better vs KTeV03.

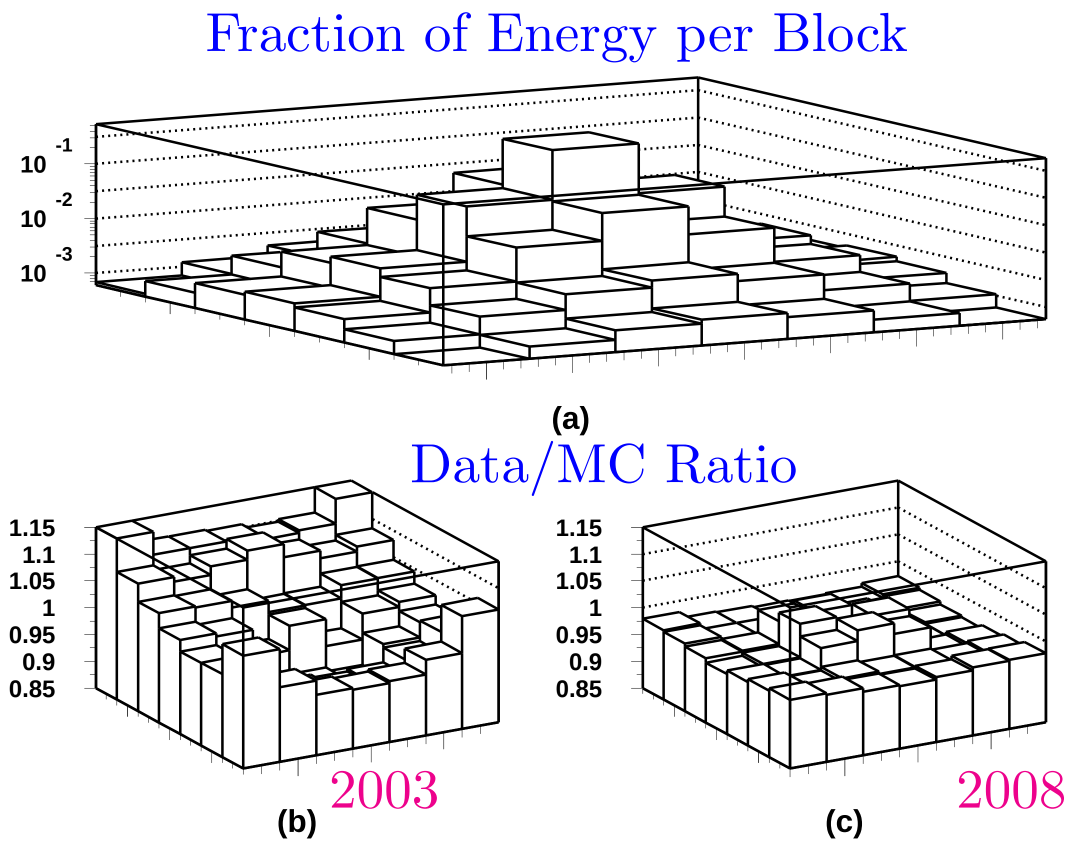
Better description of detector material, scattering and δ-rays.
Good description of tails in mass and p_t^2 distributions.





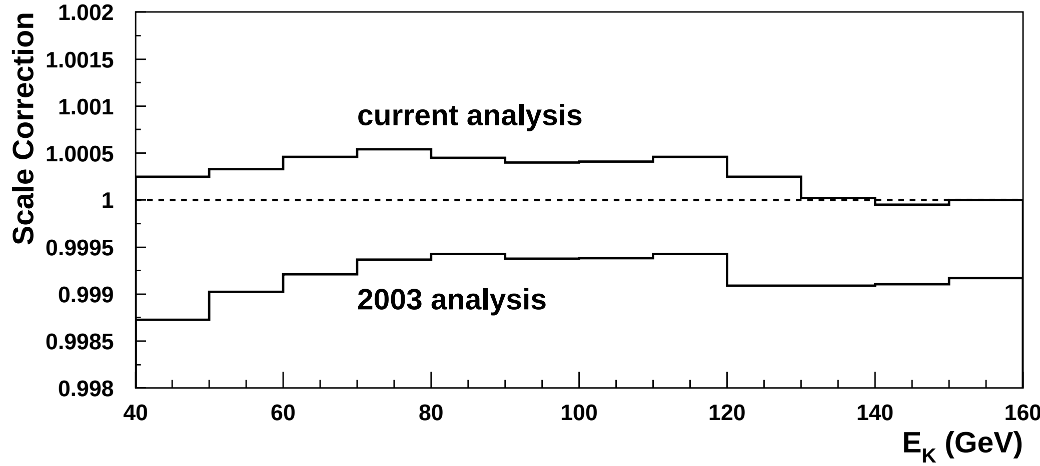
Electromagnetic Shower Simulation in CsI

- GEANT3 based detailed shower library binned in energy, position and incident angle.
- Significant improvement in the description of energy sharing between the calorimeter cells.



No extra corrections to MC applied, GEANT3 out of the box.

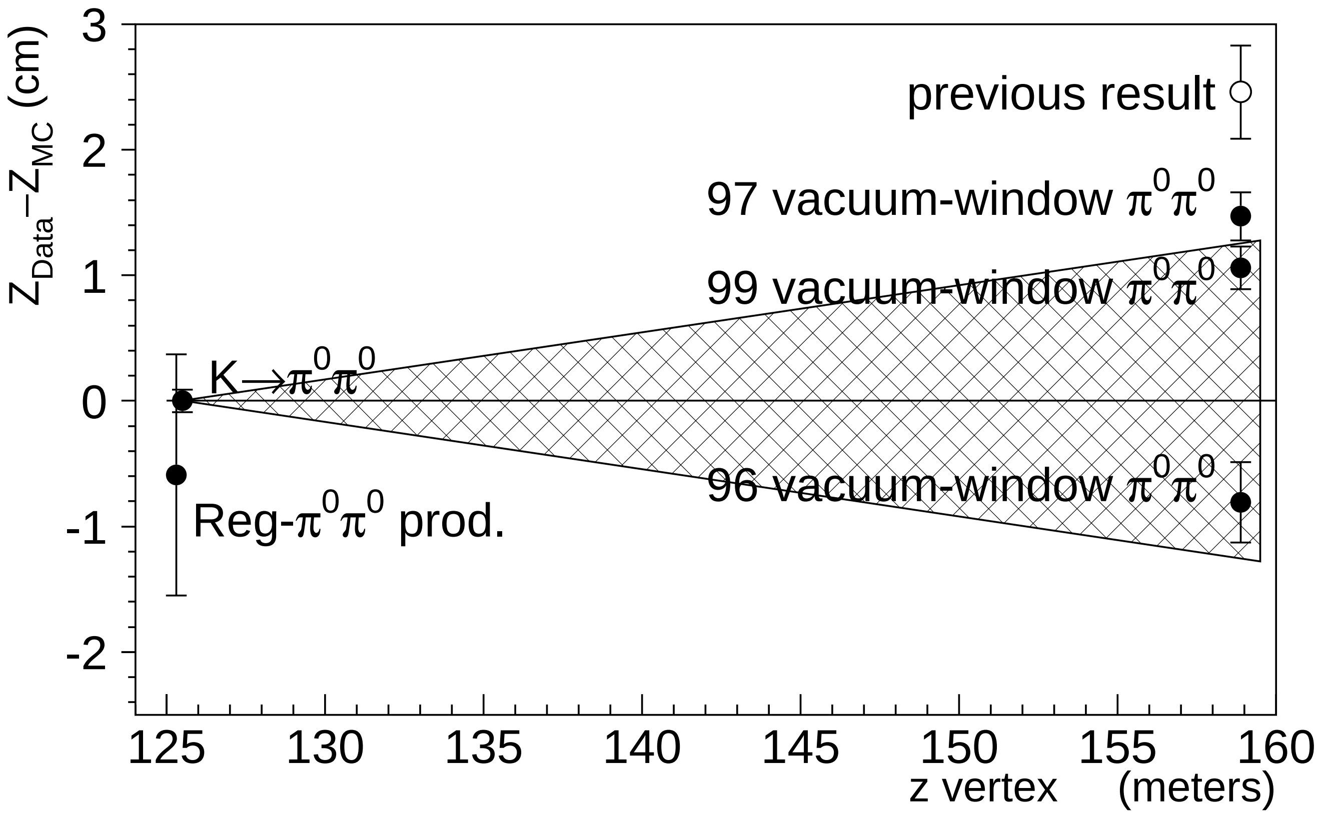
CsI Energy Calibration



← Final correction using regenerator edge reconstructed in DATA and MC

- In-situ laser system for short time variations.
- Longitudinal non-uniformity using cosmic muons.
- Main calibration source 1.5×10^9 electrons from $K_L \to \pi^\pm e^\mp \nu$ decays.
- Extra corrections using $K_L \to \pi^0\pi^0\pi^0$ and $K_L \to \pi^0\pi^0$ decays.
- Final correction using reconstructed regenerator edge.

Neutral Mode Energy Scale Systematics



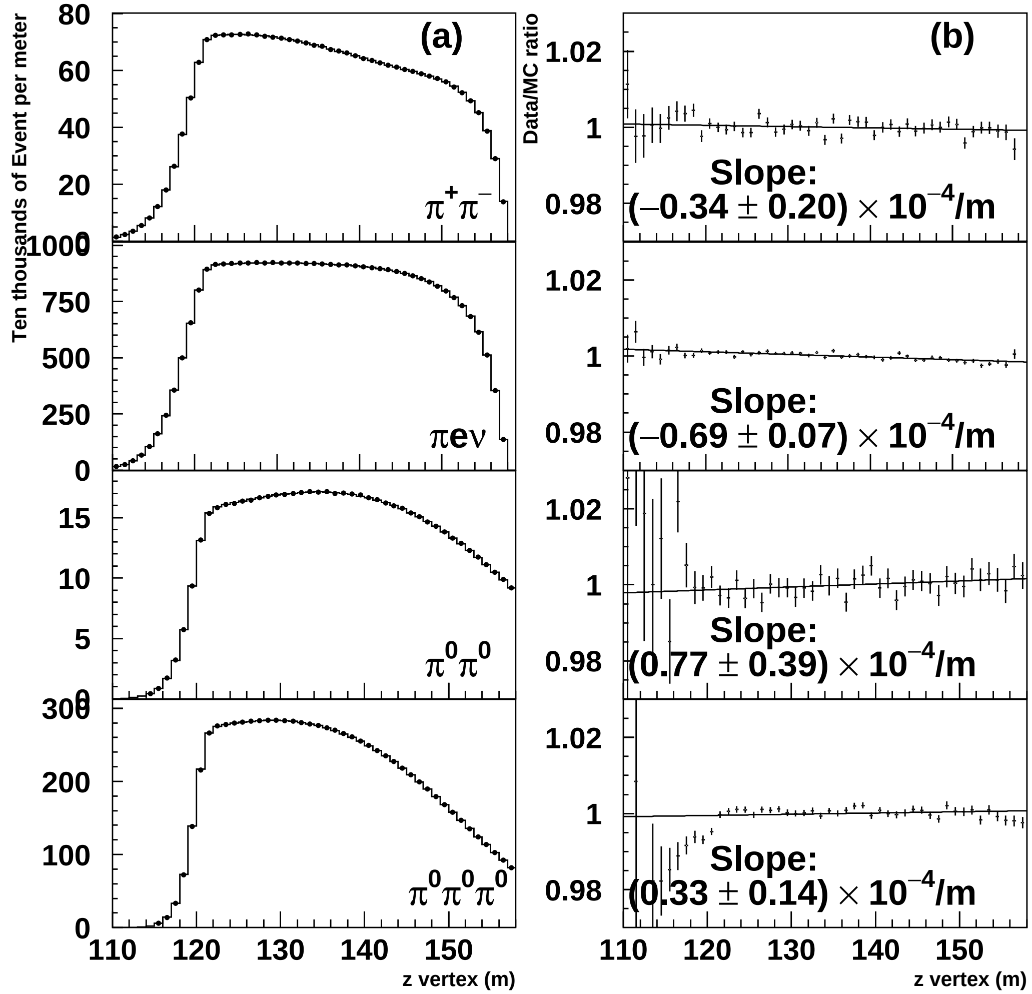
Size of the decay volume for neutral mode is defined by the energy scale vs Z. The upstream end is adjusted at the Regenerator edge, the downstream end is checked using hadronic $\pi^0\pi^0$ production at the vacuum window.

Leading $Re(\epsilon'/\epsilon)$ uncertainty is reduced by factor of ~ 2.

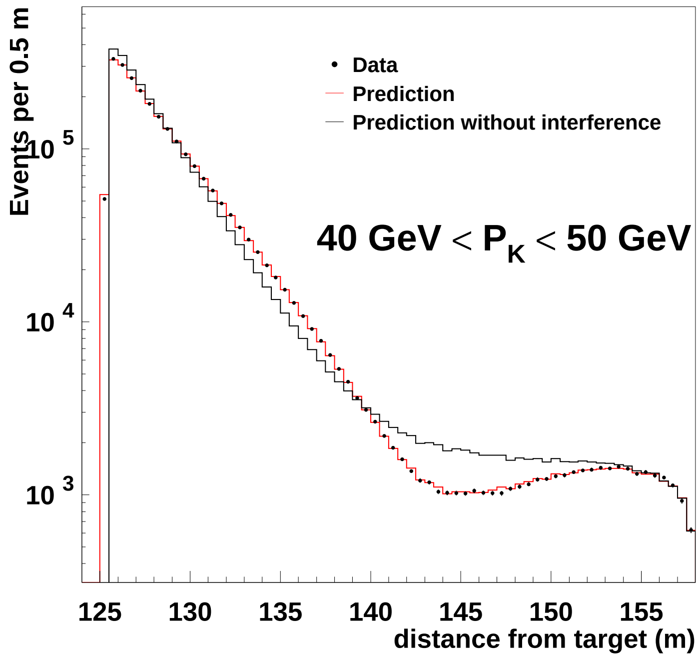
Acceptance Check

The measurement of $Re(\epsilon'/\epsilon)$ depends on how well MC describes acceptance vs Z, this can be studied comparing 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

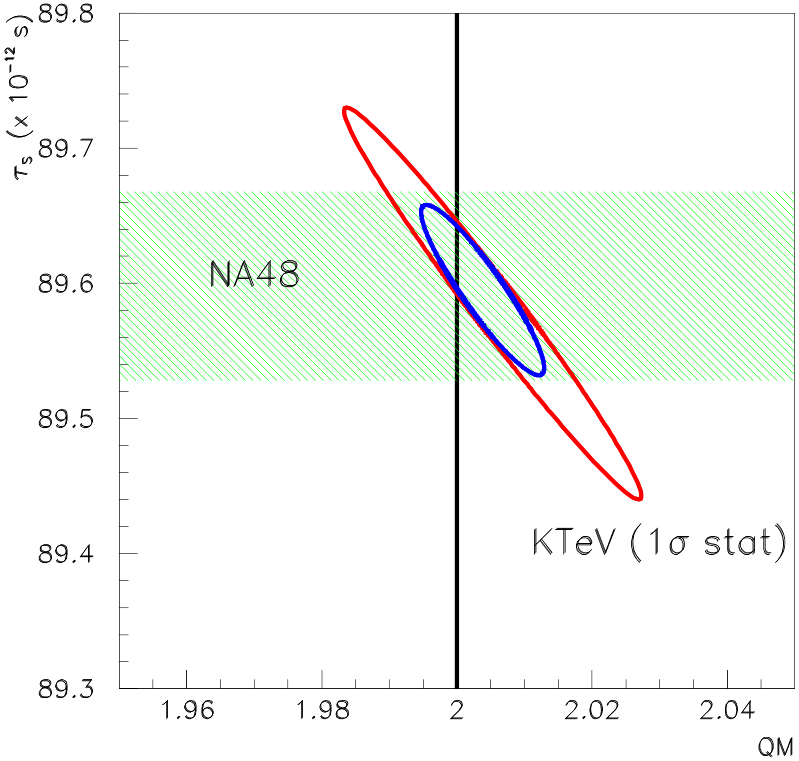
$K \to \pi\pi$ decay rate in Regenerator beam:

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

Clear interference effect.

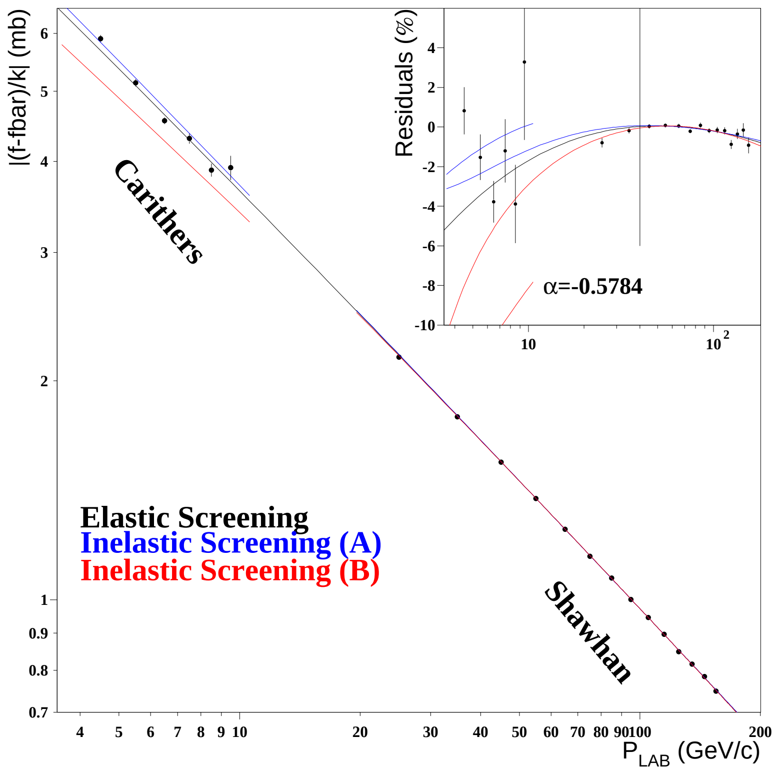
- Regeneration amplitude ρ cancels out for ϵ'/ϵ.
- For $\Re(\epsilon'/\epsilon)$ fit integrated yield in Regenerator beam. Assume CPT, fix Δm, τ_S, $\Im(\epsilon'/\epsilon) = 0$.
- For $\Im(\epsilon'/\epsilon)$ fit shape in Regenerator beam. Float Δm, τ_S, ϵ'/ϵ, ϕ_ϵ

Fit of QM "2"



- Anything (including "2") in regeneration formula can be considered as a free parameter
- NA48 has a clean source of K_S allows to constrain K_S lifetime, improve precision.

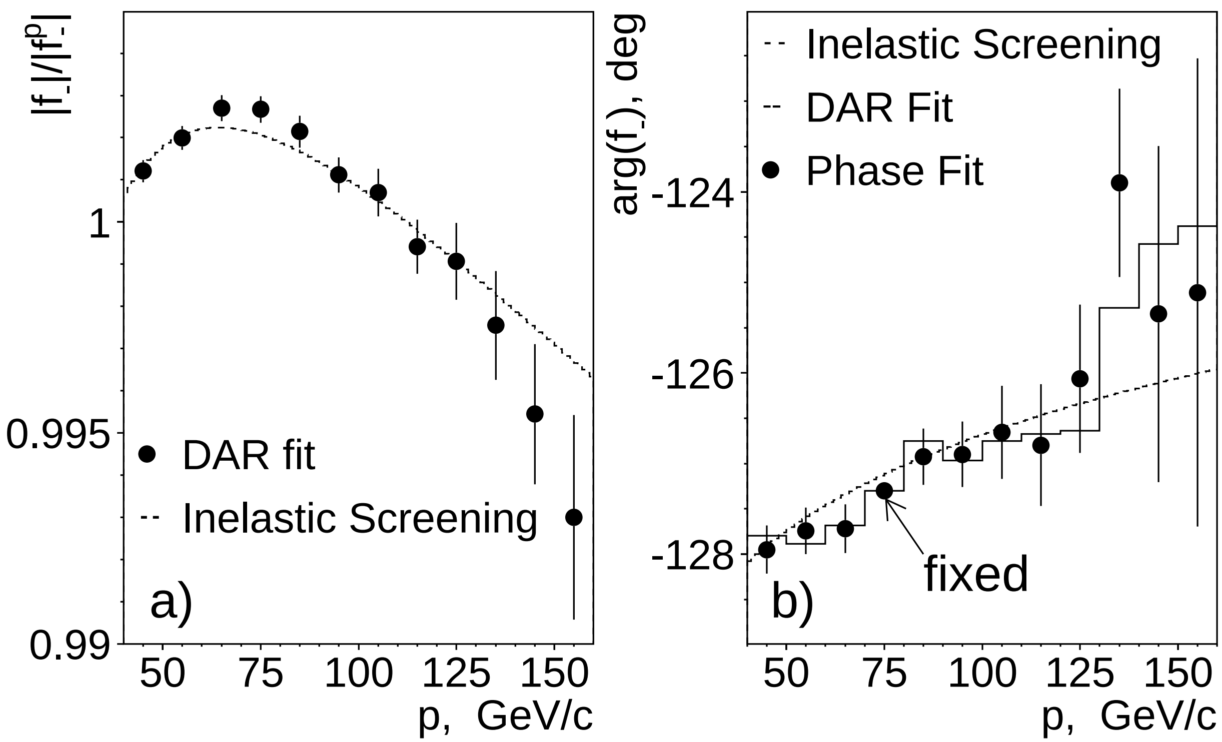
Regeneration Amplitude



$K_L - K_S$ forward scattering amplitude difference $|\frac{f-\bar{f}}{k}|$ for $P > 40$ GeV/c^2 is to a first order described by a single power law.

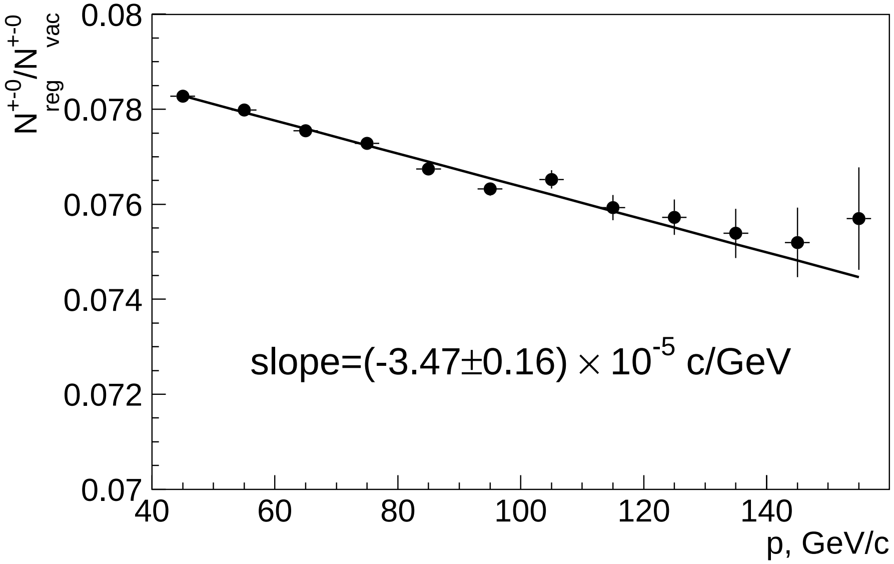
Relate measured using $K \rightarrow \pi\pi$ data regeneration amplitude and the regeneration phase via analyticity. This method is extended to estimation of *screening corrections*.

Screening Corrections



- Determine regeneration amplitude in 12×10 GeV/c kaon momentum bins. Agrees well with the screening corrections calculation.
- Calculate phase at a given p using Derivative Analyticity Relation (DAR), for the 12 p bins.
- Compare variation of the phase vs p from DAR to direct fit to the data — good agreement.

Regeneration Transmission

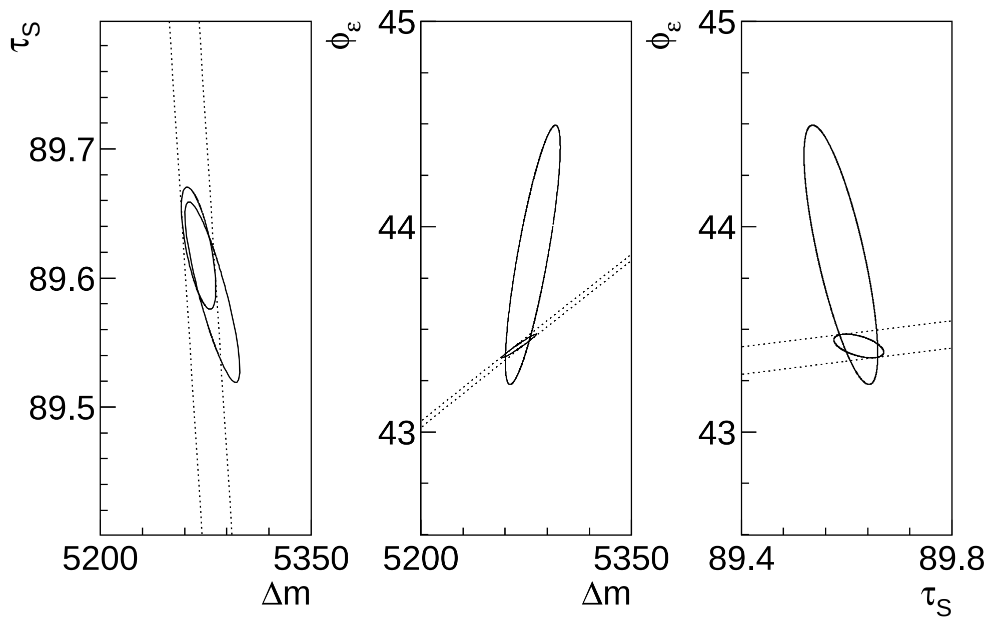


← Raw regenerator beam transmission as a function of kaon momentum.

Measure transmission directly from data ($K_L \to \pi^+\pi^-\pi^0$ decays — nine fold increase vs 1997, special trigger in 1999).

Combined with better estimate of the screening corrections leads to →total ϕ_ϵ error reduced by factor 2.

τ_S, Δm and ϕ_ϵ results



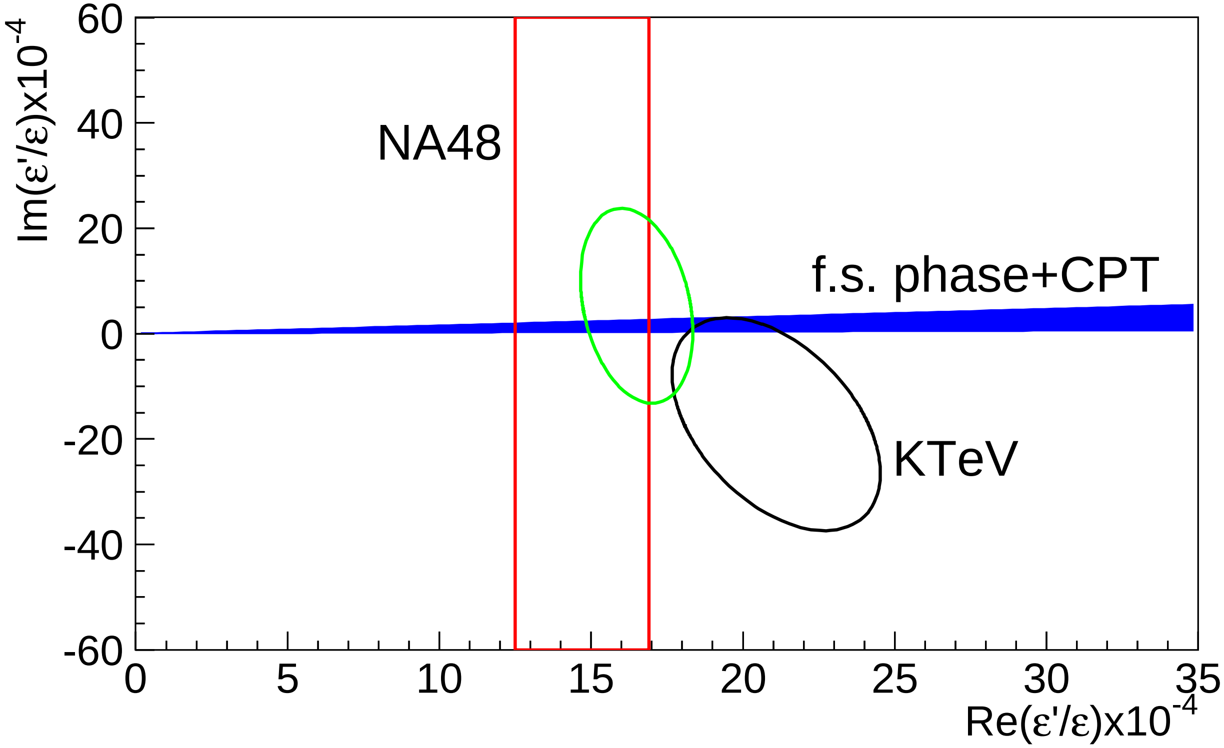
← Fit is performed without CPT assumption. Band indicate CPT constraint $\phi_\epsilon = \phi_{SW}$ applied a posteriori to obtain $\Delta m|_{CPT}$ and $\tau_S|_{CPT}$.

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

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

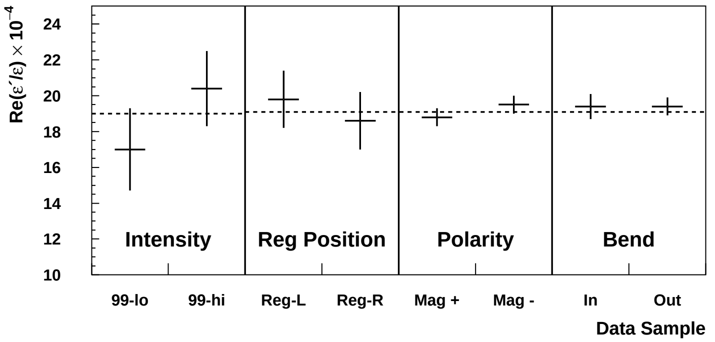
or $\Delta\phi = [0.30 \pm 0.35]^\circ$, improved vs $[0.39 \pm 0.50]^\circ$ (KTeV03) mostly due to energy scale improvement.

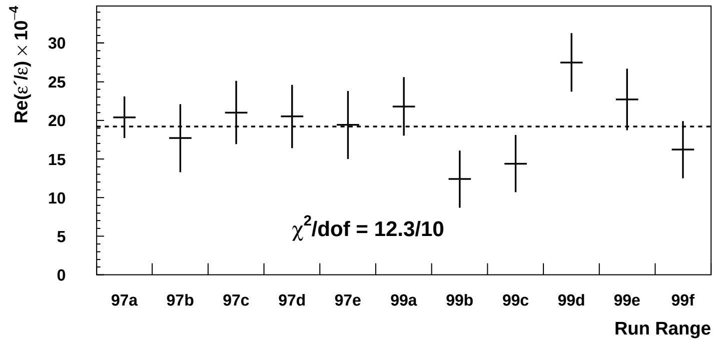
Systematic uncertainties in $Re(\epsilon'/\epsilon)$

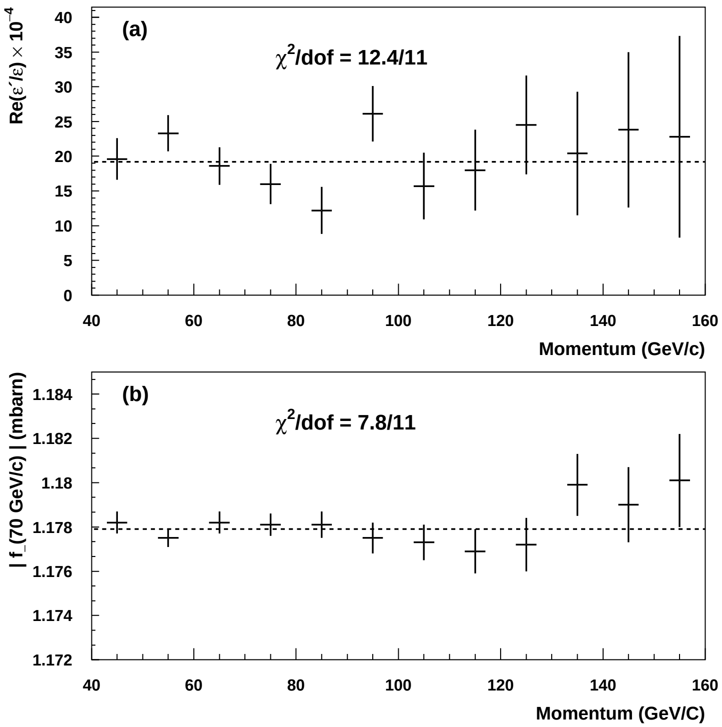
Source	$K \rightarrow \pi^+\pi^-$	$K \rightarrow \pi^0\pi^0$
Trigger	0.23	0.20
CsI reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Background	0.20	1.07
MC statistics	0.20	0.25
Total	0.81	1.55
Fitting	0.31	
Total	1.78	

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

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



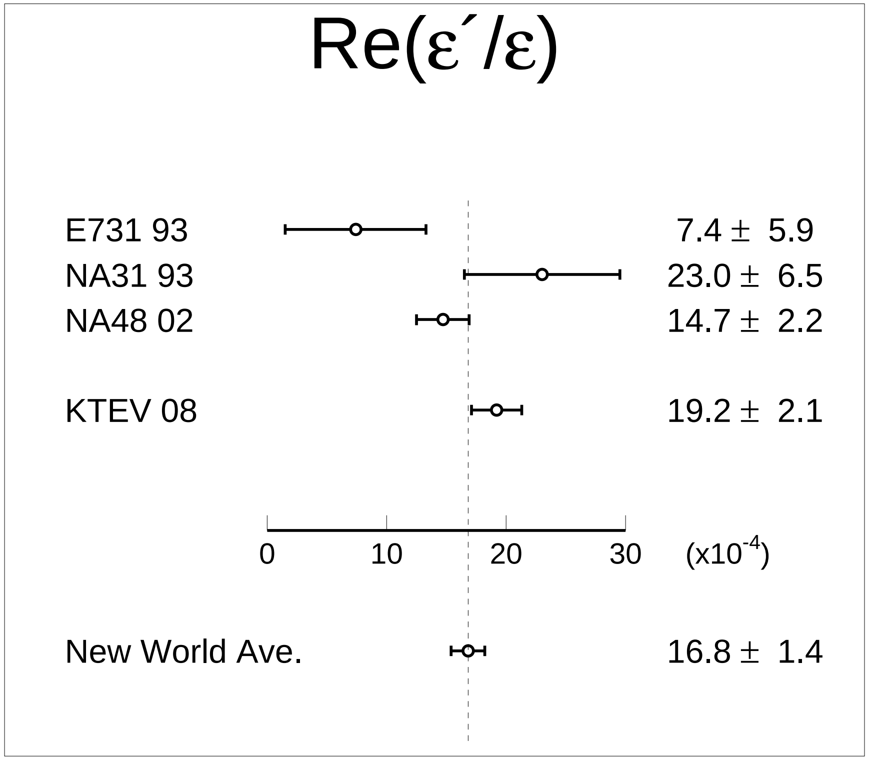




Stability of $Re(\epsilon'/\epsilon)$ is studied for various data sub-samples as a function on run period, and as a function of kaon momentum. No systematic trends are observed.

$Re(\epsilon'/\epsilon)$ 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:
  - $\phi_\epsilon - \phi_{SW} = [0.40 \pm 0.56]^\circ$
  - $Im(\epsilon'/\epsilon) = [-17.2 \pm 20.2] \times 10^{-4}$