The Measurement of ϵ'/ϵ by KTeV collaboraion

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For the KTeV Collaboration:

Arizona – Chicago – Colorado – Elmhurst

Fermilab – Osaka – Rice – Rutgers

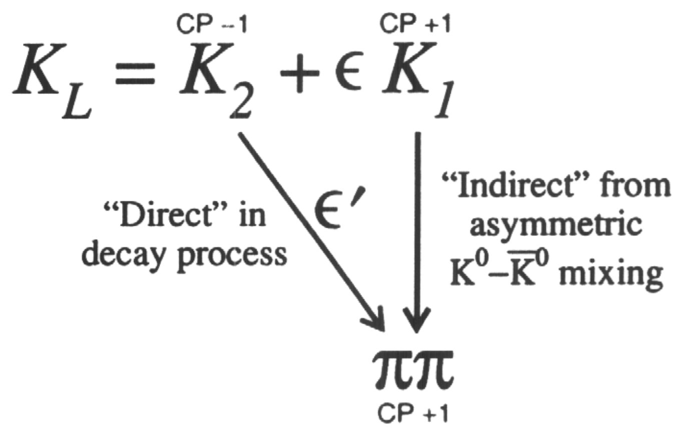
UCLA – UCSD – Virginia – Wisconsin

Introduction to 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 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:

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

$\Im(A_I)$ – CP violation
$\Re(B_I)$ – CP & CPT violation
– final state interaction phase shifts,

.

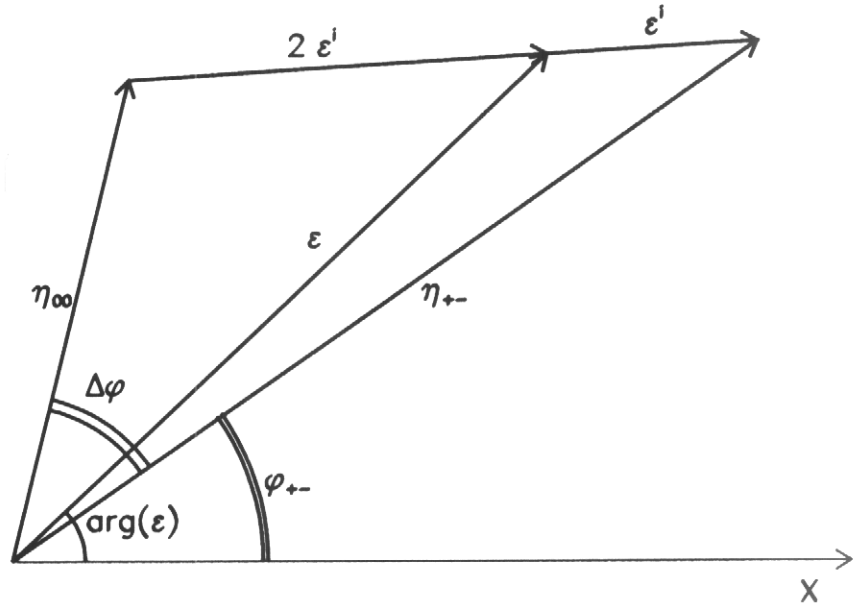
$$\begin{aligned} \epsilon'_{CP} &\approx \frac{i}{\sqrt{2}} \frac{\Re(A_2)}{\Re(A_0)} \left[\frac{\Im(A_2)}{\Re(A_2)} - \frac{\Im(A_0)}{\Re(A_0)} \right] e \\ \epsilon'_{CPT} &\approx \frac{1}{\sqrt{2}} \frac{\Re(A_2)}{\Re(A_0)} \left[\frac{\Re(B_2)}{\Re(A_2)} - \frac{\Re(B_0)}{\Re(A_0)} \right] e \end{aligned}$$

$\frac{\Re(A_2)}{\Re(A_0)} = \omega = 0.045$, "$\Delta = 1/2$ rule"
— a 50 years old problem !

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



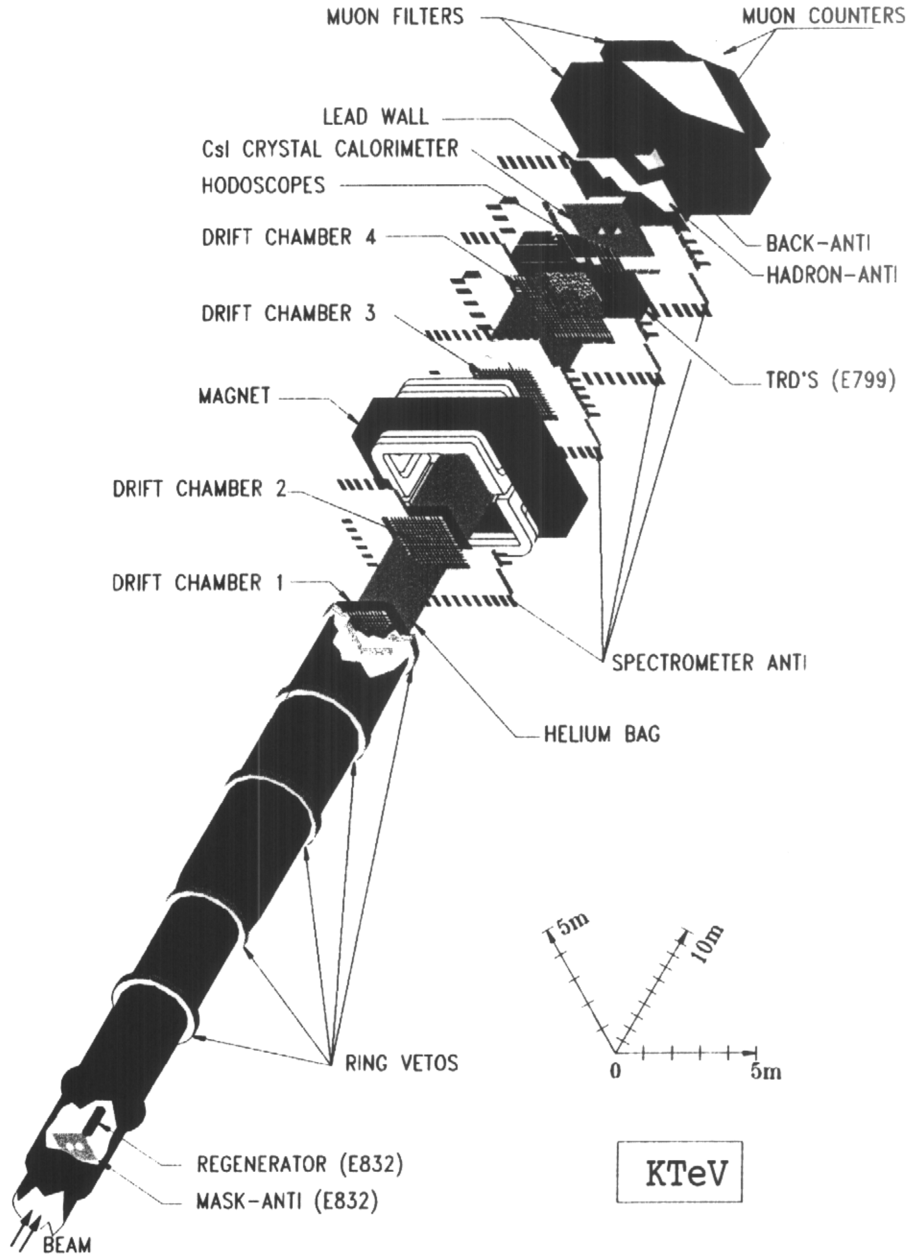
With the interference information in the regenerator beam, KTeV can measure not only decay rates but also phases as well as other kaon sector parameters:

-
-
-
-

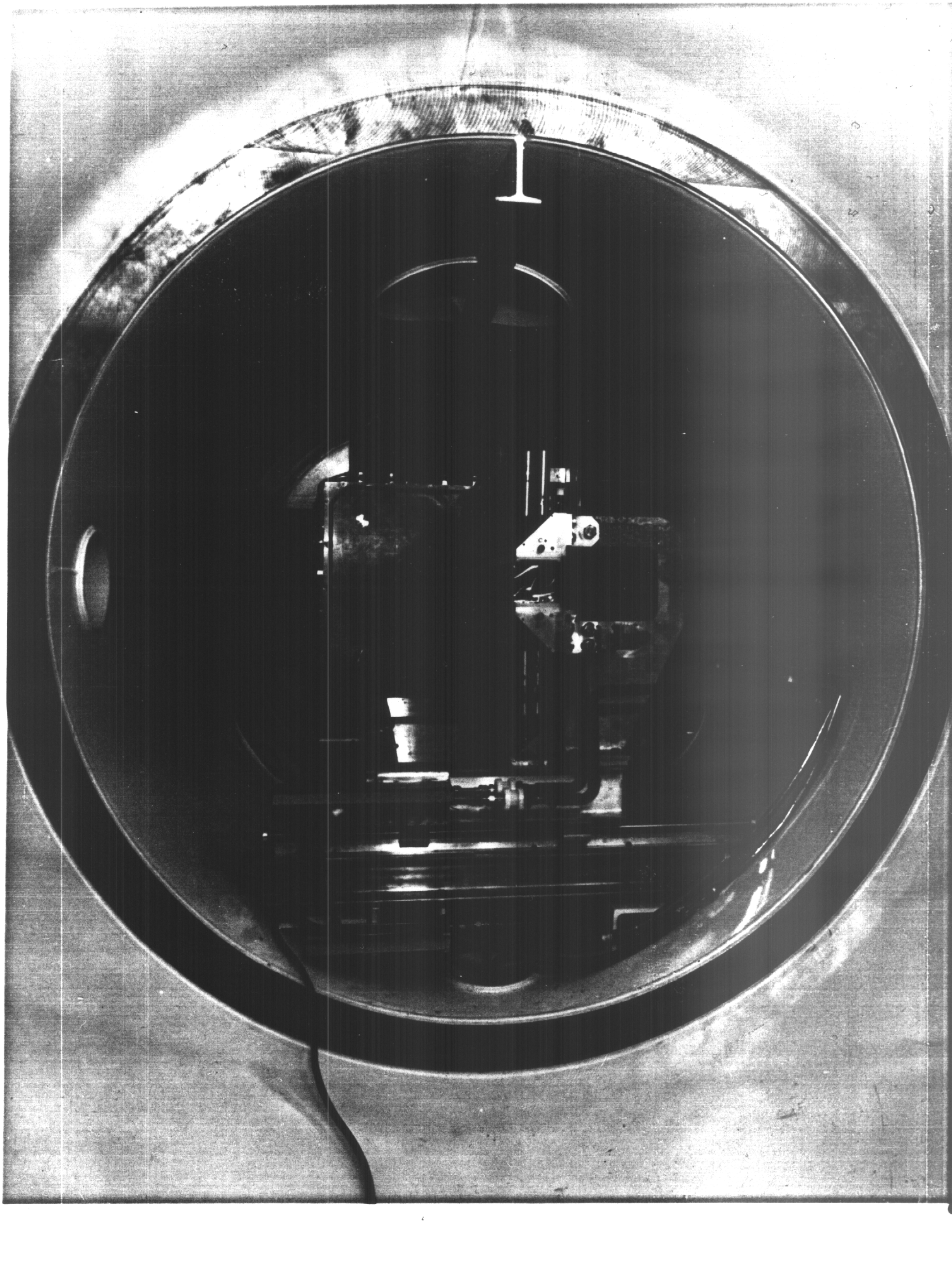
For small :

$$\Im(\epsilon'/\epsilon) = -\frac{1}{3}\Delta\phi$$

The KTeV Detector

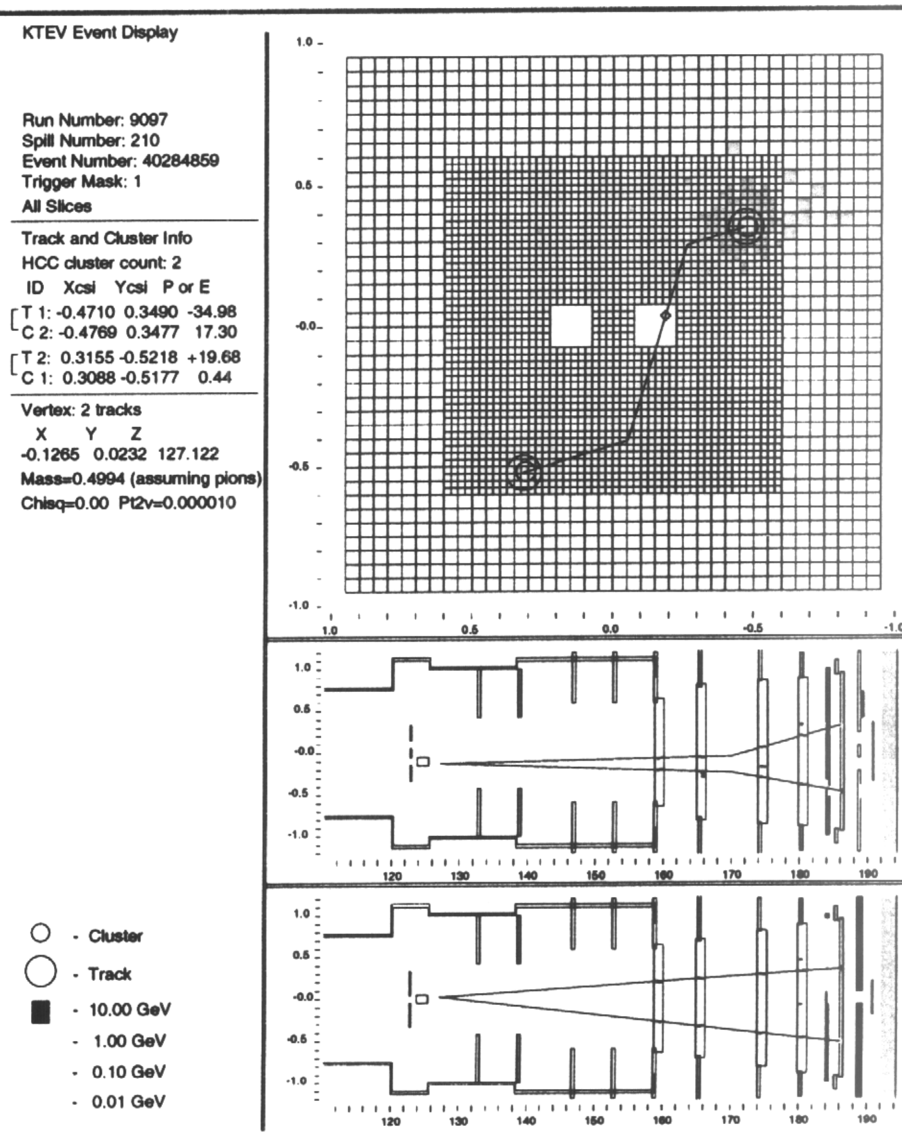


beam	$\approx K_L$ beam
"Regenerator" beam	$\approx K_S$ beam



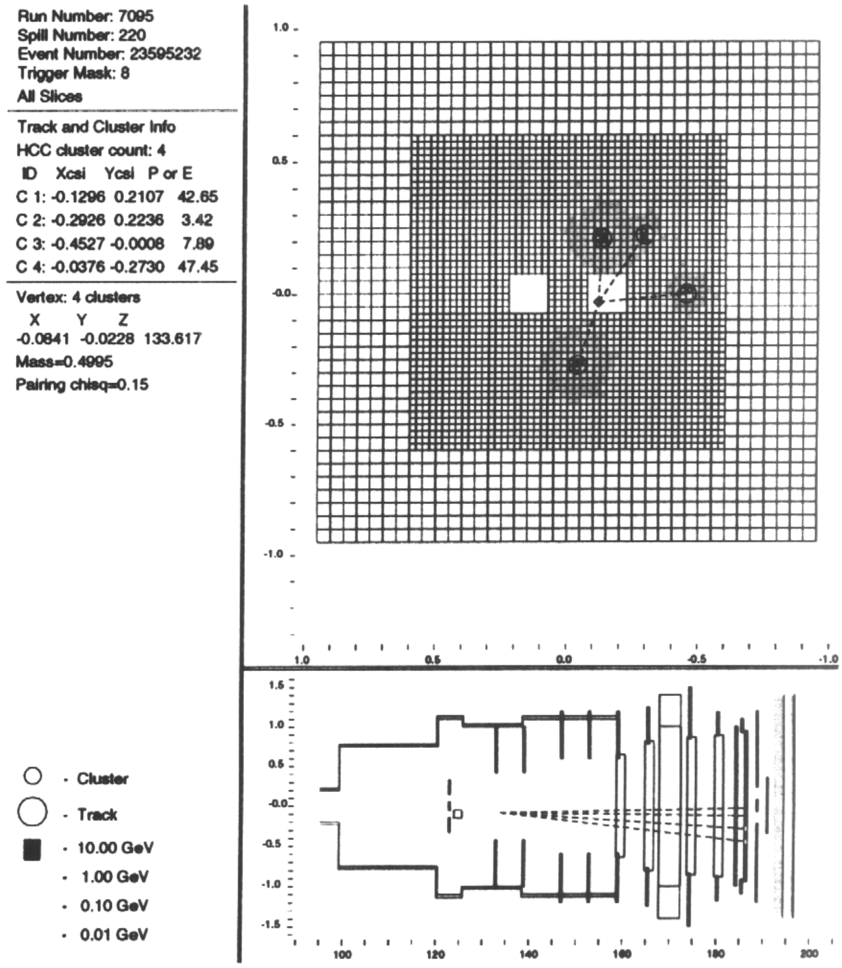
96-720-3

Charged Mode Reconstruction



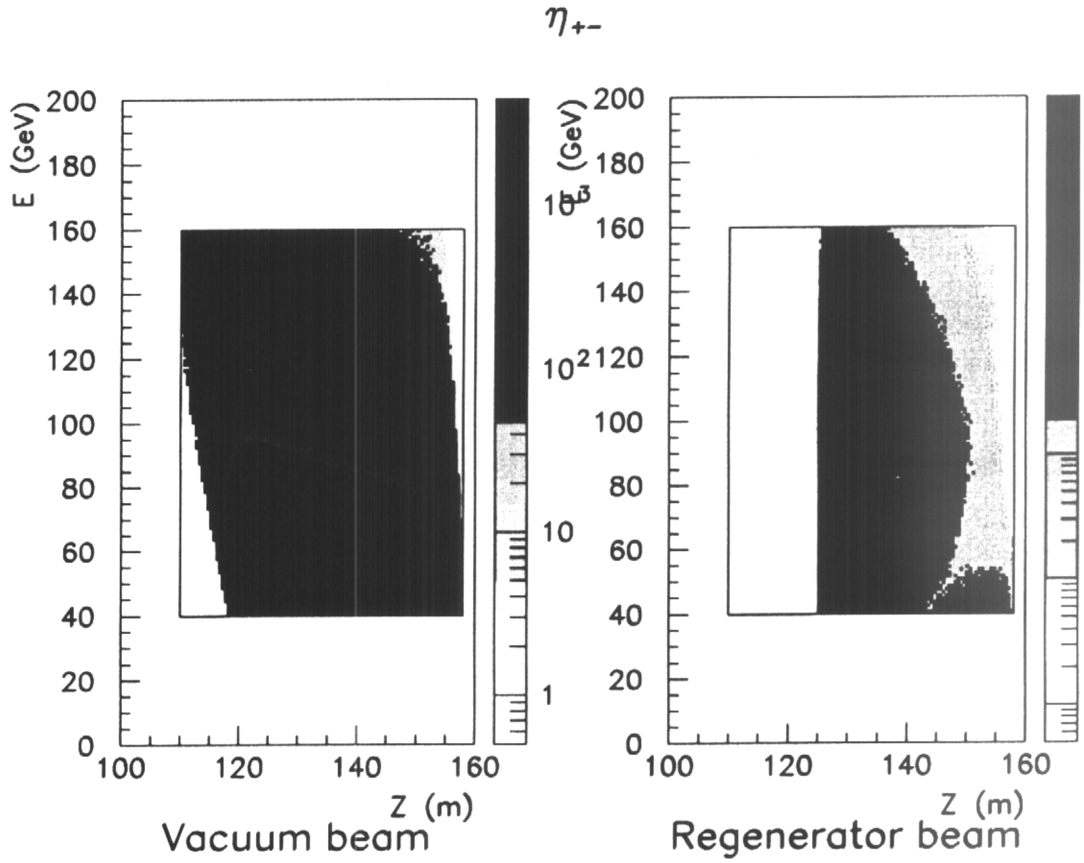
- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using X-vertex position
- Clearance cuts to define detector volume.

Neutral Mode Reconstruction



- CsI calorimeter to reconstruct photons energies and positions
- Z_v determined as average of
- Regenerator/Vacuum beam identification using X-center of energy
- Detector volume defined by veto detectors and Z_v

Data Collection

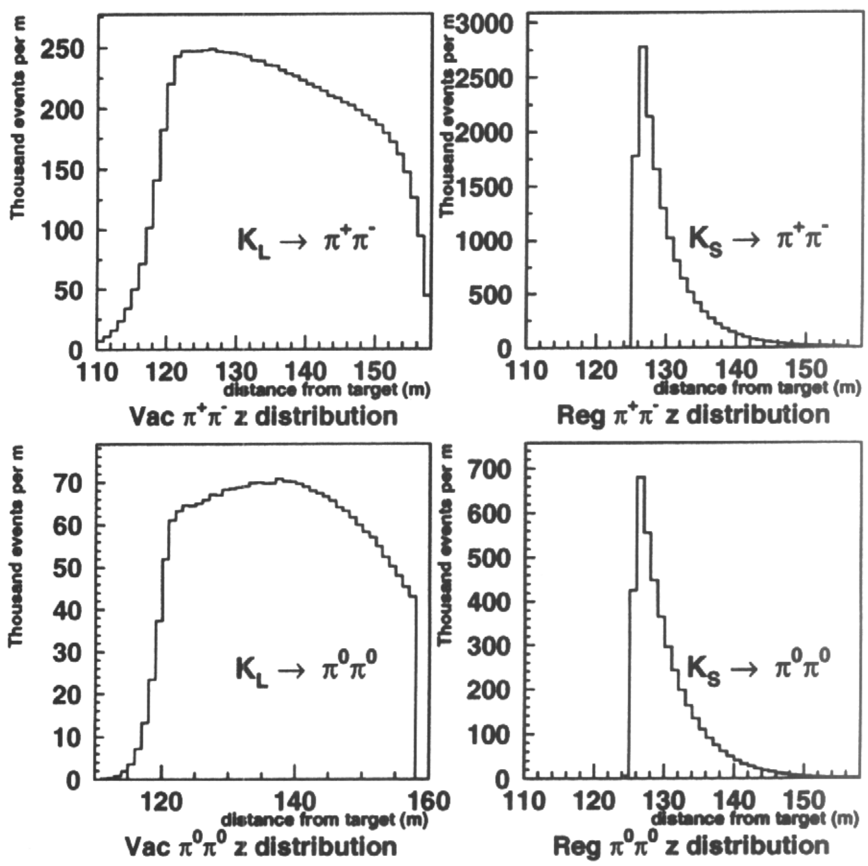


Data yields in Vacuum beam (mln):

Year	$K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
96	–	0.8
97	8.6	2.5
99	14.9	3.7

Combination of 96 and 97 datasets.

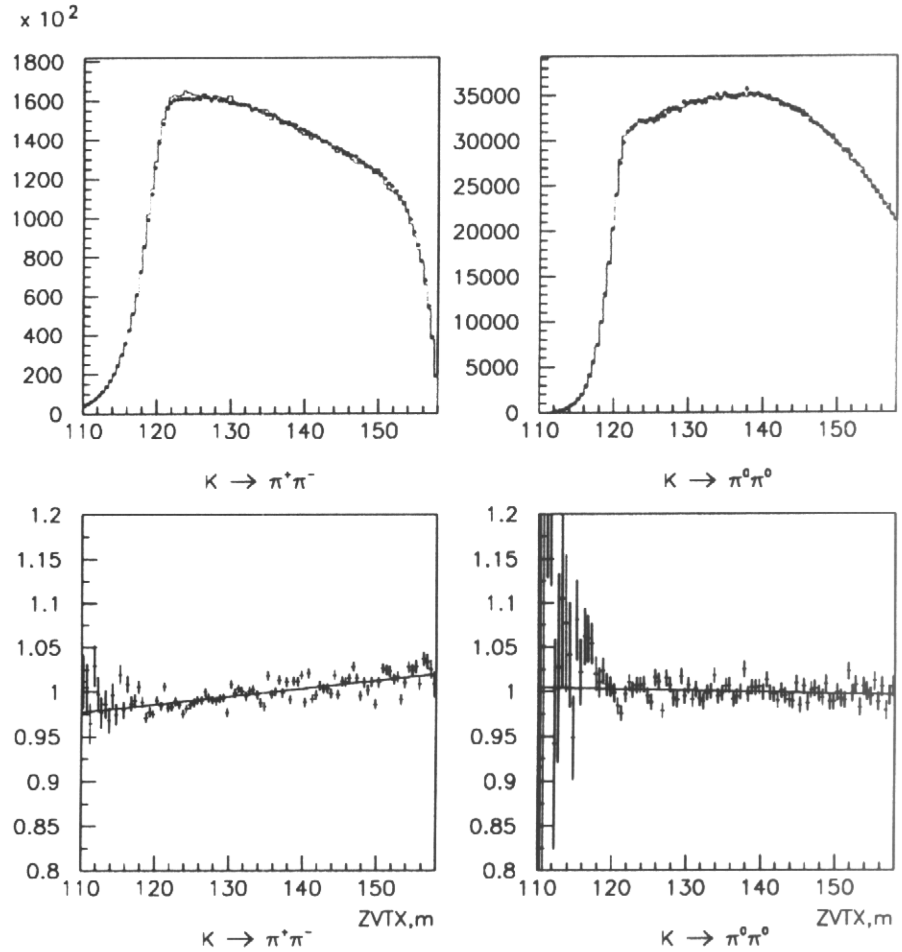
Understanding the Acceptance



Due to the different lifetimes ($\tau_L \gg \tau_S$), the K_S beam probes a different region of the detector that the K_L beam, and hence has a different acceptance.

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

Geometry only MC (97)



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

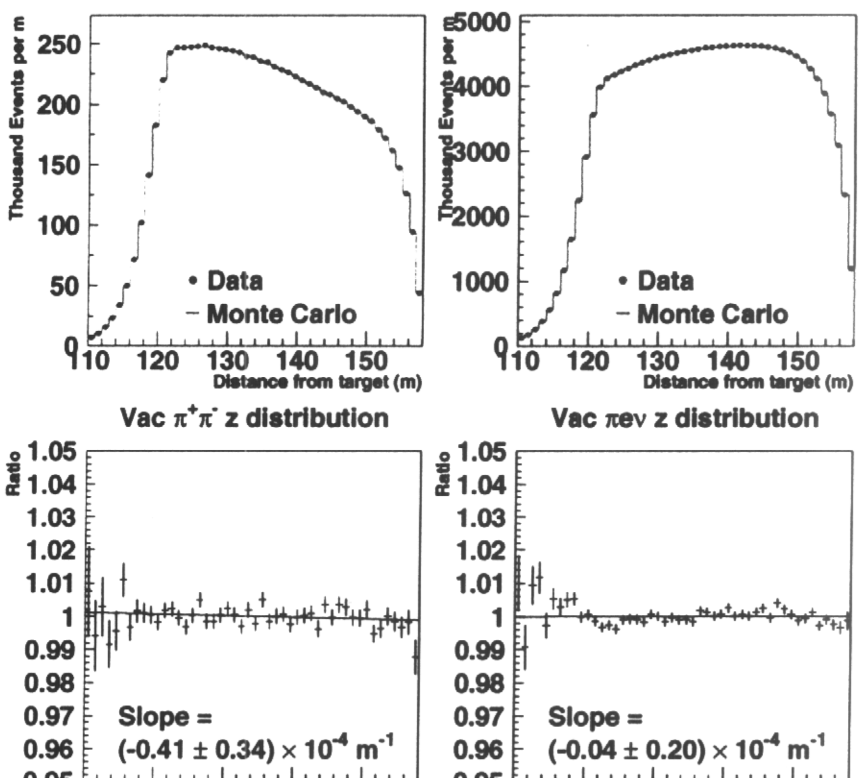
$\rightarrow$ corrections due to detector simulation $\sim 10 \times 10^{-4}$.

Final Test of MC Acceptance

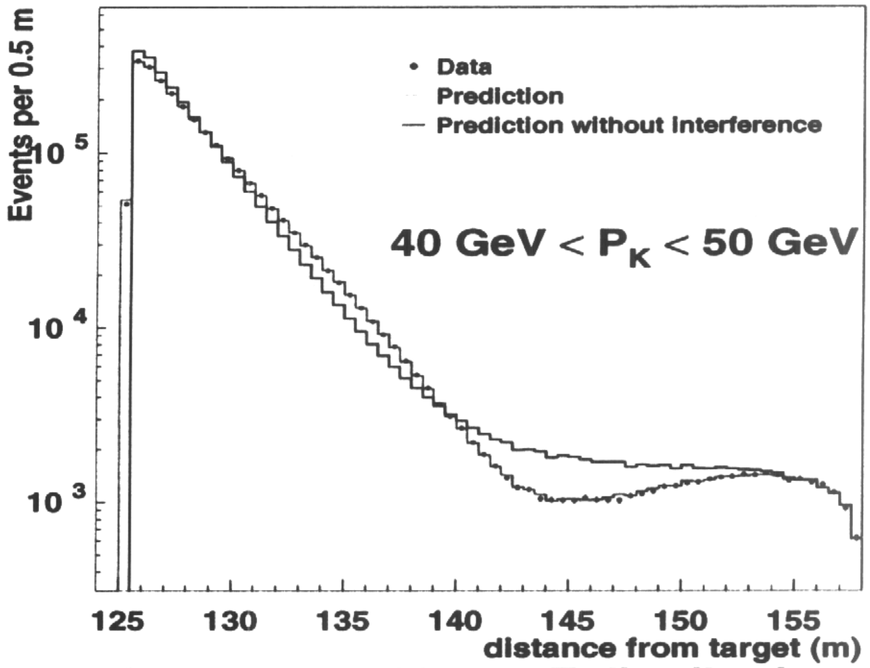
The final check of the acceptance is the vertex z distribution in the vacuum beam.

, due to different vertex z distributions in vac/reg beams.

$K \to \pi^+\pi^-$ & K_{e3} (data 1997b)



Fit Strategies



Regenerator Vertex Z distribution

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

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

Uncertainties in ϵ'/ϵ

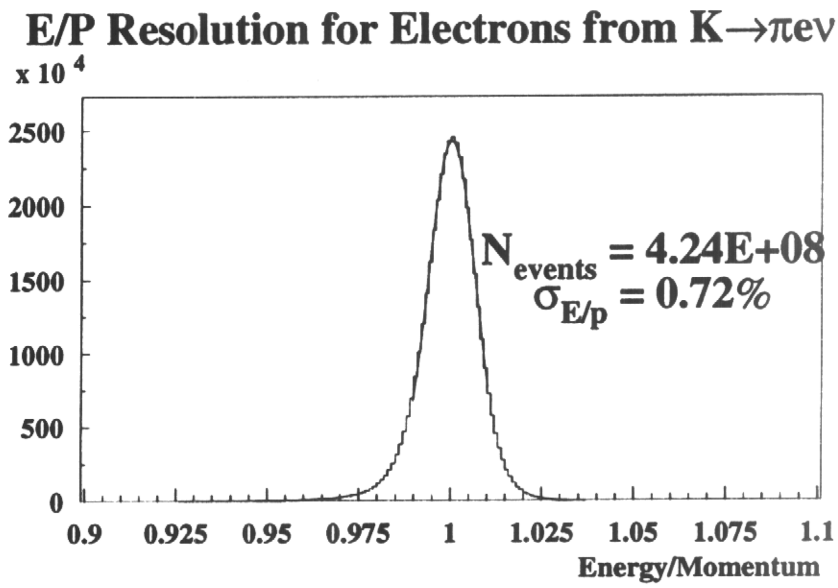
	$\Re(\epsilon'/\epsilon)$ $(\times 10^{-4})$	$\Im(\epsilon'/\epsilon)$ $(\times 10^{-4})$
Type of measurement	Counting experiment	Z-E shape (proper time)
	Statistical uncertainty	
	1.6	13.
	Main systematics	
Acceptance	1.4	16.
Migrations	1.4	22.
Background	1.1	8.
	Total systematics	
	2.3	28.
	Total uncertainty	
	2.7	31.

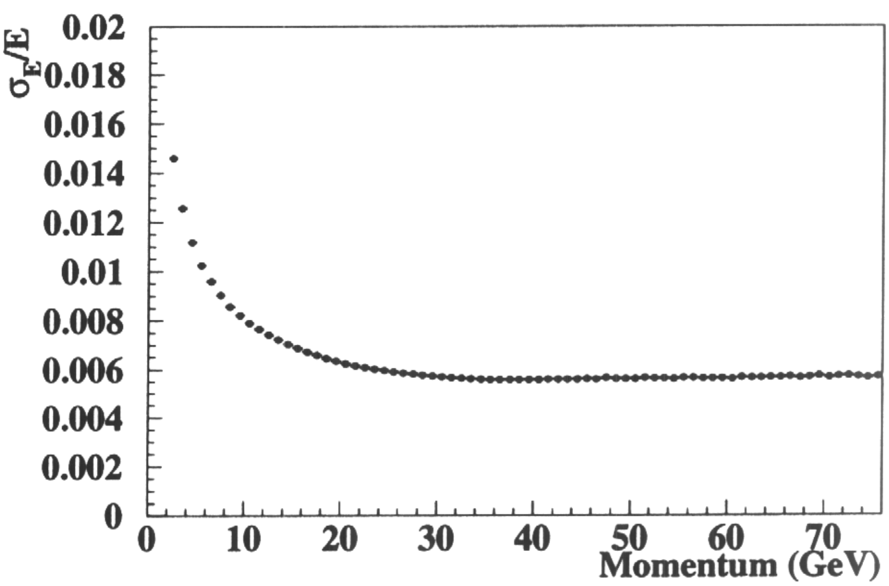
Acceptance: all data collection uncertainties and Z slope

Migrations: mainly calorimeter energy scale and non-linearity

Background: regenerator scattering background

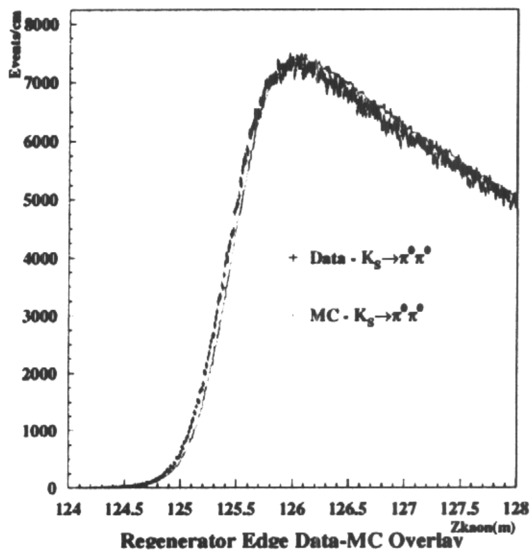
Calibration of CsI calorimeter

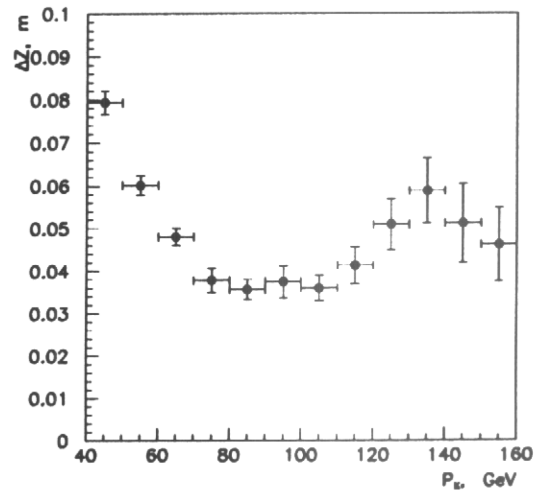




Use E/p for electrons to calibrate response of individual crystals.

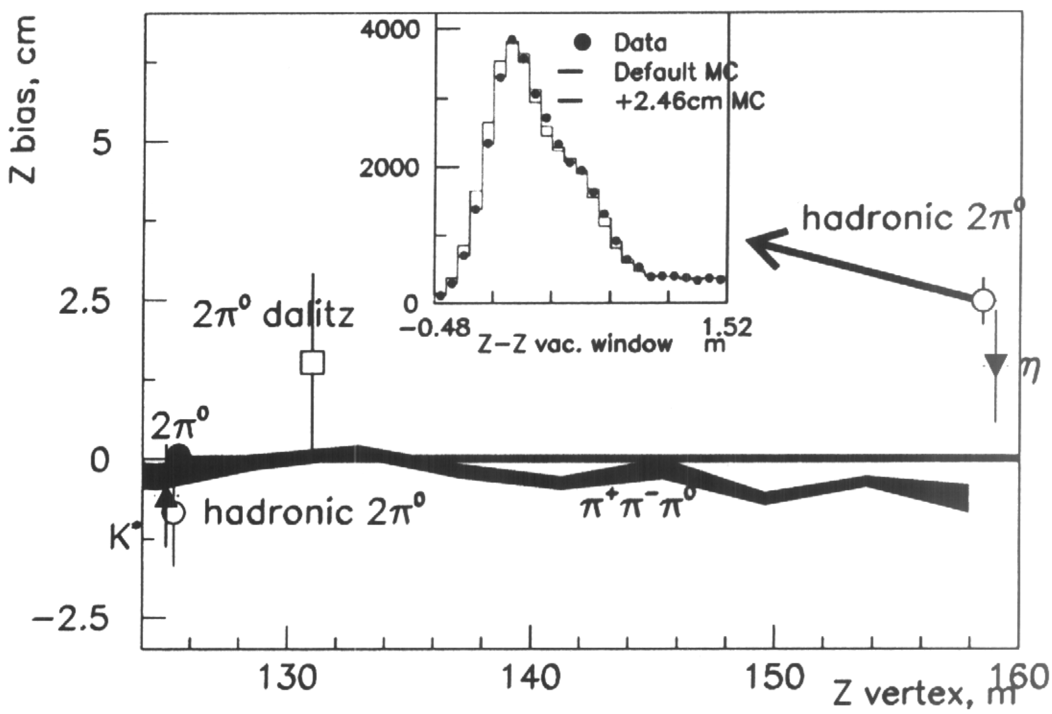
The Energy Scale Adjustment





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

Cross Checks of the Energy Scale

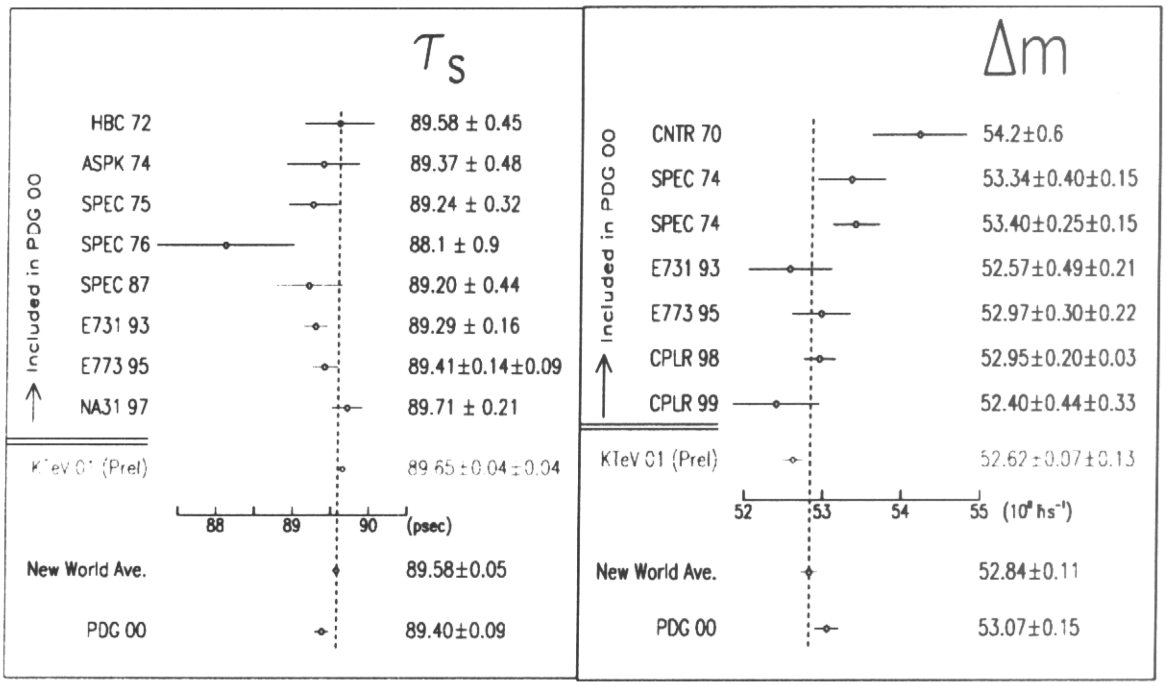


- Use different methods to cross-check energy calibration: $K \to \pi^+\pi^-\pi^0$, $K_S^* \to \pi^0 K_S$, $K \to 2\pi^0$ Dalitz, $\eta \to 3\pi^0$ hadronic prodction of $2\pi^0$.
- Use hadronic production of $2\pi^0$ at the Vacuum Window to set uncertainty in the energy scale.
- Assume linear scale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

Kaon Sector Parameters as Measured in KTeV

$$\Delta m = (52.62 \pm 15) \times 10^{8} \hbar s^{-1}$$
$$\tau_S = (89.65 \pm \ 6) \times 10^{-12} s$$
$$\phi_{+-} = [44.12 \pm 0.72 \text{ (stat)} \pm 1.14 \text{ (syst)}]^{o}$$

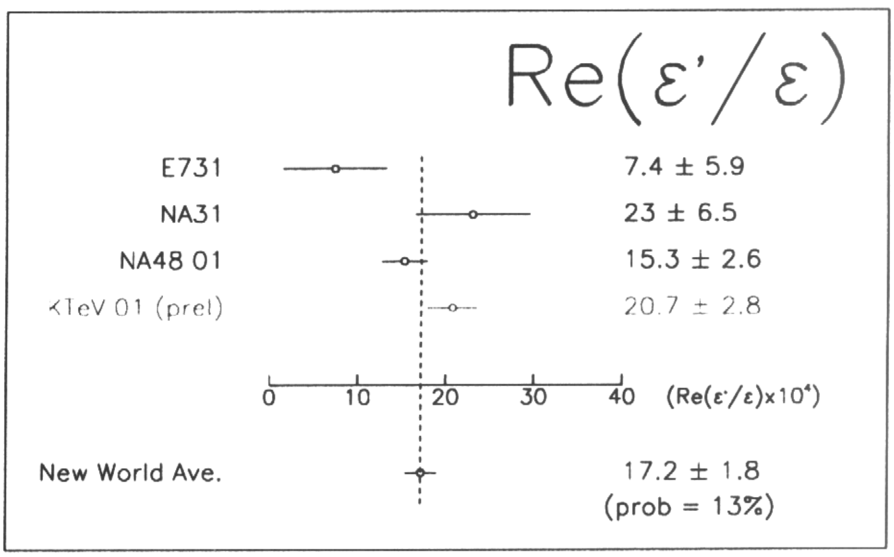
KTeV results for Δm and τ_S are as precise as current world averages.



KTeV Result on $\Re(\epsilon'/\epsilon)$

Fit to $\Re(\epsilon'/\epsilon)$ with CPT conservation assumption:

$$\Re(\epsilon'/\epsilon) = [20.7 \pm 1.5\ (\text{stat}) \pm 2.4\ (\text{syst}) \pm 0.5\ (\text{MC stat})] \times 10^{-4}$$
$$= [20.7 \pm 2.8\ (\text{tot})] \times 10^{-4}$$



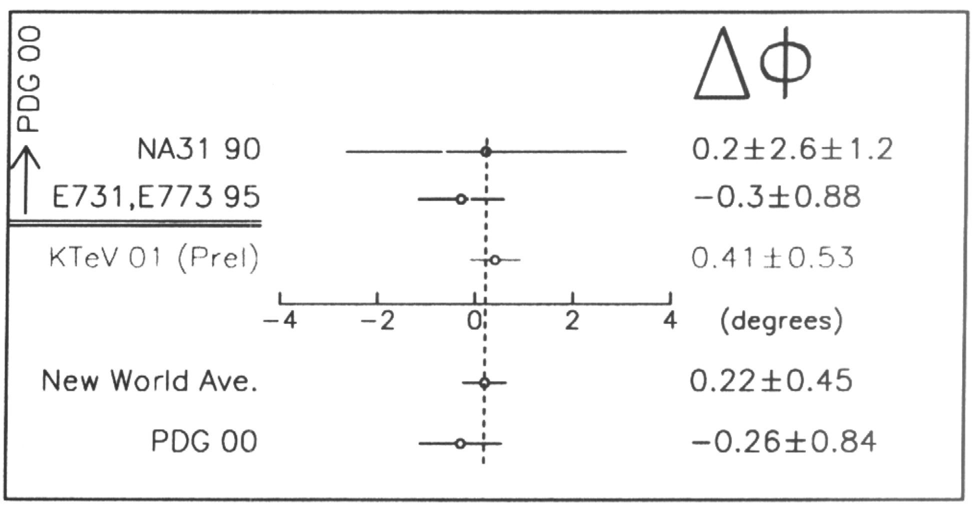
Fit without CPT assumption

Top secret:

In the fit to determine $\Im(\epsilon'/\epsilon)$ we must float $\Re()$ part as well. Because of the correlation, the error in $\Re(\epsilon'/\epsilon)$ is increased:

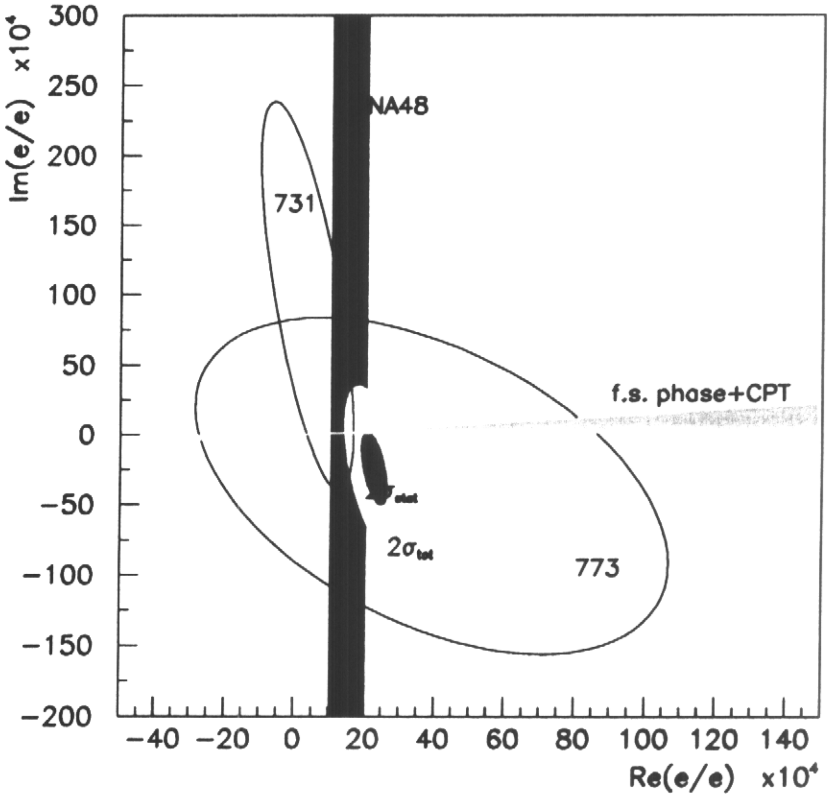
up from by .

→ NA48 beats KTeV if CPT is violated !



Correlation of $\Re(\epsilon'/\epsilon)$ and $\Im(\epsilon'/\epsilon)$

$$\begin{aligned}\Im(\epsilon'/\epsilon) &= [-24.1 \pm 12.8 \text{ stat} \pm 27.9 \text{ syst}] \times 10^{-4} \\ &= [-24.1 \pm 30.7] \times 10^{-4}\end{aligned}$$



- Different Fermilab experiments have various regenerator lengths (K_L to K_S ratios) different correlation of $\Re(\epsilon'/\epsilon)$ and $\Im(\epsilon'/\epsilon)$
- Inclusion of NA48 helps to reduce error on $\Im(\epsilon'/\epsilon)$ by about 15%.

Conclusions

- Direct CP violation in kaon sector is established. $\Re(\epsilon'/\epsilon)$ is known to 10%.
- Measurements of $\Im(\epsilon'/\epsilon)$ are not quite as precise yet. Current data is consistent with CPT conservation.
- Results from KTeV and NA48 are consistent/complimentary.
- With more KTeV data (99) and improvements in the understanding of the calorimeter energy scale we might hope to reduce uncertainty in $\Im(\epsilon'/\epsilon)$.
- The current round of experiments might end up with knowledge of $\Re(\epsilon'/\epsilon)$ and about uncertainty in . It is a great progress but there is certainly some room for improvement !