Results from KTeV and Status of $Re(\epsilon'/\epsilon)$

A. Glazov, University of Chicago.

- Neutral Kaon mixing and CP violation
- Theory and (old) Experiments on $Re(\epsilon'/\epsilon)$
- Fixed target detectors to measure $Re(\epsilon'/\epsilon)$
- Analysis of $K \to \pi^+\pi^-$ and $K \to \pi^0\pi^0$ modes
- Systematic vs Statistical uncertainty
- Results on Direct CP violation
- What is coming next ?

The KTeV collaboration:
Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin.

CP violation: direct vs indirect

- K^0 and $\overline{K}^0$ are mixed. K_S and K_L are observable states.

$$|K_{L,S}(t)> = e^{-im_{L,S}t}e^{-\Gamma_{L,S}t/2}|K_{L,S}(0)>$$
$$\Gamma_L = 1/\tau_L >> \Gamma_S$$
$$\Delta m = m_L - m_S << m_S$$

- $K_L \to \pi\pi$ decay was observed in 1964, first sign of CP violation
- "Indirect" CP violation – K_L, K_S are not CP eigenstates:

$$\begin{aligned} K_S &= (1+\epsilon)K^0 + (1-\epsilon)\overline{K}^0 = \\ &= K_{even} + \epsilon K_{odd} \\ K_L &= (1+\epsilon)K^0 - (1-\epsilon)\overline{K}^0 = \\ &= K_{odd} + \epsilon K_{even} \end{aligned}$$

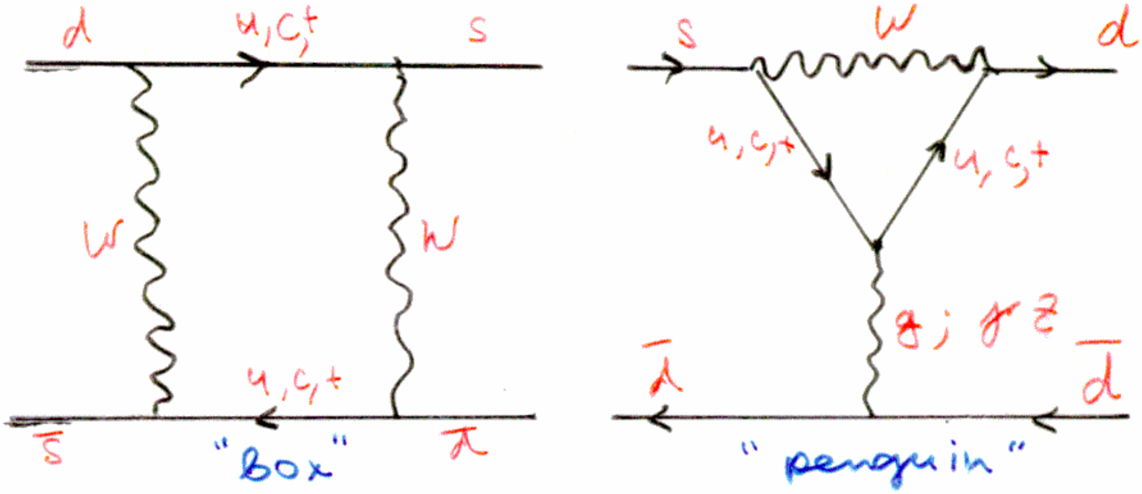
- "Direct" – CP violated in decay amplitude

$$K^0 \to \pi\pi \neq \overline{K}^0 \to \pi\pi$$

can be measured as a difference between $\pi^+\pi^-$ and $\pi^0\pi^0$ decays:

$$1 + 6Re(\epsilon'/\epsilon) \approx \frac{\Gamma(K_L \to \pi^+\pi^-)\ /\ \Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)\ /\ \Gamma(K_S \to \pi^0\pi^0)}$$

Theoretical estimations



Standard Model explains CP violation as due to complex phase in quark mixing matrix. Both Indirect and Direct modes are present due to "box" and "penguin" diagrams – $\epsilon'/\epsilon \neq 0$.

In **Superweak Model** only indirect CP violation is present – $\epsilon'/\epsilon = 0$

Estimation of ϵ'/ϵ within the Standard Model is **difficult**. Both very large (m_{top}) and very small (m_π) scales are present.

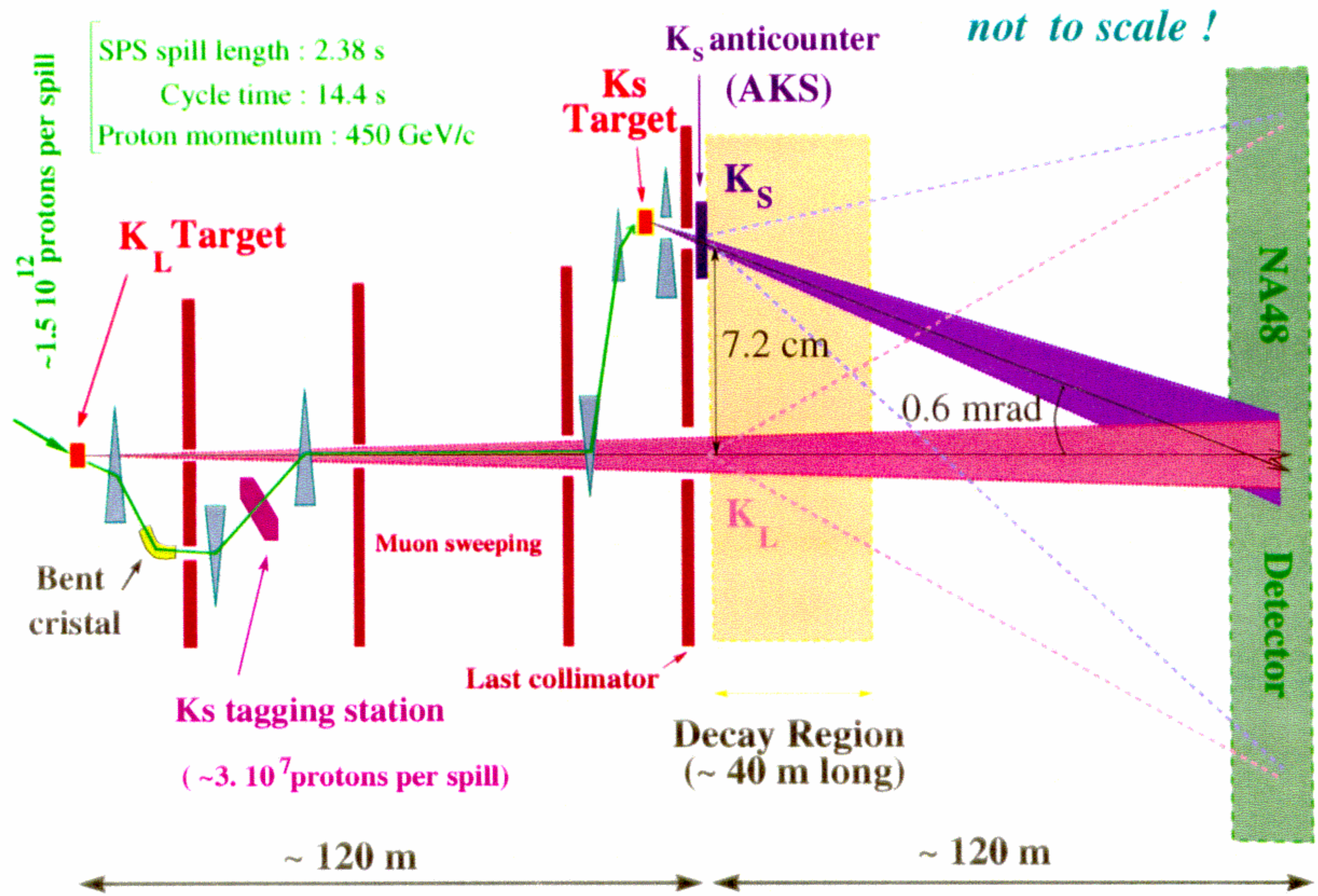
Theory estimations:

Munich	Group 1999	$3.6 \pm 3.4 \times 10^{-4}$
Rome	Group 1997	$4.6 \pm 3.0 \times 10^{-4}$
Trieste	Group 1997	$17^{+14}_{-10} \times 10^{-4}$

Old experimental results:

FNAL E731	$Re(\epsilon'/\epsilon) = (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$
CERN NA31	$Re(\epsilon'/\epsilon) = (23. \pm 6.5) \times 10^{-4}$

The NA48 Beams



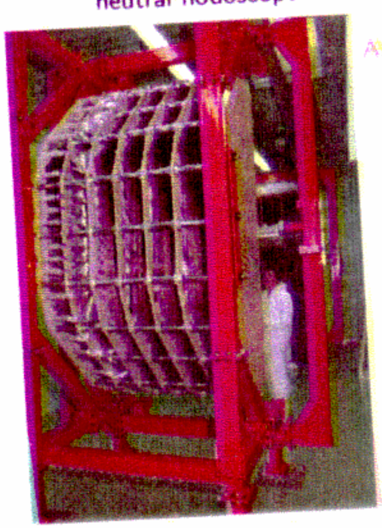
- The **tagging station** provides a measurement of proton time with **< 200 ps** resolution
- The beginning of the fiducial region is defined by an anti–counter (AKS) on the K_S beam line

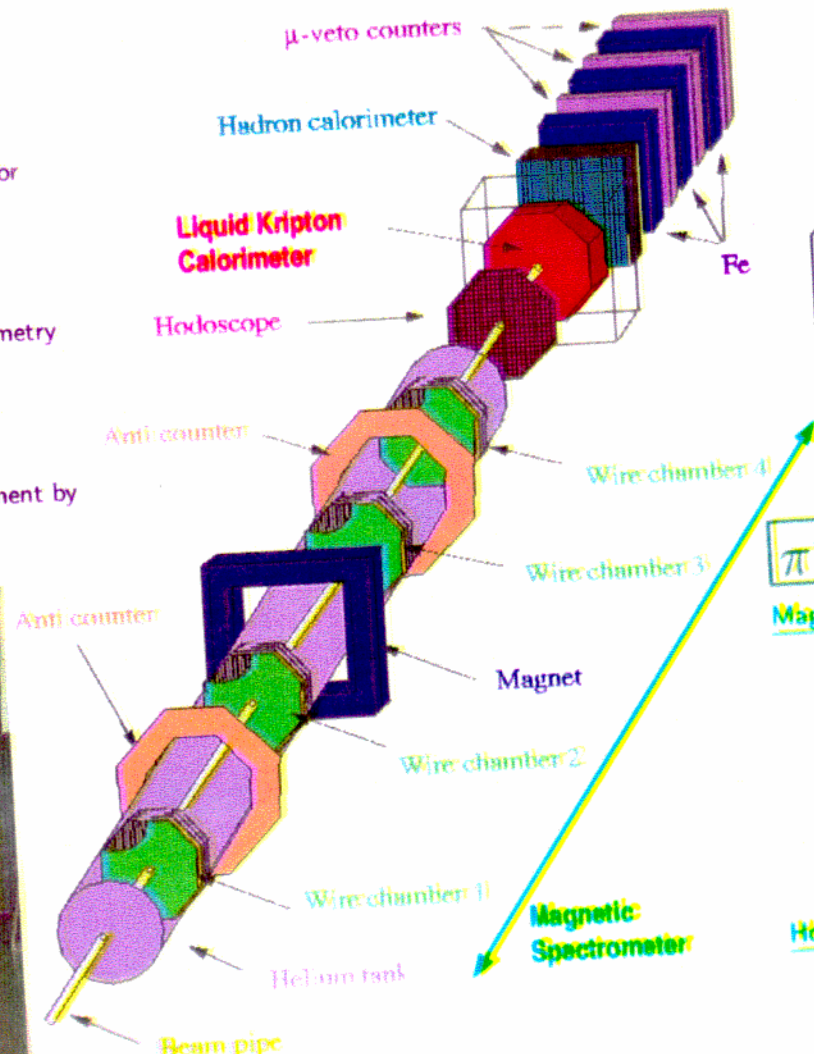
The Central Detector

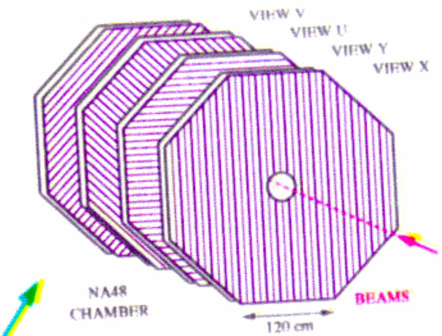
$\pi^0\pi^0$

LKr electromagnetic calorimeter:

- quasi–homogeneous detector based on 9 m^3 LKr
- Cu–Be electrodes
- 13212 $2 \times 2 \times 127$ cm^3
- $\pm$ 48 mrad accordion geometry
- projective geometry
- geometry machined with 0.2 mm/m accuracy
- redundant time measurement by scintillating fiber neutral hodoscope







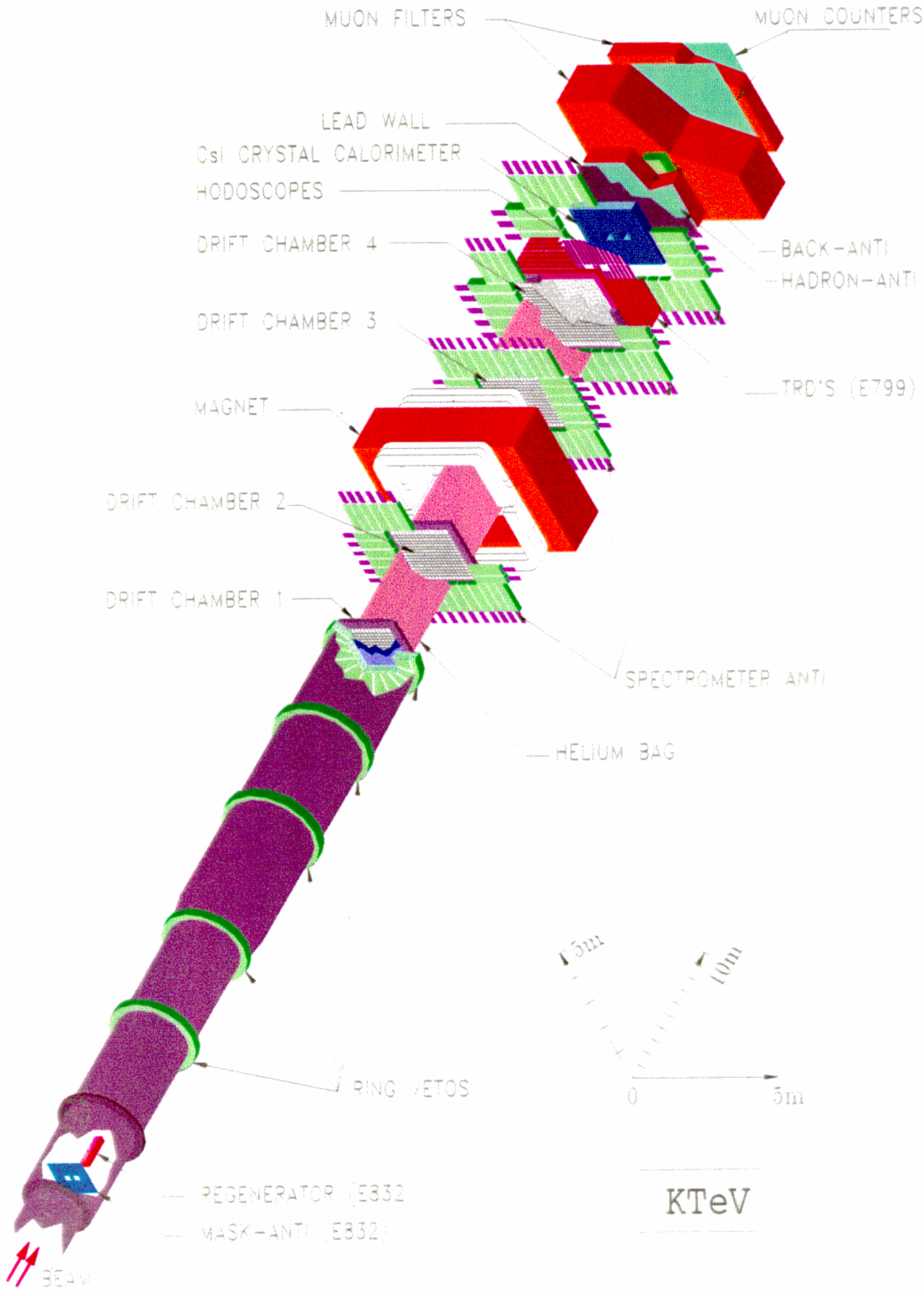
$\pi^+\pi^-$

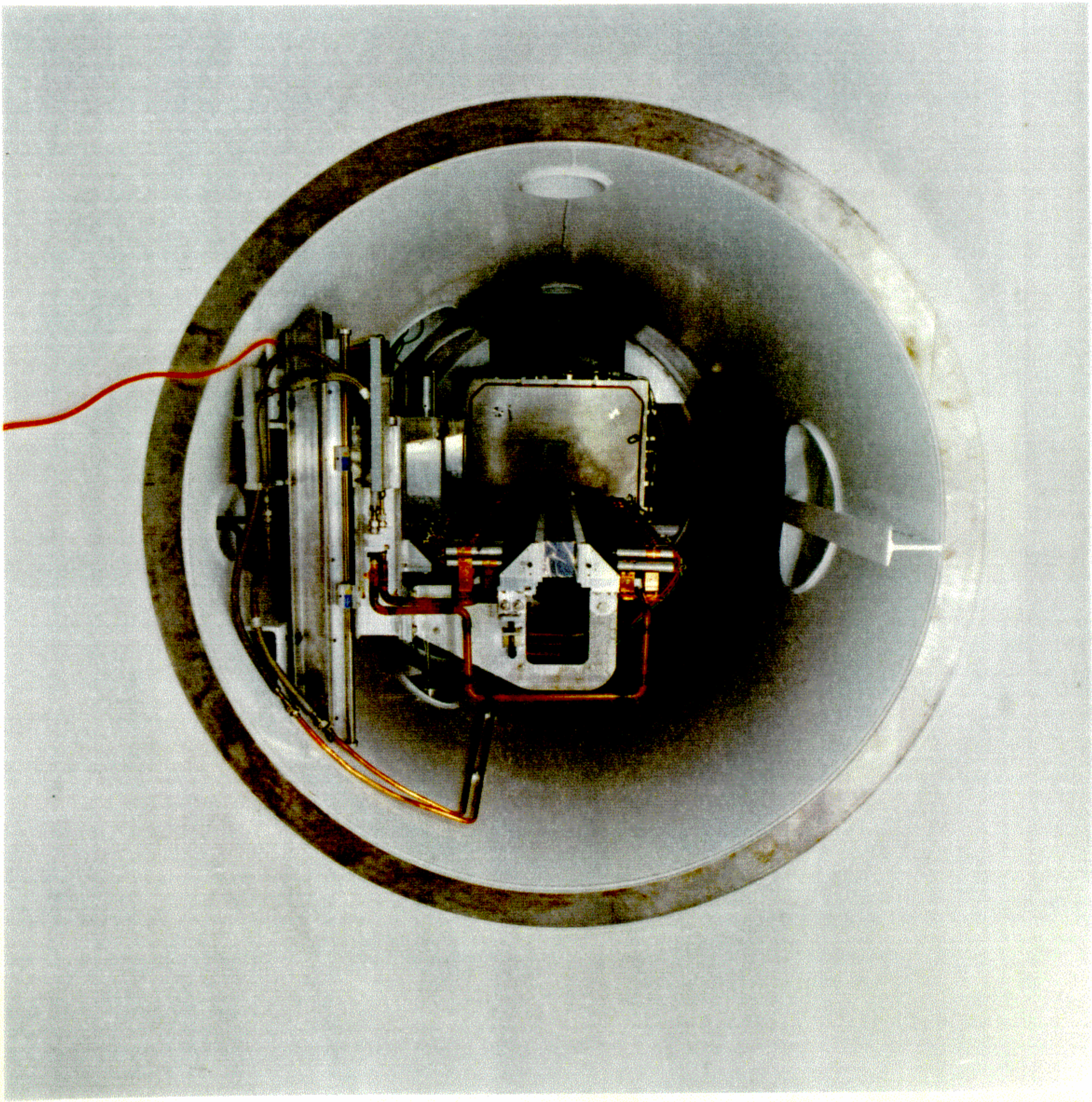
Magnetic Spectrometer:

- 4 chambers with 4 views each, 2 staggered planes per view
- 90 μm spacepoint resolution
- wire position known better than 100 μm/m
- magnet providing 265 MeV/c p_T kick

Hodoscope:

- 2 planes of scintillators for precise measurement of event time


MUON FILTERS
MUON COUNTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
BACK-ANTI
HADRON-ANTI
DRIFT CHAMBER 4
DRIFT CHAMBER 3
TRD'S (E799)
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
SPECTROMETER ANTI
HELIUM BAG
RING VETOS
REGENERATOR (E832)
MASK-ANTI (E832)
BEAM
5m
10m
0
5m
KTeV



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KTeV Regenerator

Difference in K^0, $\overline{K^0}$ interaction with carbon leads to K_S **regeneration**:

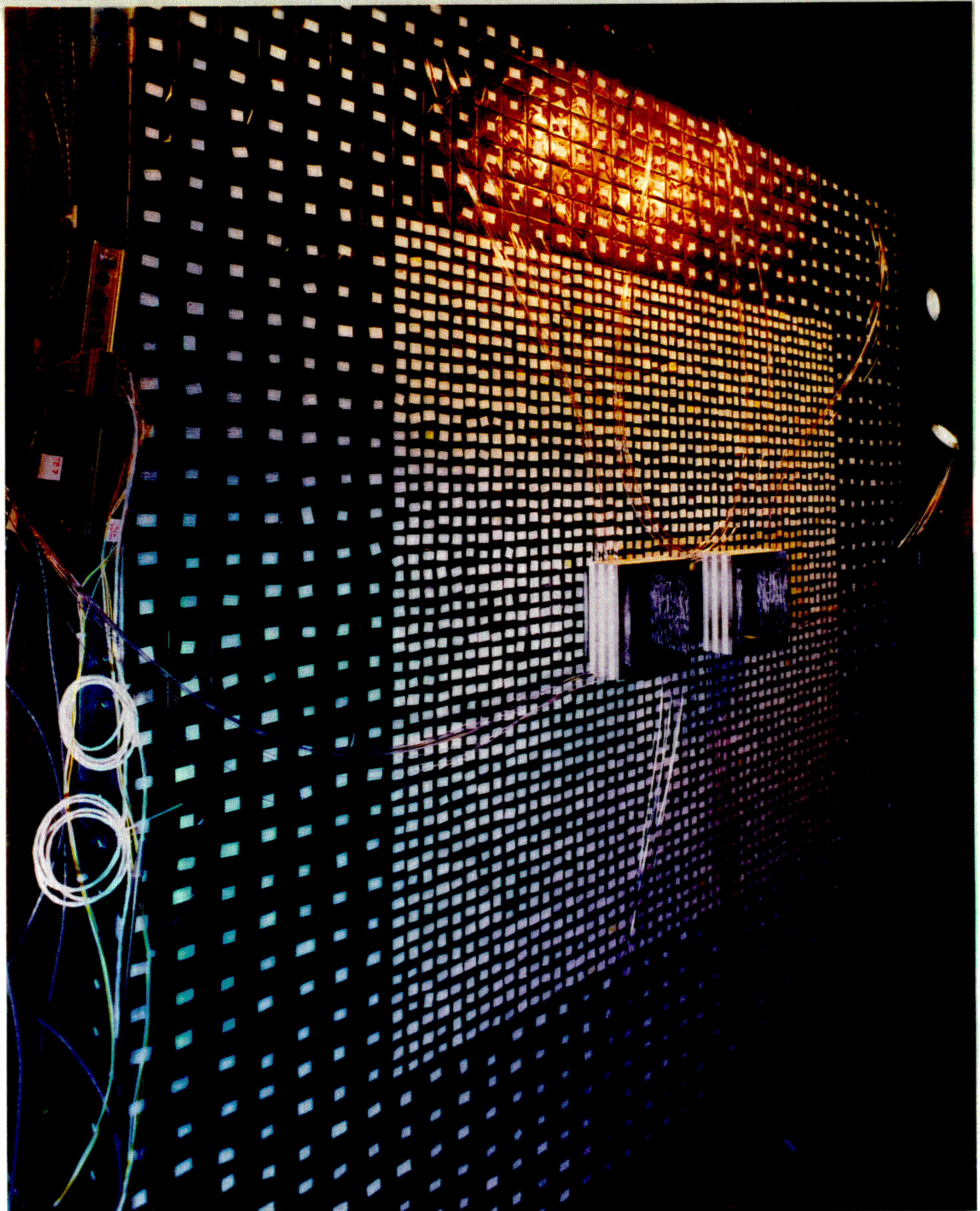
$$
\begin{aligned}
f: \quad & K^0 + C_{12} \to K^0 + C_{12} \\
\overline{f}: \quad & \overline{K^0} + C_{12} \to \overline{K^0} + C_{12} \\
& K_L + C_{12} \to (f + \overline{f}) K_L + (f - \overline{f}) K_S + C_{12}
\end{aligned}
$$

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 $K_S \to \pi\pi$ decays dominate.
- At larger proper time $K_L - K_S$ *interference* is important

\+ $\rightarrow$ sensitivity to Δm

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



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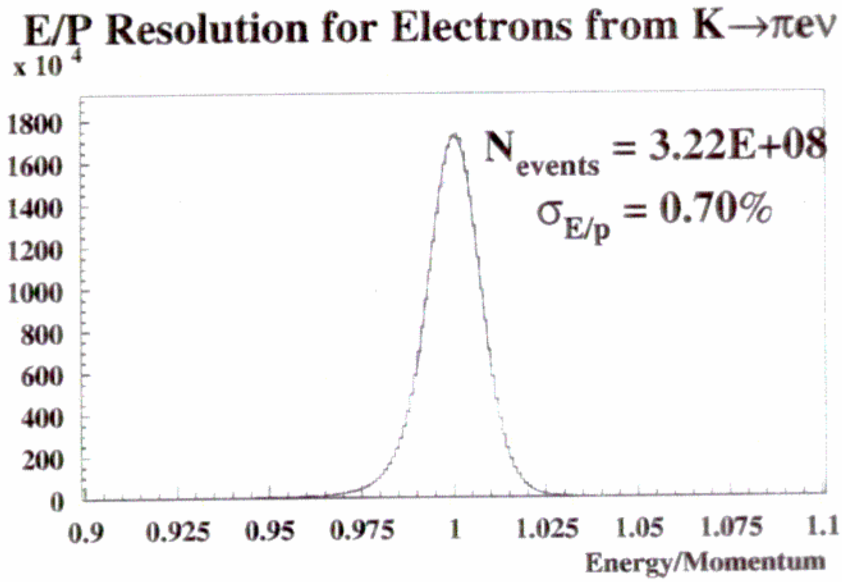
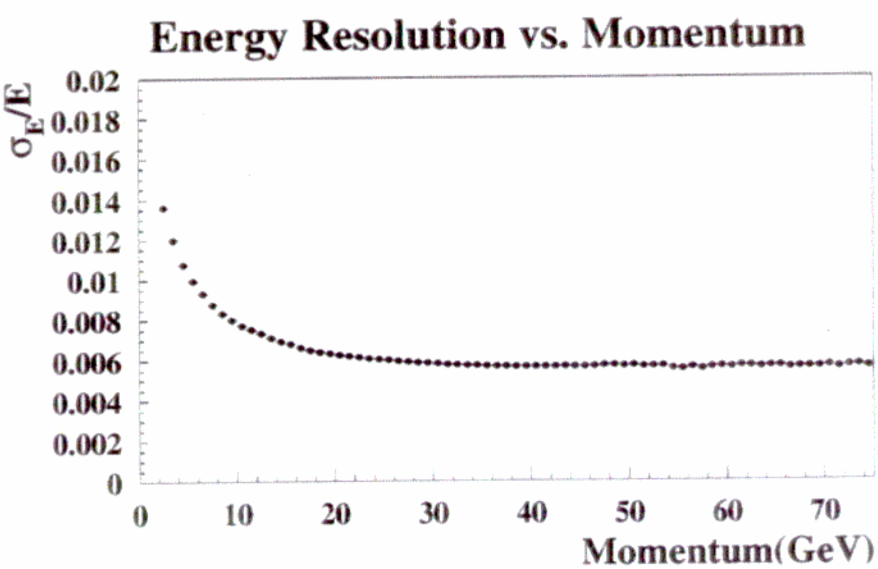
CsI Calorimeter Performance in 1997





CsI is Calibrated with Electrons from $K \rightarrow \pi e \nu$ Decays.

$K_L \to \pi^+\pi^-$

KTEV Event Display

/usr/kpasa/data11/glazov/k2pi_9105.dat

Run Number: 9105
Spill Number: 1
Event Number: 9296
Trigger Mask: 1
All Slices

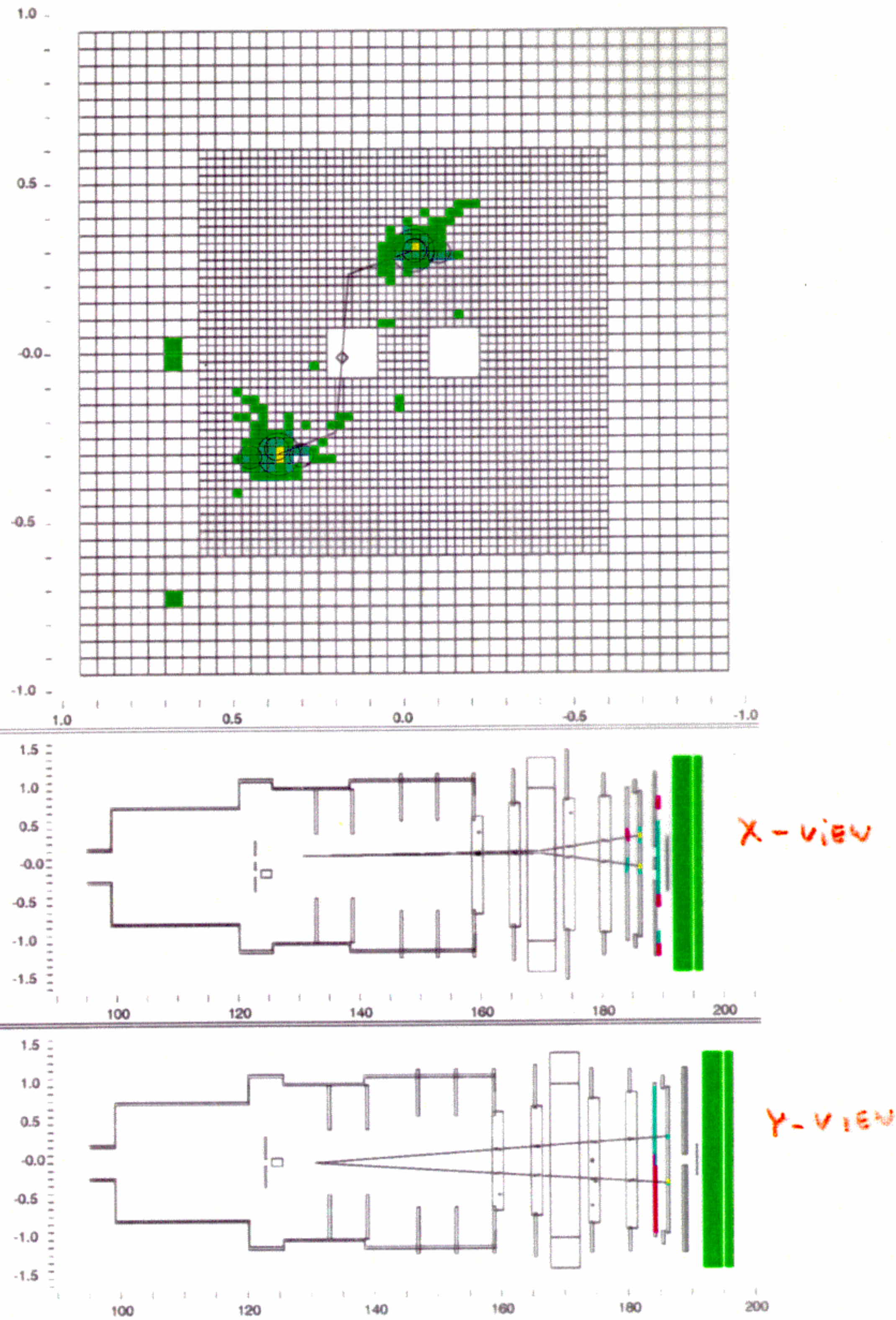
Track and Cluster Info
HCC cluster count: 1

ID	Xcsi	Ycsi	P or E
T 1:	-0.0291	0.3016	-36.06
C 4:	-0.0328	0.3010	8.49
T 2:	0.3668	-0.2975	+40.35
C 3:	0.3732	-0.2817	8.43
C 1:	0.4514	-0.3068	0.54
C 2:	0.3004	-0.3023	0.61
C 5:	-0.1040	0.2979	0.52

Vertex: 2 tracks

X	Y	Z
0.1261	-0.0093	130.443

Mass=0.4982 (assuming pions)
Chisq=1.02 Pt2v=0.000004



- Cluster
- Track
- 10.00 GeV
- 1.00 GeV
- 0.10 GeV
- 0.01 GeV

$K_L \to \pi^0 \pi^0$

KTEV Event Display

/usr/kpasa/data11/glazov/k2pi0_6918.dat

Run Number: 6918
Spill Number: 3
Event Number: 254580
Trigger Mask: 8
All Slices

Track and Cluster Info

HCC cluster count: 4

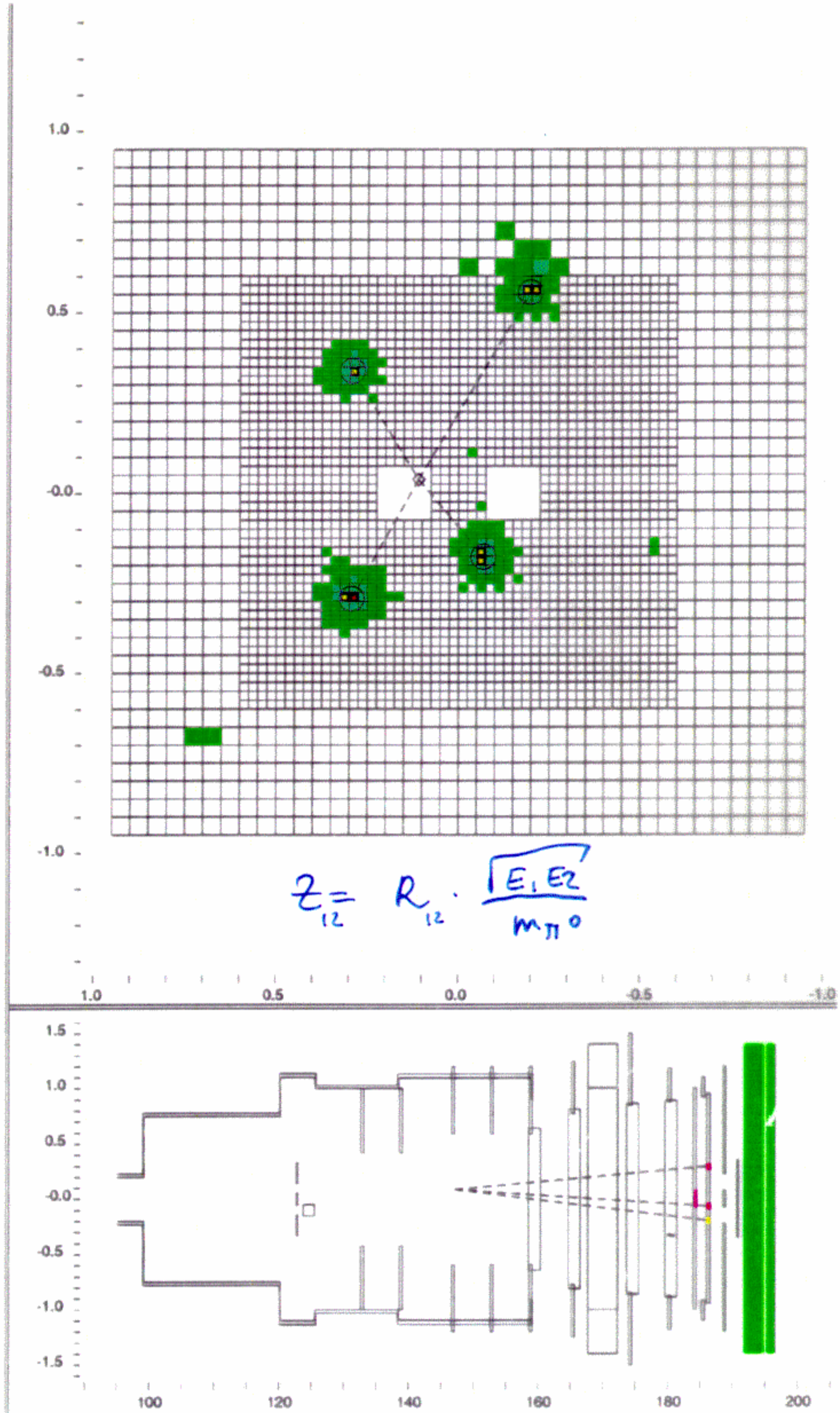
ID	Xcsi	Ycsi	P or E
C 1:	0.2918	0.3398	10.45
C 2:	0.2939	-0.2926	16.51
C 3:	-0.1967	0.5560	9.26
C 4:	-0.0686	-0.1765	11.77

Vertex: 4 clusters

X	Y	Z
0.0868	0.0295	147.056

Mass=0.4987

Pairing chisq=1.09



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

○ - Cluster
○ - Track
10.00 GeV
1.00 GeV
0.10 GeV
0.01 GeV

Data Samples

Statistical error of the measurement is determined by the yield of $K_L \to \pi^0\pi^0$ events.

Results from NA48 collaboration:

- First Result based on 1997 data,
  $\to \mathbf{N_{00} = 0.489 \times 10^6}$
- Preliminary Result based on 1998 data,
  $\to \mathbf{N_{00} = 1.14 \times 10^6}$

Results from KTeV collaboration:

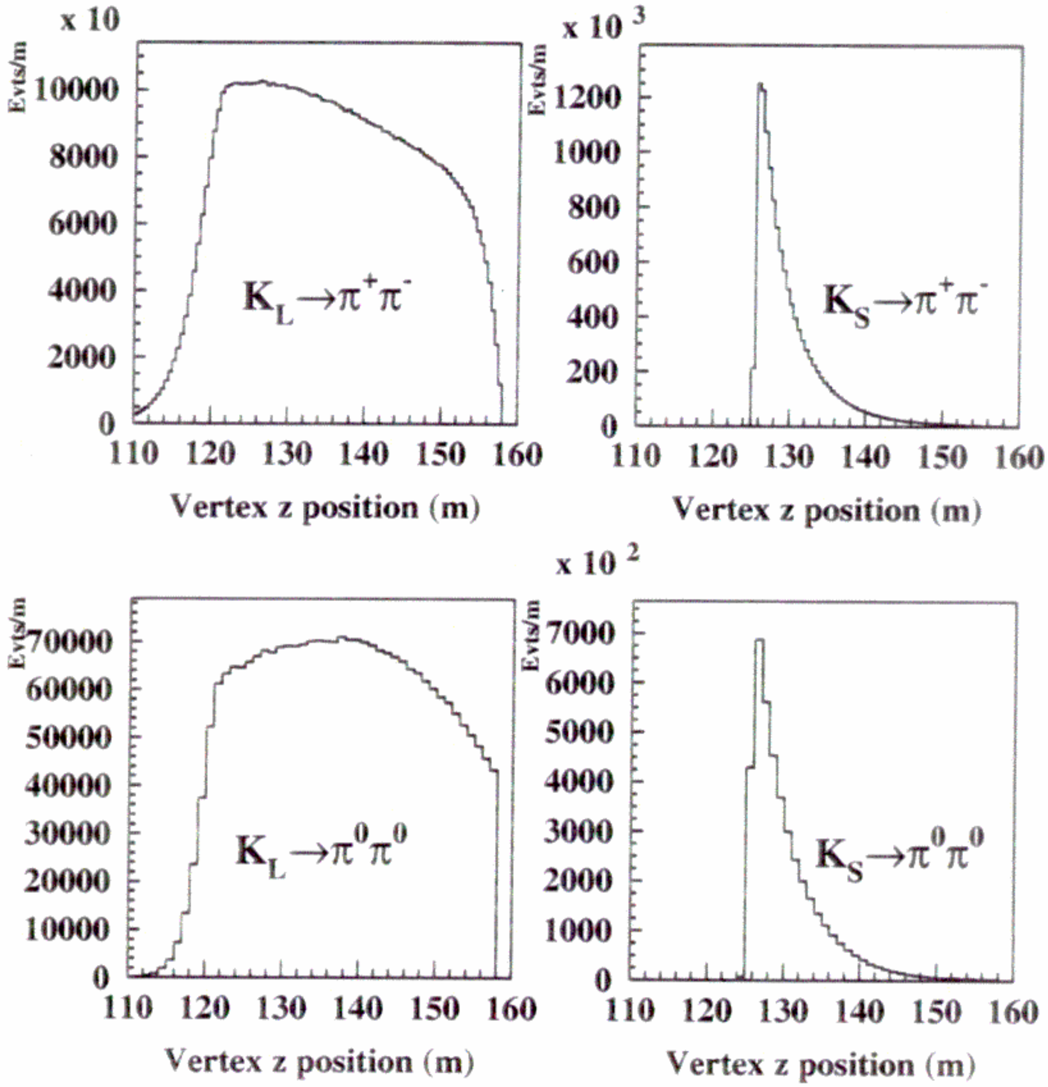
- First Result based on 1996 data for $K_L \to \pi^0\pi^0$ and beginning of 1997 data for $K_L \to \pi^+\pi^-$.
  $\to \mathbf{N_{00} = 0.862 \times 10^6}$
- Complete 1997 data set,
  $\to \mathbf{N_{00} = 2.5 \times 10^6}$:
  - Charge mode analysis has been finalized, new preliminary result on single ratio.
  - Neutral mode is still in progress.

Results to come:

NA48 About 2×10^6 $K_L \to \pi^0\pi^0$ events in 1999, now collecting data.

KTeV About 4×10^6 $K_L \to \pi^0\pi^0$ events in 1999, experiment is over.

Reconstructed Vertex Z Distribution (1997)

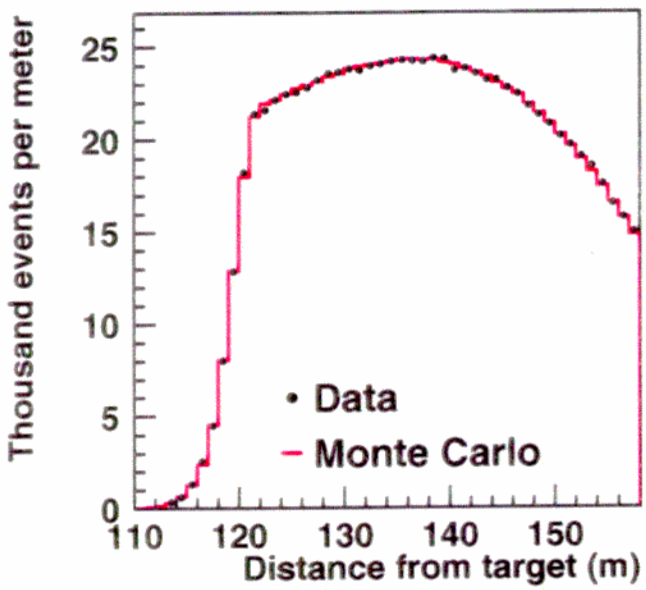


Two ways to account for differences:

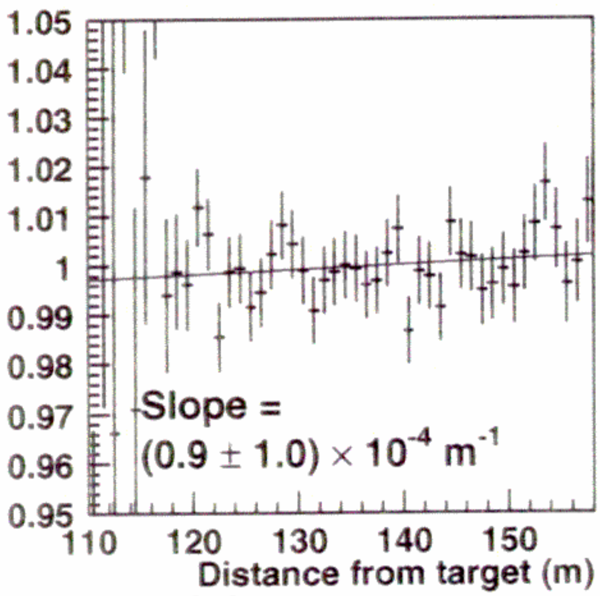
MC:	Use Monte Carlo simulation for acceptance calculation, **KTeV**
Reweighting:	Reweight K_L beam data to match K_S beam. **NA48**, cross check method for KTeV.

1996 data

$K_L \to \pi^0\pi^0$

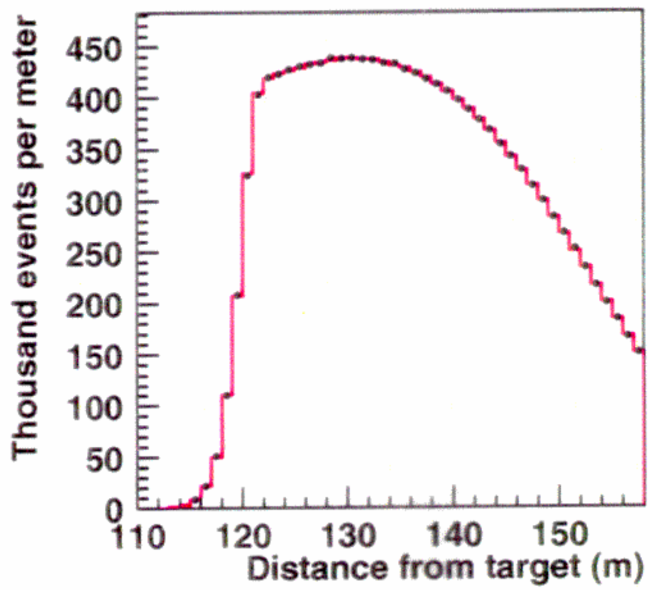


Vac $\pi^0\pi^0$ Z distribution

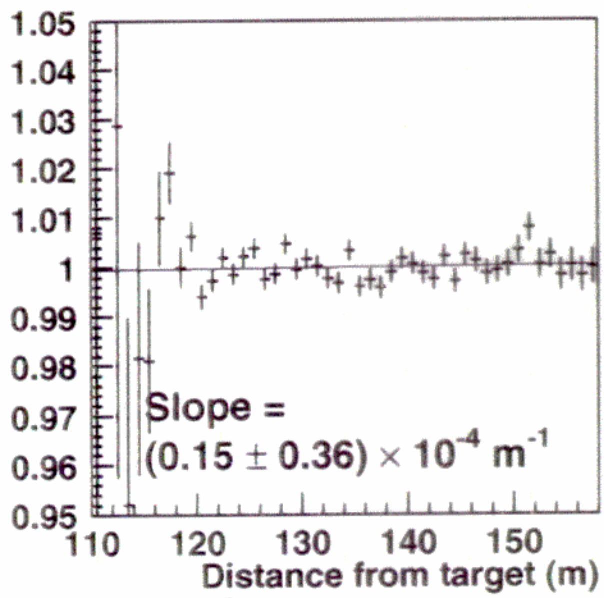


$\pi^0\pi^0$ Data/MC ratio

$K_L \to \pi^0\pi^0\pi^0$



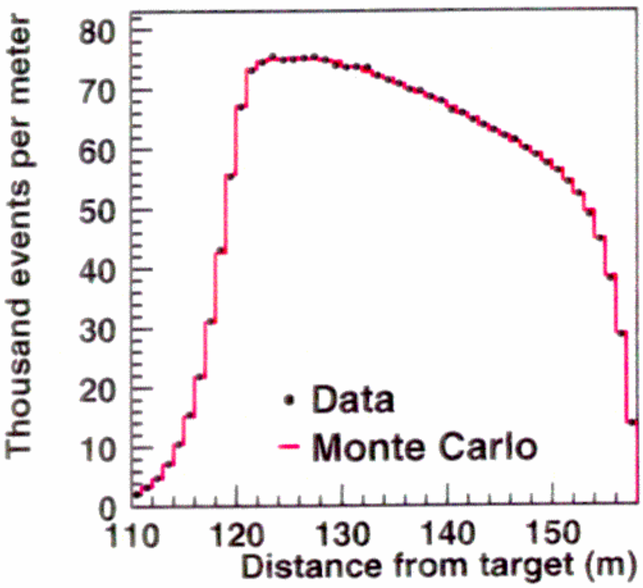
Vac $3\pi^0$ Z distribution



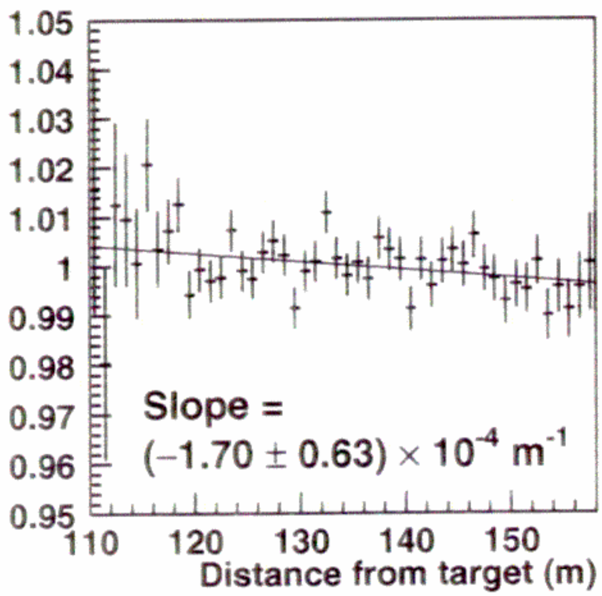
$3\pi^0$ Data/MC ratio

1997a data

$K_L \to \pi^+\pi^-$

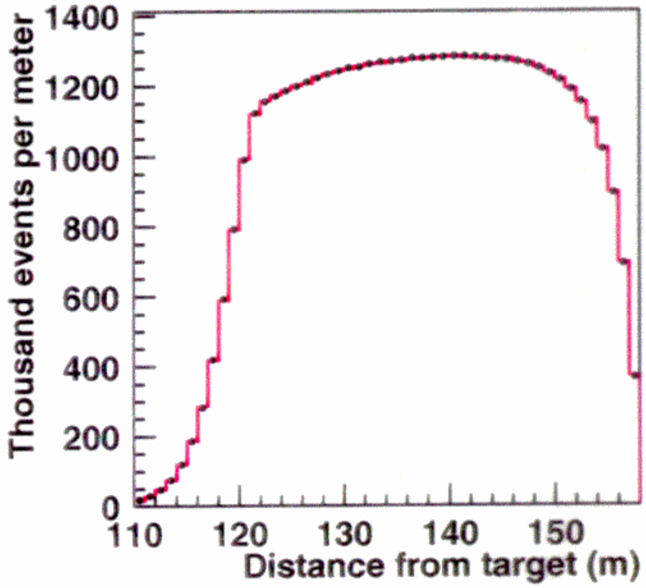


Vac $\pi^+\pi^-$ Z distribution

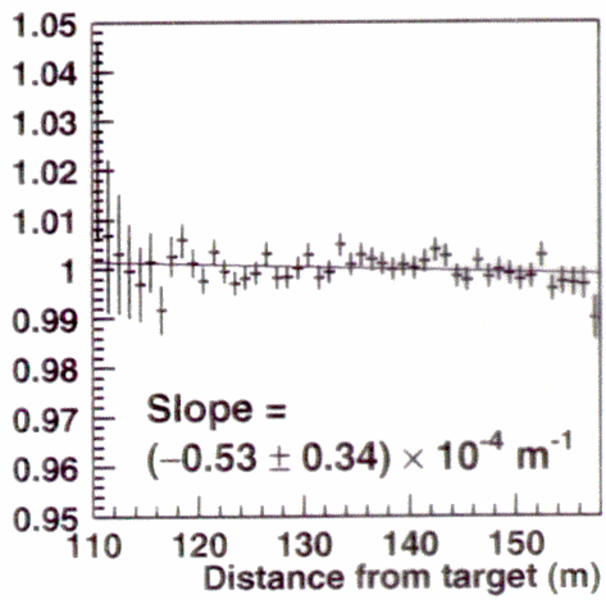


$\pi^+\pi^-$ Data/MC ratio

$K_L \to \pi e \nu$

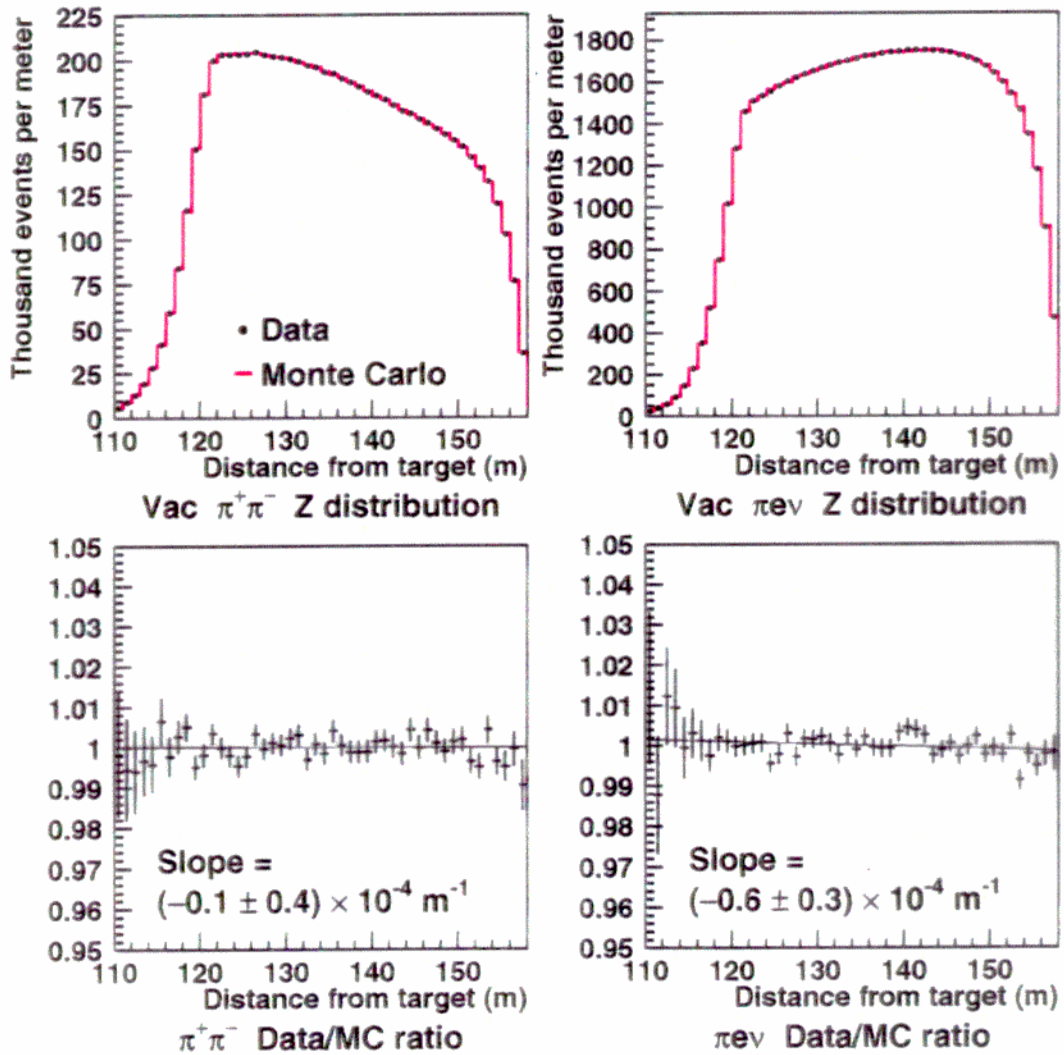


Vac $\pi e \nu$ Z distribution

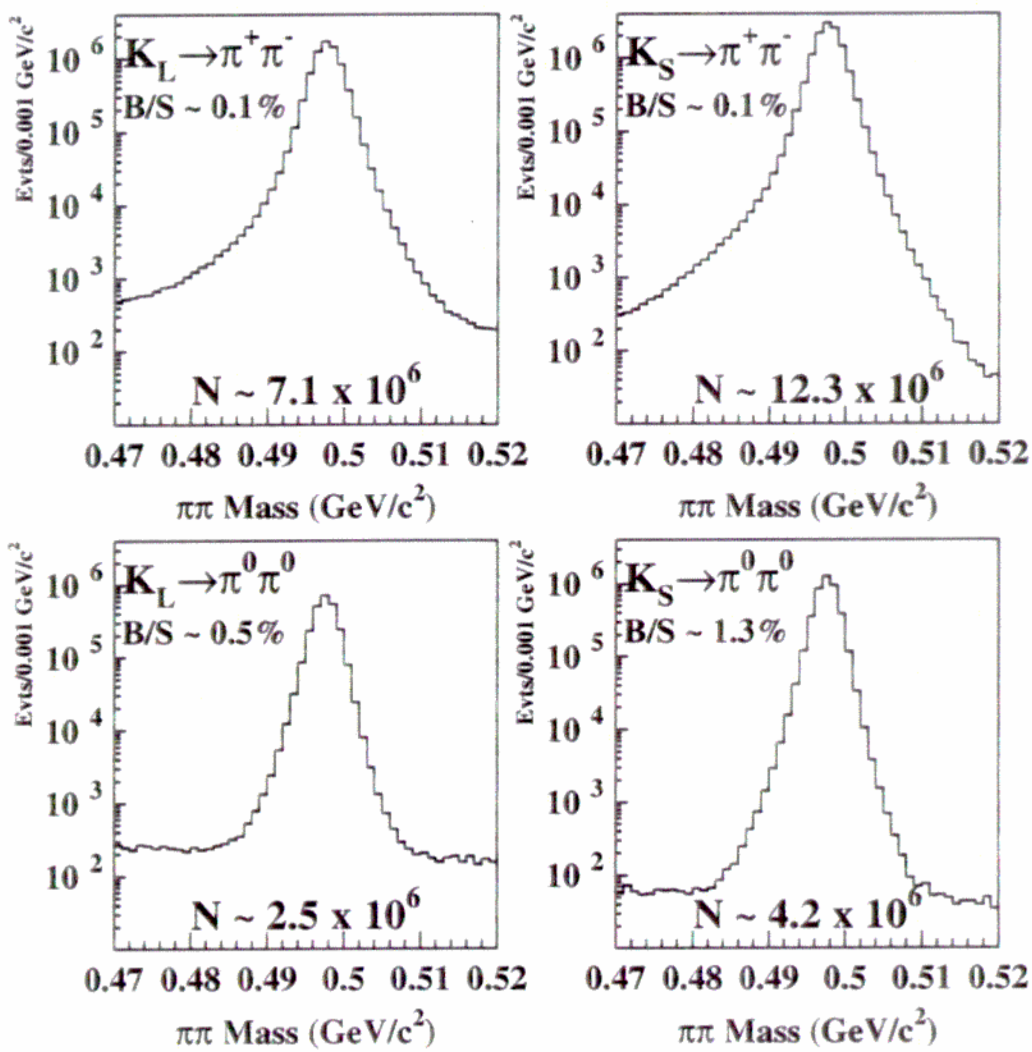


$\pi e \nu$ Data/MC ratio

Reconstructed Vertex Z Charged Mode 1997



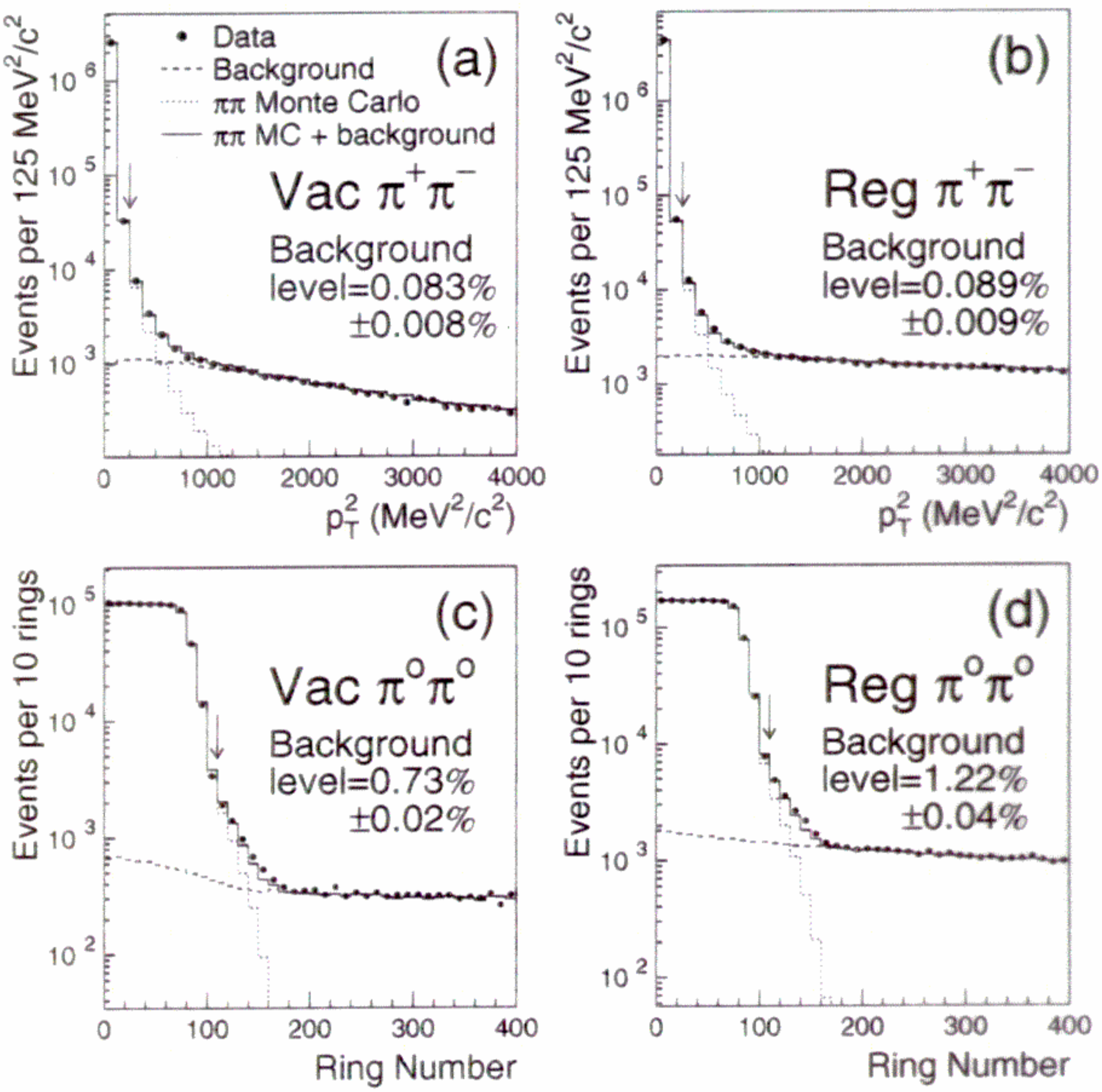
Reconstructed Invariant Mass Distribution (1997)



- Charged mode backgrounds are due to semileptonic $K \to \pi e \nu$, $K \to \pi \mu \nu$ decays.
- Neutral mode backgrounds are due to $K \to 3\pi^0$ decays

+ Background due to kaon *scattering* in regenerator.

Reconstructed P_t^2 and Ring Number (1996)

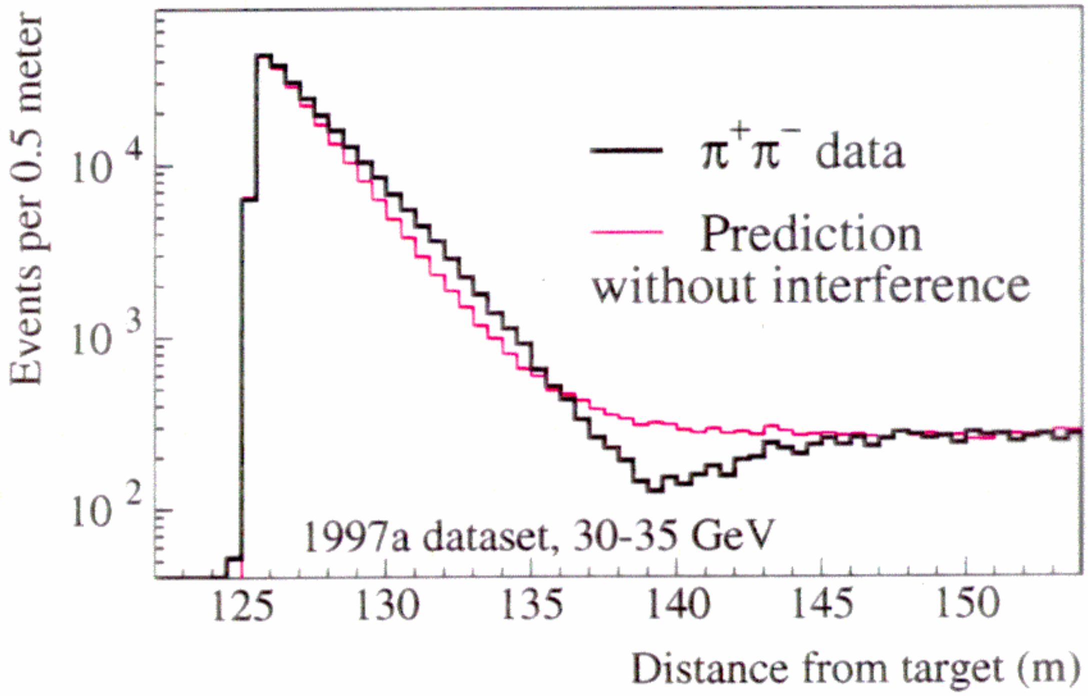


- In charged mode kaon p_t^2 is well reconstructed, background due to scattering is low.
- For neutral mode photon directions are unknown, $\rightarrow$ large impact of kaon scattering.

Summary of Systematic Uncertainties

Source of uncertainty	Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$	Uncertainty ($\times 10^{-4}$) from $\pi^0\pi^0$
Trigger (L1/L2/L3)	0.5	0.3
Energy scale	0.1	0.7
Calorimeter nonlinearity	—	0.6
Detector calibration, alignment	0.3	0.4
Analysis cut variations	0.6	0.8
Background subtraction	0.2	0.8
Limiting apertures	0.3	0.5
Detector resolution	0.4	0.1
Drift chamber simulation	0.6	—
Z dependence of acceptance	**1.6**	**0.7**
Monte Carlo statistics	0.5	0.9
Regenerator-beam attenuation:		
1996 versus 1997	0.2	
Energy dependence	0.2	
Δm, τ_s, regeneration phase	0.2	
TOTAL	2.8	

Preliminary KTeV Results on the K-mixing parameters



$$N_{reg}(Z) = |\rho|^2 e^{-Z/\gamma\beta c\tau_S} + |\eta|^2 e^{-Z/\gamma\beta c\tau_L} + 2|\rho||\eta| cos(\Delta m Z/\gamma\beta c + \phi_\rho - \phi) e^{-Z/\gamma\beta c\tau_{av}}$$

Preliminary results:

$$\Delta m = (0.5280 \pm 0.0013) \times 10^{-10}\ \hbar s^{-1}$$

$$\tau_S = (0.8967 \pm 0.0007) \times 10^{-10}\ s^{-1}$$

$$\Delta\phi = \phi_{00} - \phi_{+-} = 0.09^o \pm 0.46^o$$

Fitting for $Re(\epsilon'/\epsilon)$

- To a good first approximation KTeV is a ***counting*** experiment, $Re(\epsilon'/\epsilon)$ can be calculated as a simple acceptance corrected double ratio.

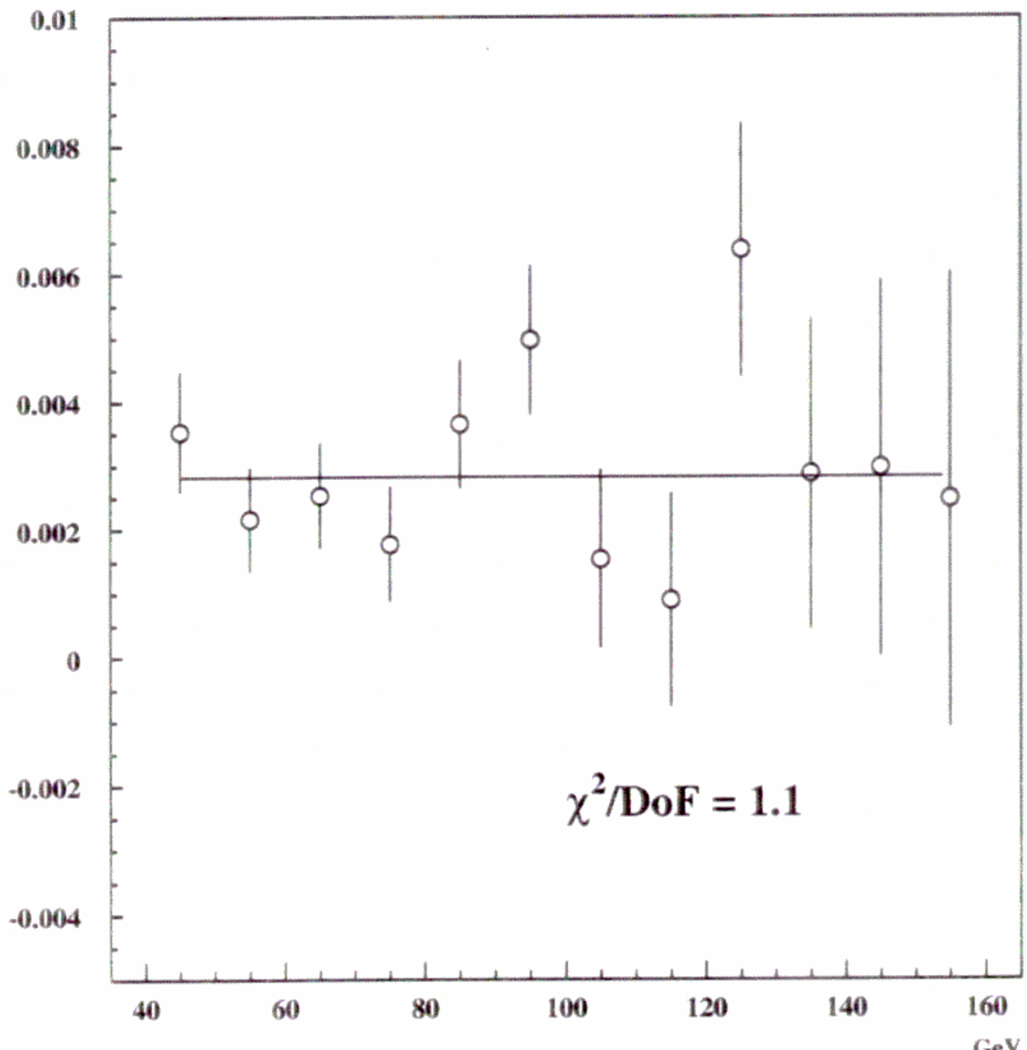
- To fully take into account small K_L (K_S) contamination in regenerator (vacuum) beam we use ***fitting*** for $Re(\epsilon'/\epsilon)$.

1. Full kaon state evolution from the target/through regenerator is calculated analytically
2. Monte Carlo is used to calculate acceptance.
3. Prediction is compared with data in 10-GeV energy bins to avoid uncertainty in production spectrum.
4. In addition, in case of τ_S, Δm and $\Delta\phi$ fits, data is binned in Z to explore the time evolution of the kaon state.
5. Value of $Re(\epsilon'/\epsilon)$ was **hidden** until systematics was finalized.

Double Ratio result:	$(26.5 \pm 3.0) \times 10^{-4}$
Fitting Result:	$(28.0 \pm 3.0) \times 10^{-4}$

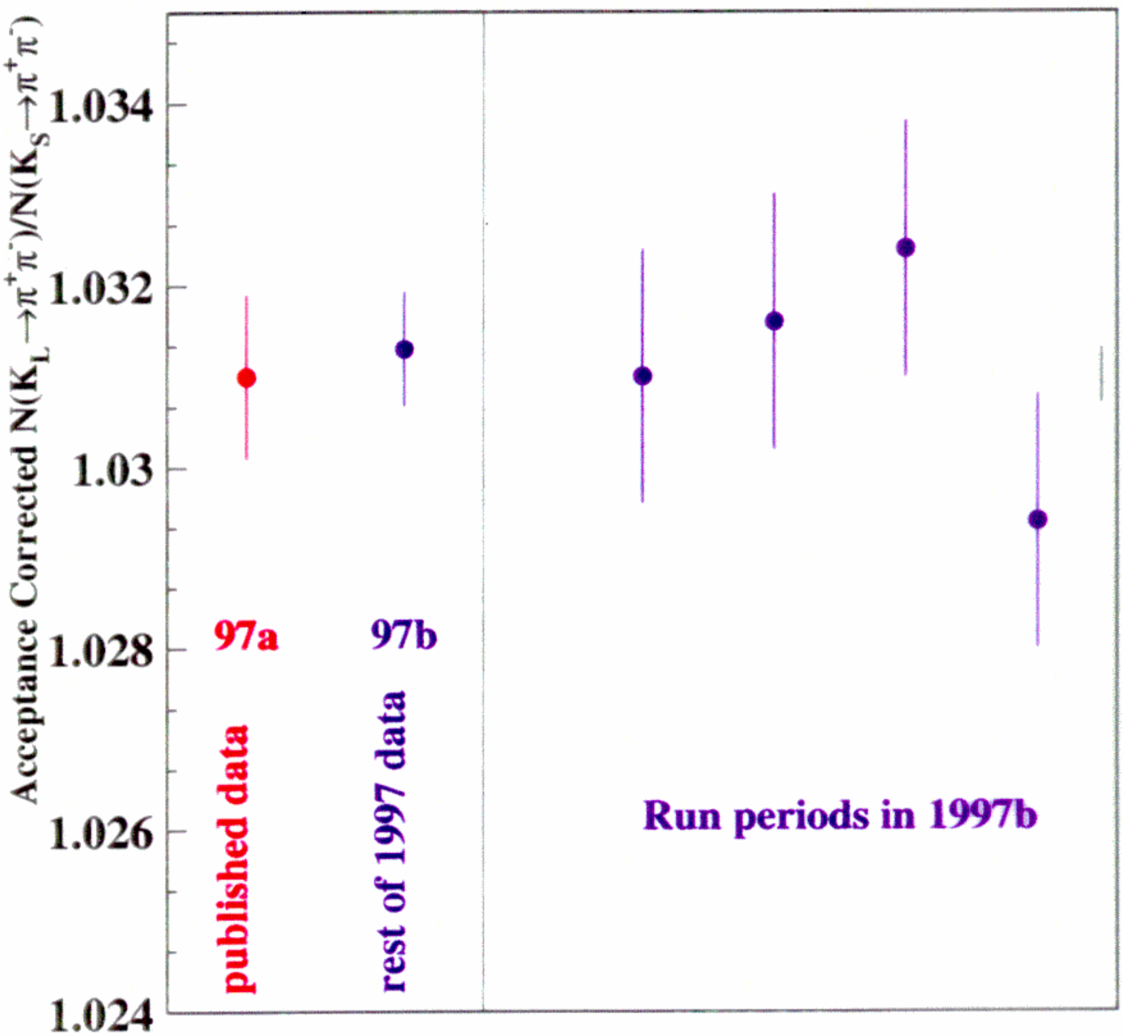
(statistical error only)

$Re(\epsilon'/\epsilon)$ in P_K Bins



Re(ε′/ε) versus Kaon Energy

Charged Mode 1997 Single Ratio



- Charged mode data collected in 1997 is consistent.
- Systematic error is reduced by about 2/3.

Status of ϵ'/ϵ measurements

KTeV:

$Re(\epsilon'/\epsilon) = (28.0 \pm 3.0 \text{ (stat) } \pm 2.8 \text{ (syst) }) \times 10^{-4}$

A. Alavi-Harati*et al.* Phys. Rev. Lett. **83**, 22 (1999).

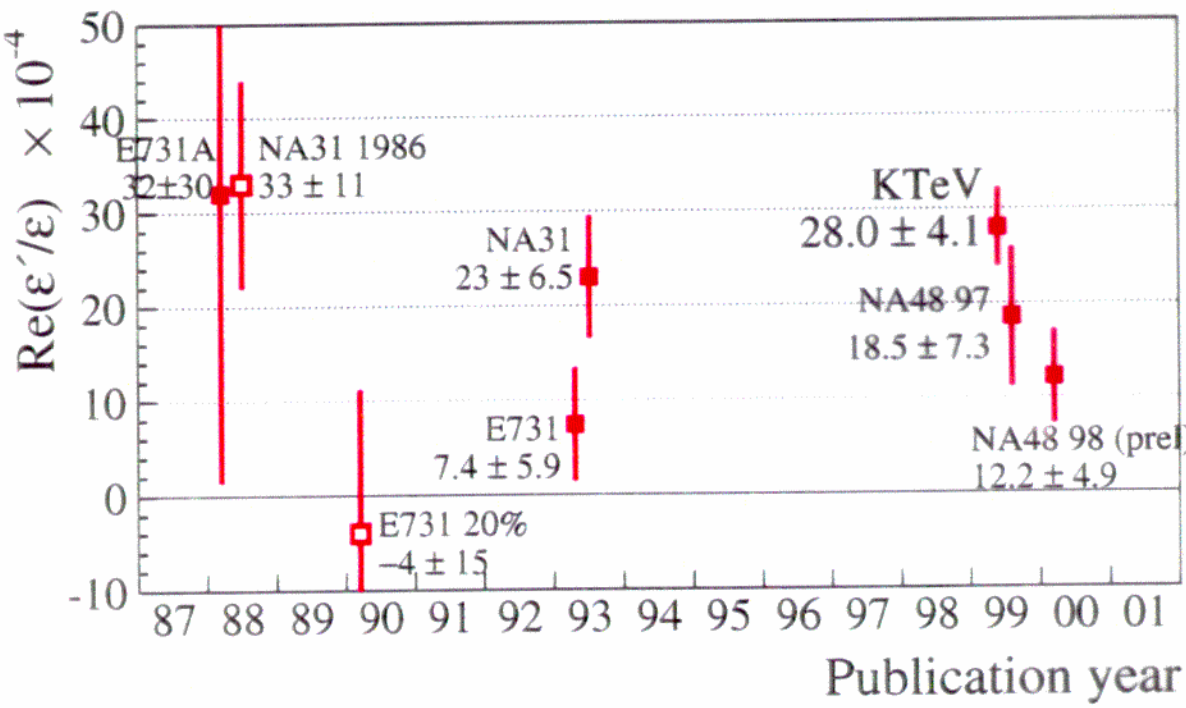
NA48:

$Re(\epsilon'/\epsilon) = (18.5 \pm 4.5 \text{ (stat) } \pm 5.8 \text{ (syst) }) \times 10^{-4}$

G. Anzivino*et al.* Phys. Lett. **B 465**, 335 (1999).

$Re(\epsilon'/\epsilon) = (12.2 \pm 2.9 \text{ (stat) } \pm 4.0 \text{ (syst) }) \times 10^{-4}$

(1998, preliminary)



Average: $Re(\epsilon'/\epsilon) = (19.1 \pm 2.4) \times 10^{-4}(5.0\% c.l.)$

What is next ?

Further measurements of $Re(\epsilon'/\epsilon)$:

KTeV Finalize 1997 data, analyze 1999.
$\rightarrow$ stat. uncertainty $= 1 \times 10^{-4}$. Systematics ?

NA48 Analyze 1999, collect data in 2000-2001.
Similar to KTeV uncertainty.

KLOE Measurement at ϕ factory using tagged K_L/K_S from $\phi \rightarrow K_S K_L$ decay. Totally different systematics.

$Re(\epsilon'/\epsilon)$ can be measured with up to 5% precision !

$\rightarrow$ need for better theoretical understanding.

Direct CP violation beyond $Re(\epsilon'/\epsilon)$:

- Measurement of $K_L \rightarrow \pi^0 \nu \overline{\nu}$ (**KAMI ?**).
- Measurement of $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ (**CKM ?**).

Kaon/B physics are complementary !