ε'/ε Results from KTeV

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- Introduction
- The KTeV Detector
- $K \to \pi^+\pi^-$, $K \to \pi^0\pi^0$ analysis
- Results
- Ongoing analysis and datataking
- Conclusions

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

Indirect vs. Direct CP Violation

Two possible contributions to $K_L \to \pi\pi$:

- "Indirect" - asymmetric K^0-$\overline{K}^0$ oscillations

$$K_L \sim (1+\varepsilon)K^0 - (1-\varepsilon)\overline{K}^0$$

$$\sim K_{odd} + \varepsilon K_{even} \longrightarrow \pi\pi$$

$\varepsilon = 2.28 \times 10^{-3}$

- "Direct" - CP violation in decay amplitude $K_{odd} \to \pi\pi$, parameterized by ε'

$$K^0 \to \pi^+\pi^-(\pi^0\pi^0) \neq \overline{K}^0 \to \pi^+\pi^-(\pi^0\pi^0)$$

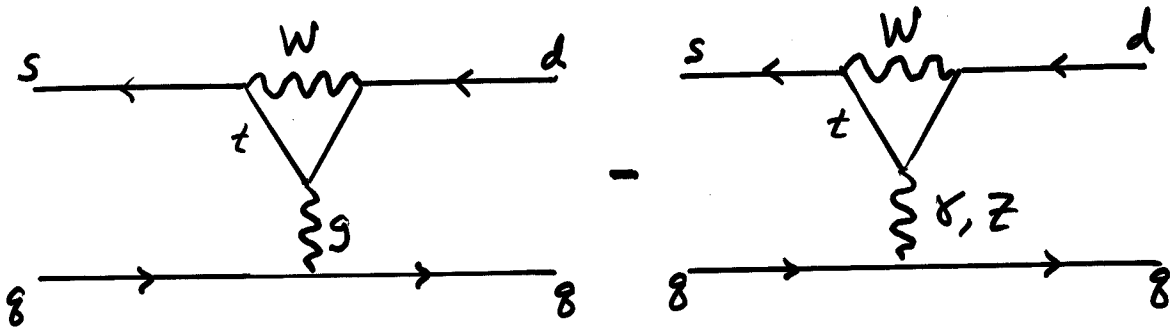
To distinguish between direct and indirect CP violation, compare $K_{L,S} \to \pi^+\pi^-, \pi^0\pi^0$:

$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_s \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_s \to \pi^0\pi^0)} - 1\right]$$

$\varepsilon'/\varepsilon \neq 0 \longrightarrow$ direct CP violation

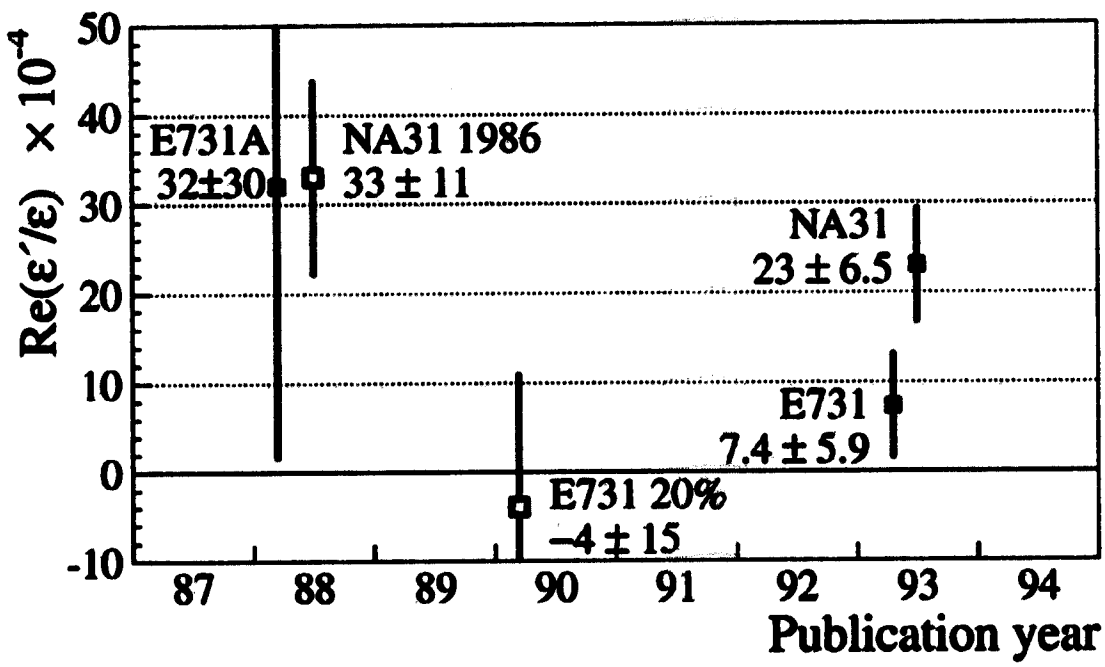
Predictions:

- Standard Model: $Re(\varepsilon'/\varepsilon) \sim (0\text{-}30)\times10^{-4}$



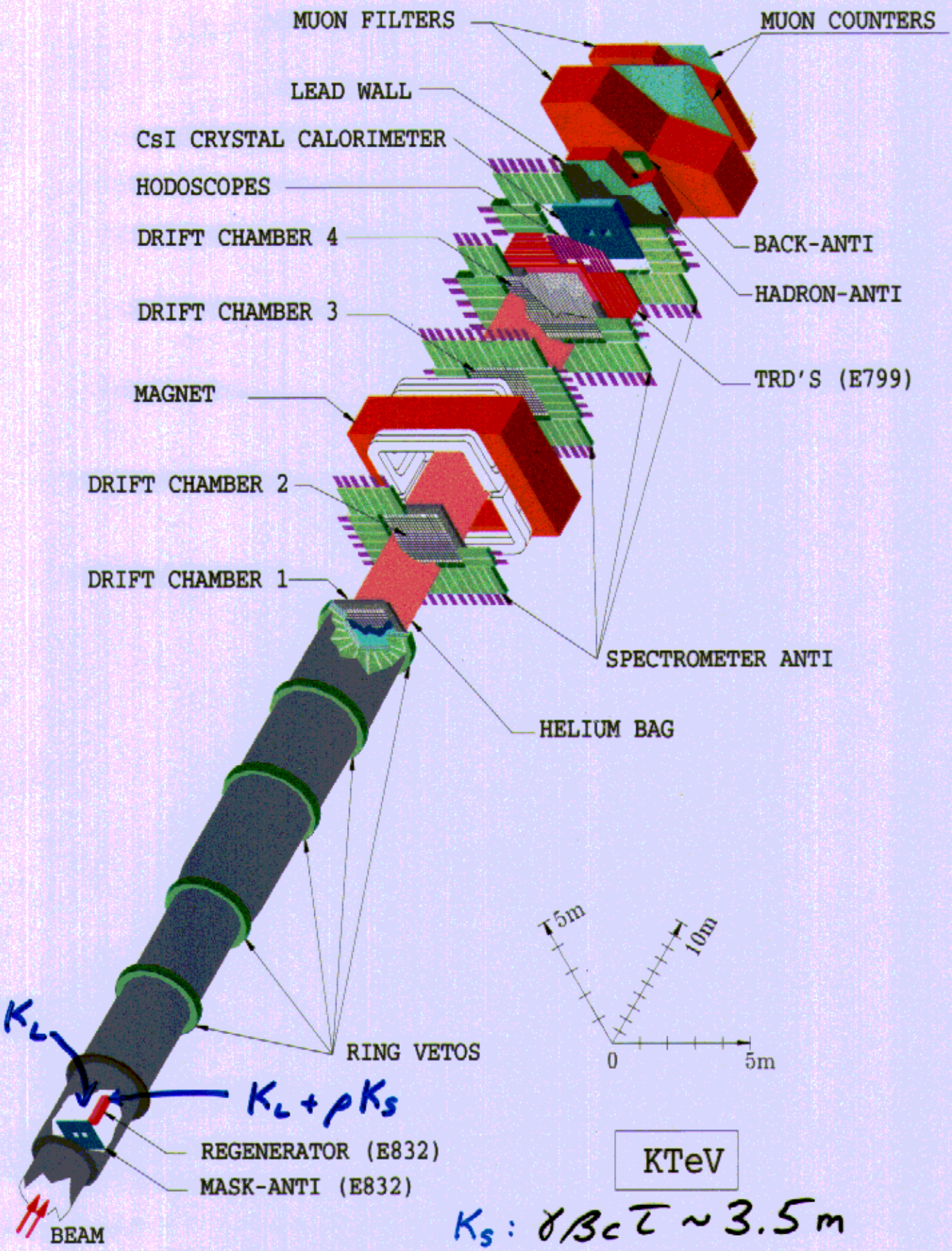
- Superweak Model: $Re(\varepsilon'/\varepsilon) = 0$

Recent measurements:



Three groups are trying to measure ε'/ε at the $1\text{-}2 \times 10^{-4}$ level: KTeV, NA48, KLOE

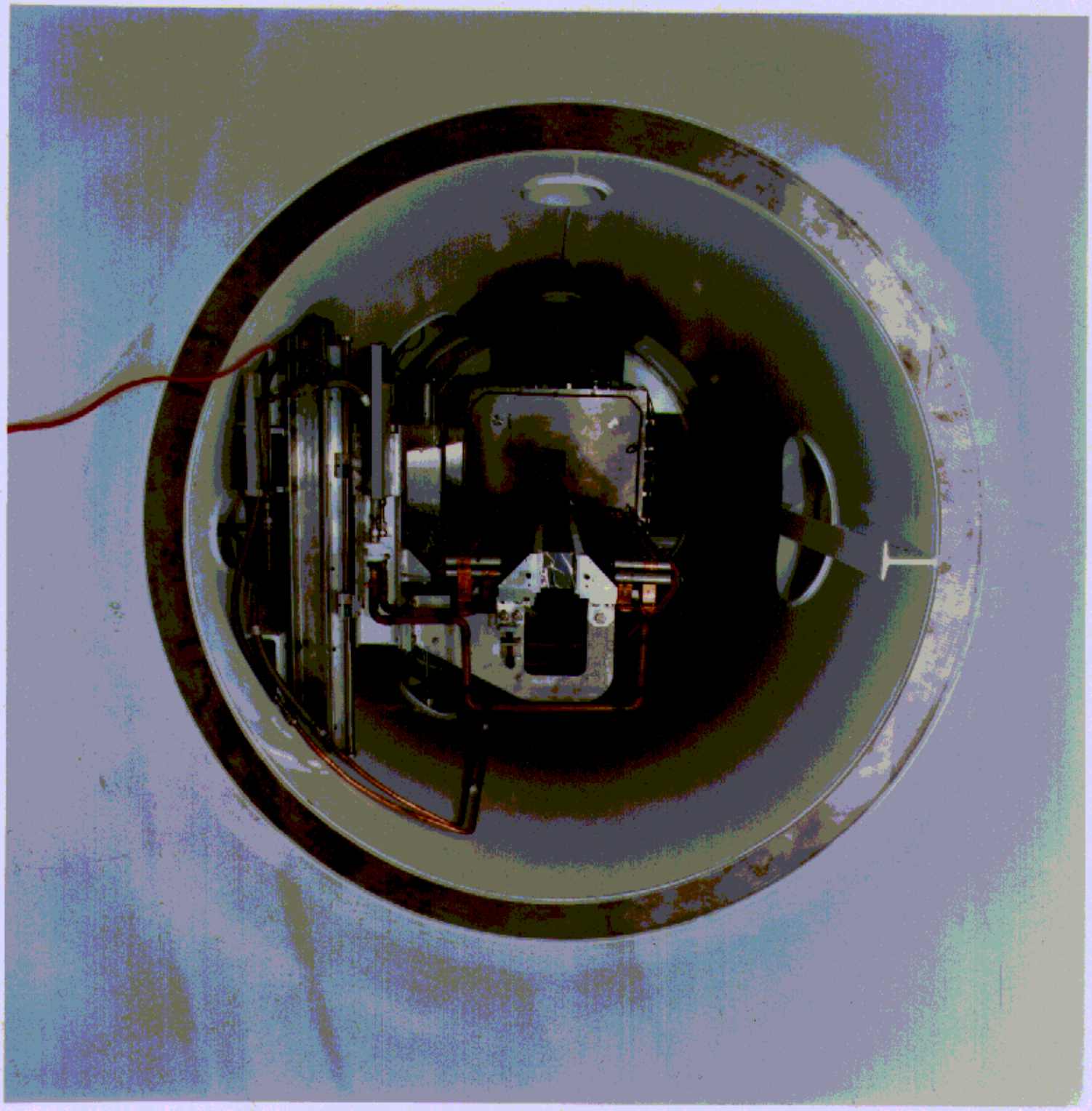
KTeV



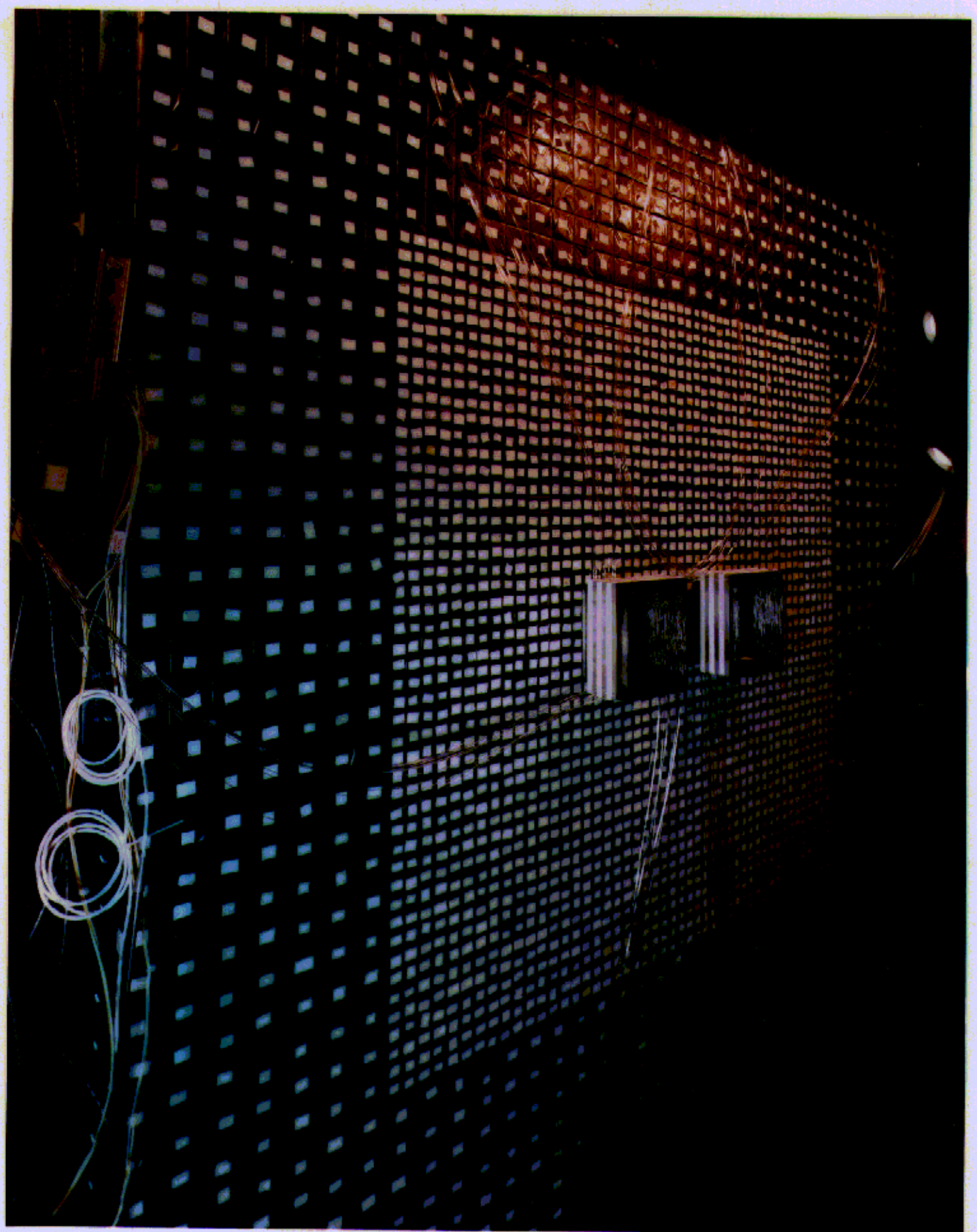
KTeV

K_S : $\gamma\beta c\tau \sim 3.5$ m

For $E_K \sim 70$ GeV, K_L : $\gamma\beta c\tau \sim 2.2$ km



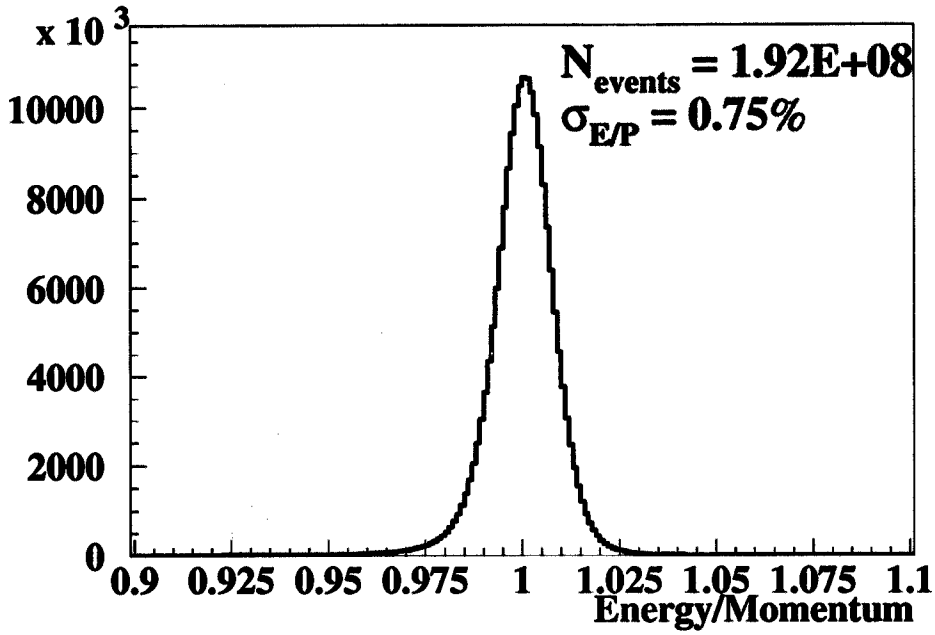
96-720-3



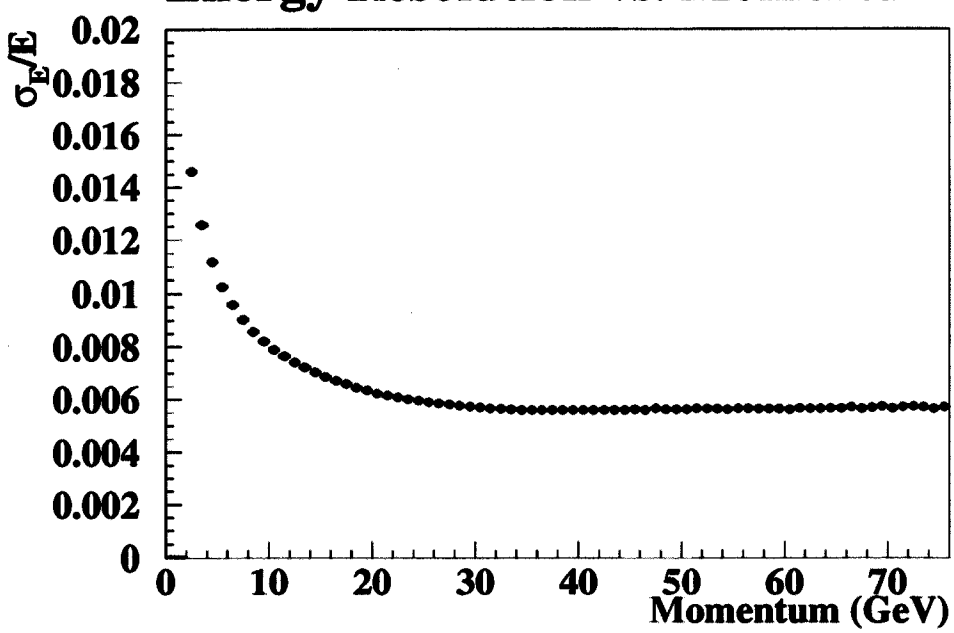
96-1123

1996 CsI Calorimeter Performance

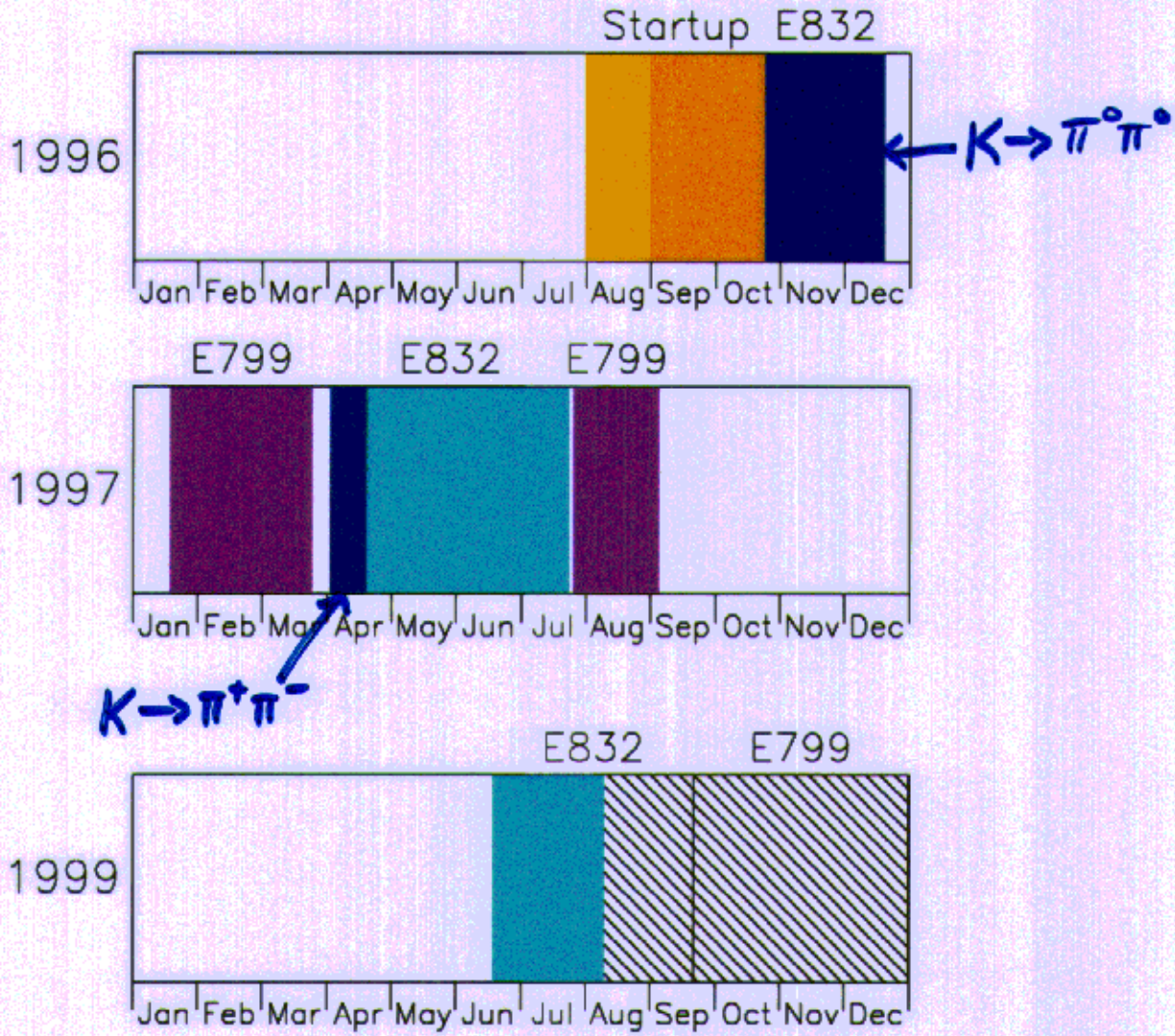
E/P Resolution for Electrons from K→πeν



Energy Resolution vs. Momentum



KTeV Datataking



Data sets used for first ϵ'/ϵ analysis

- $K \to \pi^0\pi^0$ data from 1996.
- $K \to \pi^+\pi^-$ data from first 18 days of E832 running in 1997.

E832: ϵ'/ϵ E799: rare decays

$K_L \rightarrow \pi^+\pi^-$

KTEV Event Display

/usr/kpasa/chic03/jagraham/k2pi_kzc067.dat

Run Number: 9073
Spill Number: 78
Event Number: 11268486
Trigger Mask: 1
All Slices

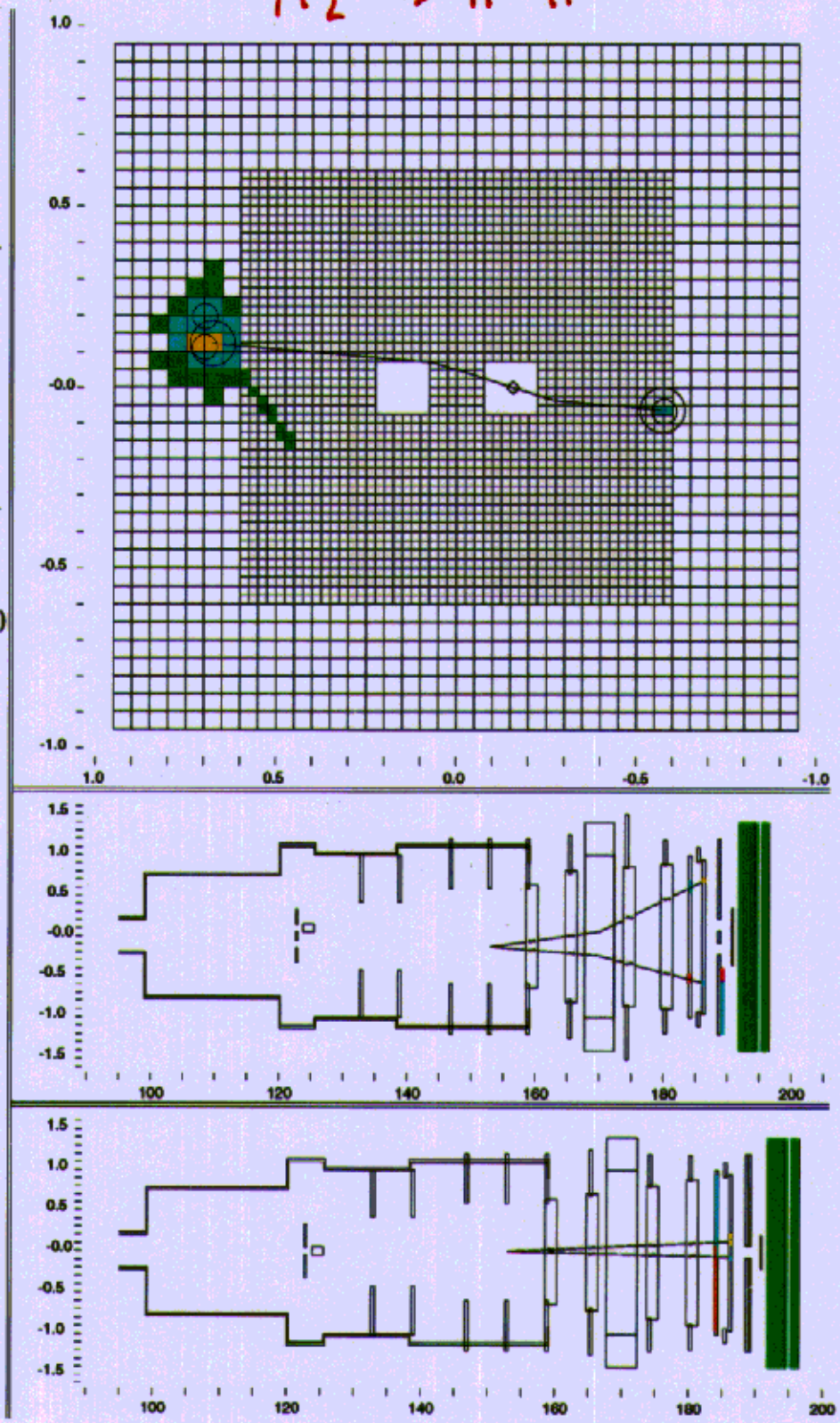
Track and Cluster Info
HCC cluster count: 1

ID	Xcsi	Ycsi	P or E
T 1:	-0.5718	-0.0620	+30.09
C 3:	-0.5766	-0.0657	0.34
T 2:	0.6770	0.1238	-15.02
C 1:	0.6996	0.1131	9.20
C 2:	0.6982	0.1982	1.19

Vertex: 2 tracks

X	Y	Z
-0.1288	0.0000	152.972

Mass=0.4967 (assuming pions)
Chisq=1.64 Pt2v=0.000003



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

KTEV Event Display

/usr/kpasa/data06/data/postcard_2pi0.dat

Run Number: 6918
Spill Number: 3
Event Number: 337734
Trigger Mask: 8
All Slices

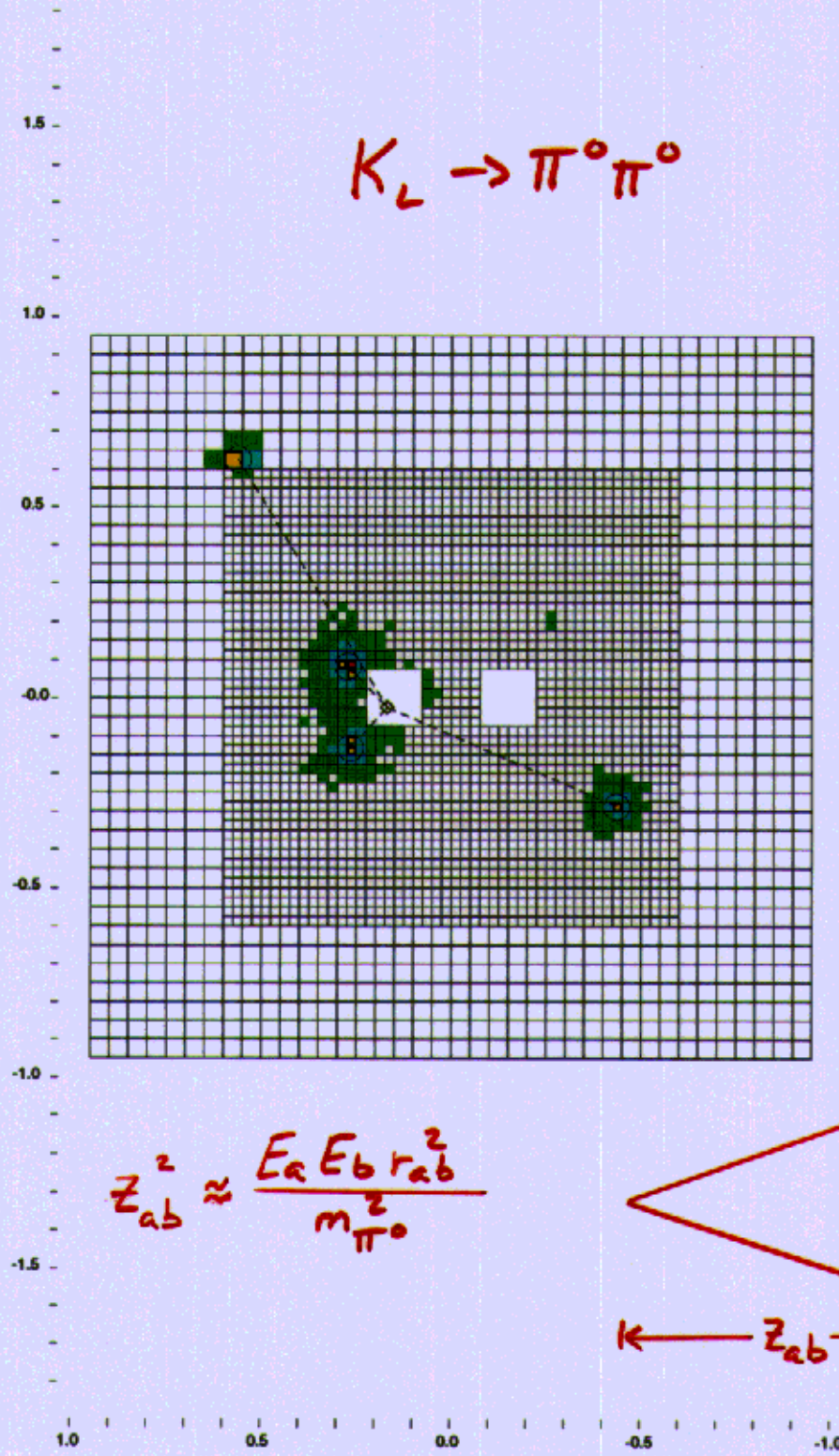
Track and Cluster Info
HCC cluster count: 4

ID	Xcsi	Ycsi	P or E
C 1:	0.5621	0.6272	1.41
C 2:	0.2722	0.0836	26.92
C 3:	0.2656	-0.1320	16.00
C 4:	-0.4359	-0.2878	8.03

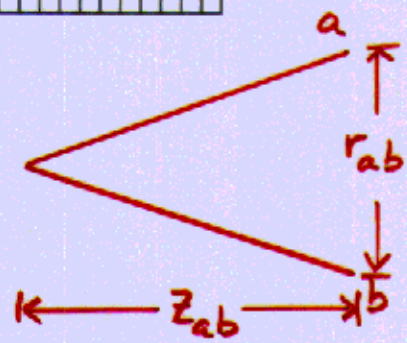
Vertex: 4 clusters

X	Y	Z
0.1390	-0.0203	152.835

Mass=0.4969
Pairing chisq=1.60



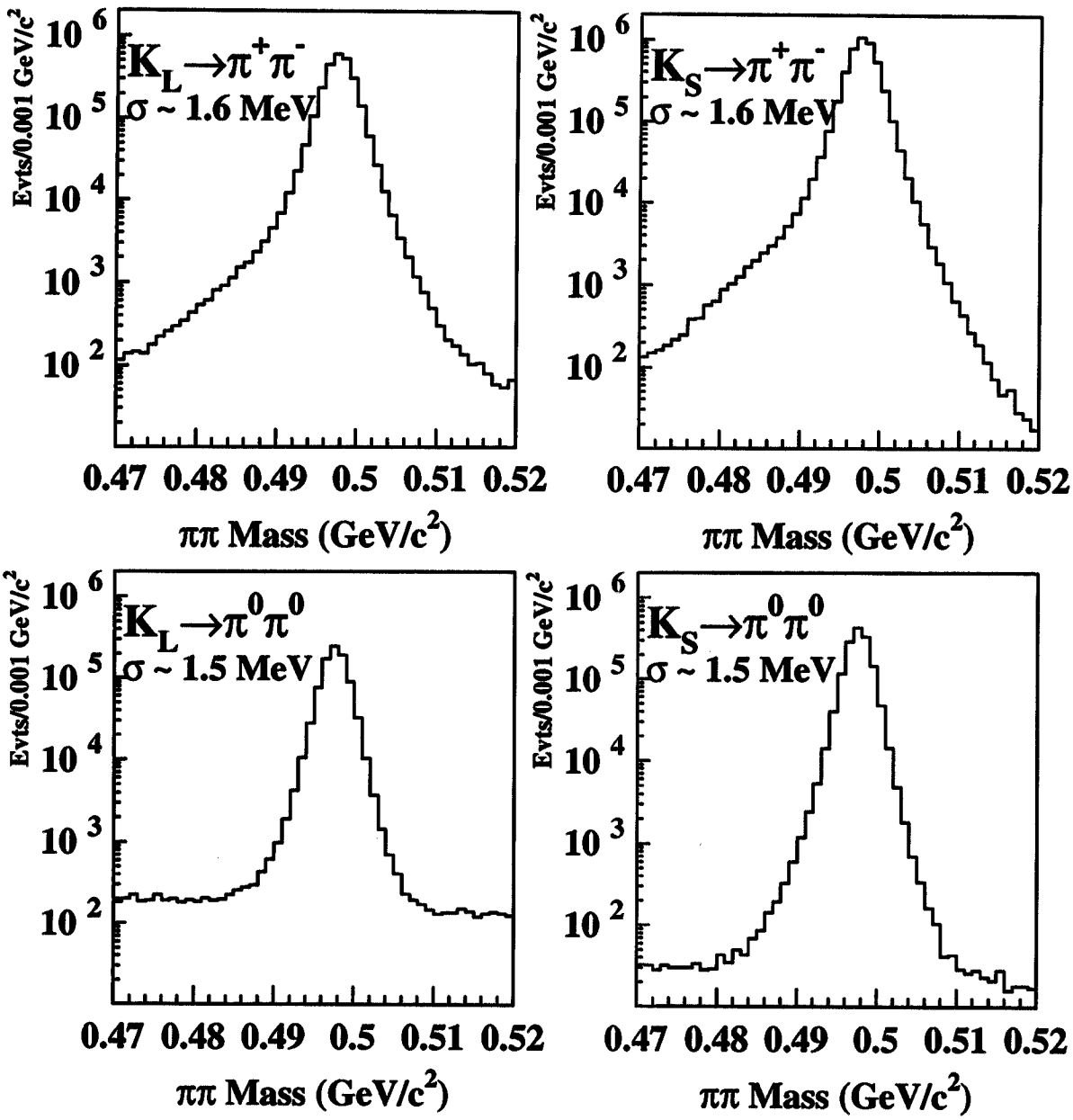
$$z_{ab}^2 \approx \frac{E_a E_b r_{ab}^2}{m_{\pi^0}^2}$$



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

Reconstructed Mass Distributions

not background subtracted



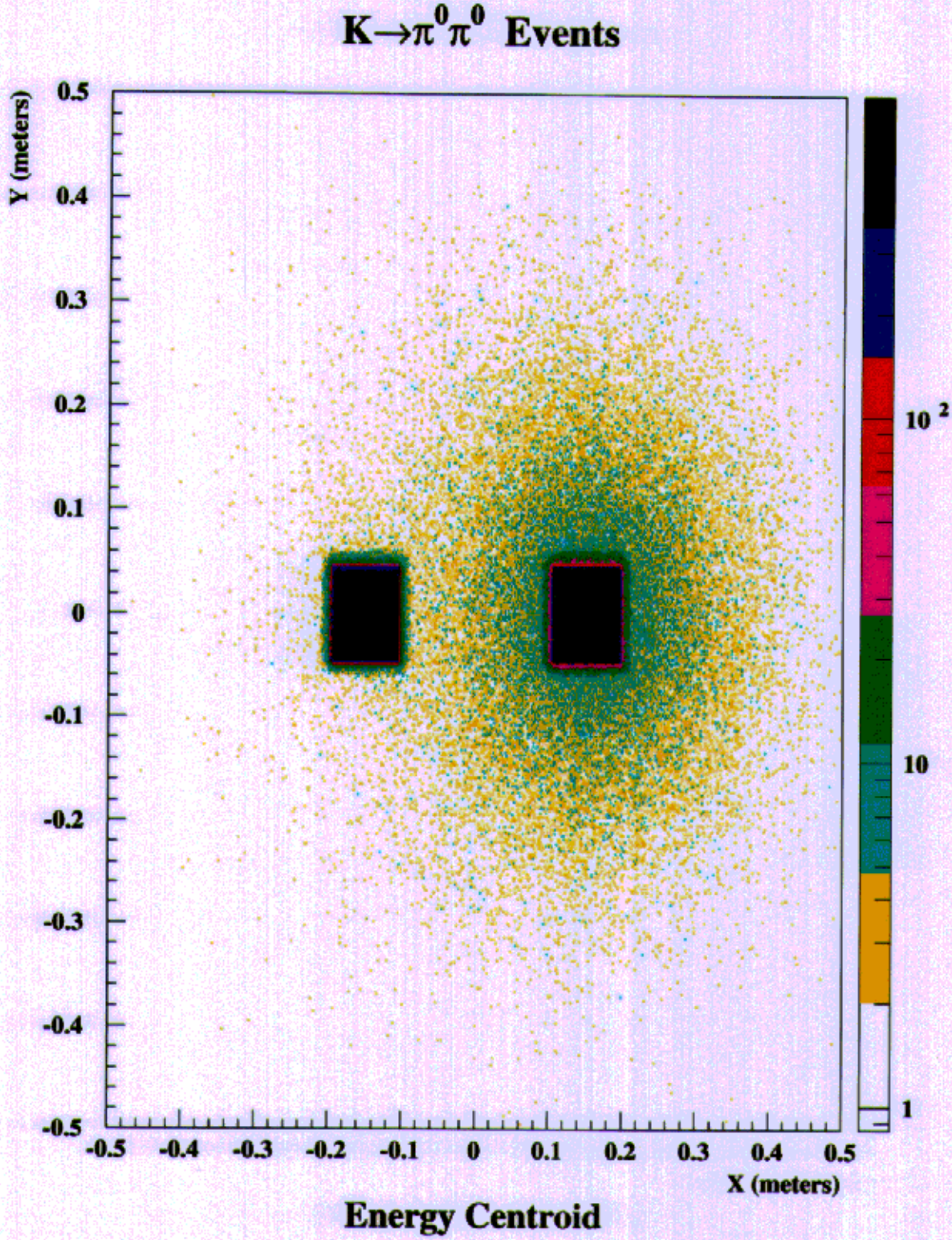
Backgrounds

Main classes of background:

- Misidentified kaon decays
  - For $K \to \pi^+\pi^-$: $K_L \to \pi e \nu$, $K_L \to \pi \mu \nu$
  - For $K \to \pi^0\pi^0$: $K_L \to \pi^0\pi^0\pi^0$
- Scattered $K \to \pi\pi$ events
  - From regenerator and final collimator

Background levels (in %)

	Vac $\pi^+\pi^-$	Reg $\pi^+\pi^-$	Vac $\pi^0\pi^0$	Reg $\pi^0\pi^0$
Misidentified K:				
$K \to \pi l \nu$	0.069	0.003		
$K \to 3\pi^0$			0.27	0.01
Scattered K:				
regenerator		0.072	0.30	1.07
collimator	0.014	0.014	0.16	0.14
Total	**0.083**	**0.089**	**0.73**	**1.22**


K→π0π0 Events
Y (meters)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
X (meters)
10 2
10
1
Energy Centroid

Yield after Background Subtraction

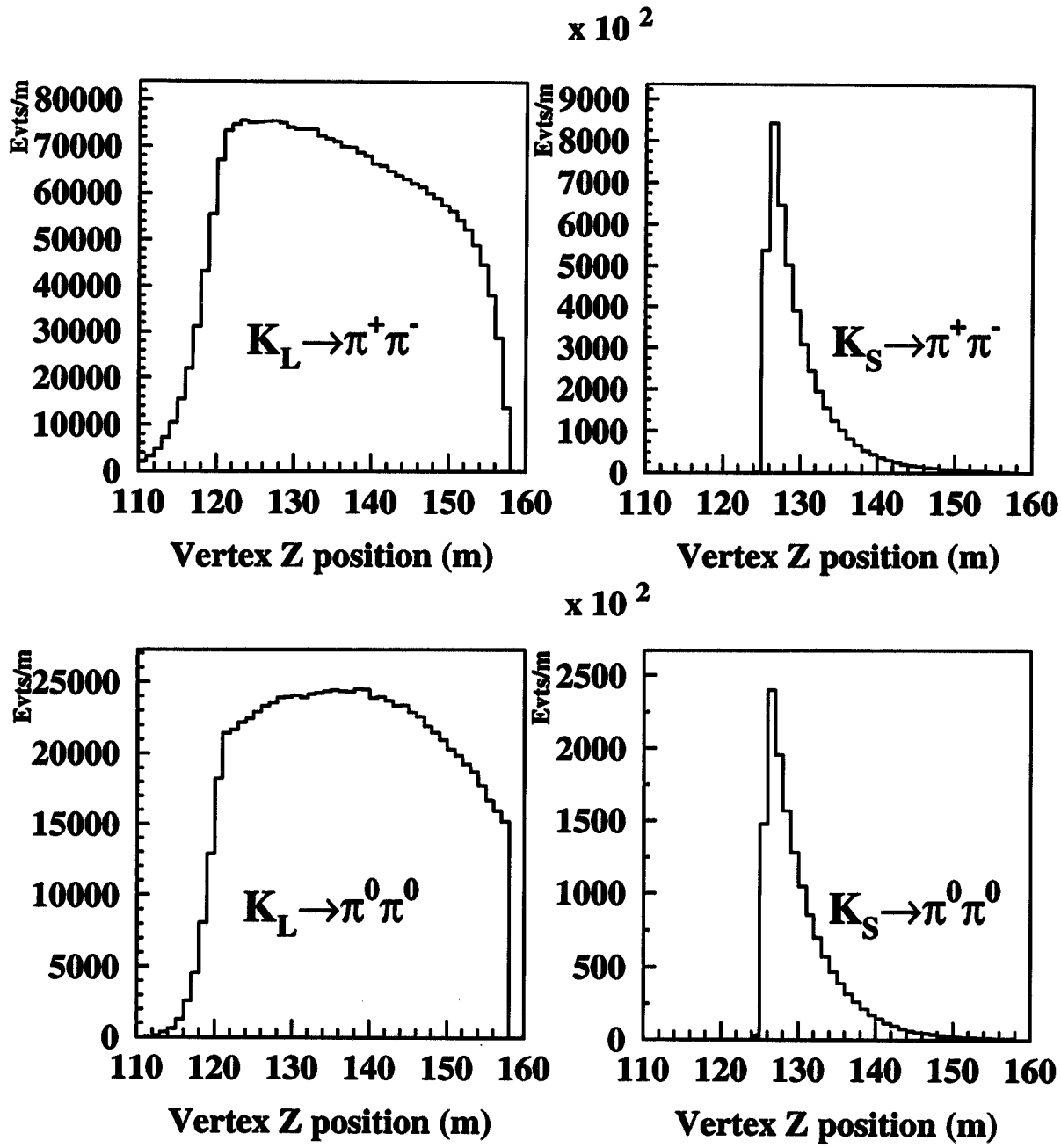
	K_L Vacuum Beam	"K_S" Reg. Beam
$K \to \pi^+\pi^-$	2,607,274	4,515,928
$K \to \pi^0\pi^0$	862,254	1,433,923

Raw double ratio:

$$R = \frac{2607274 / 4515928}{862254 / 1433923} = 0.960$$

(no acceptance correction)

Reconstructed Vertex Z Distributions



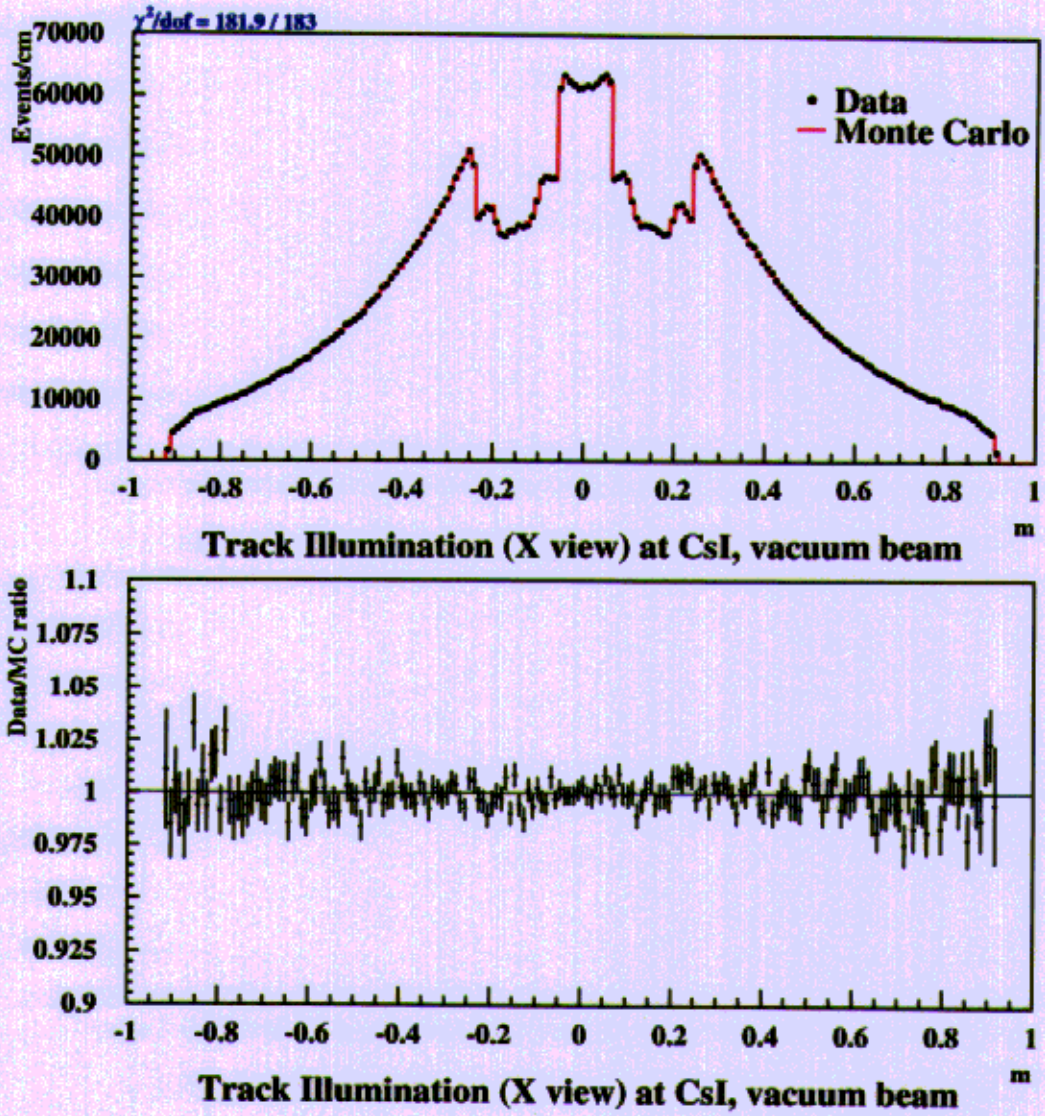
Acceptance

Detailed Monte Carlo simulation including:

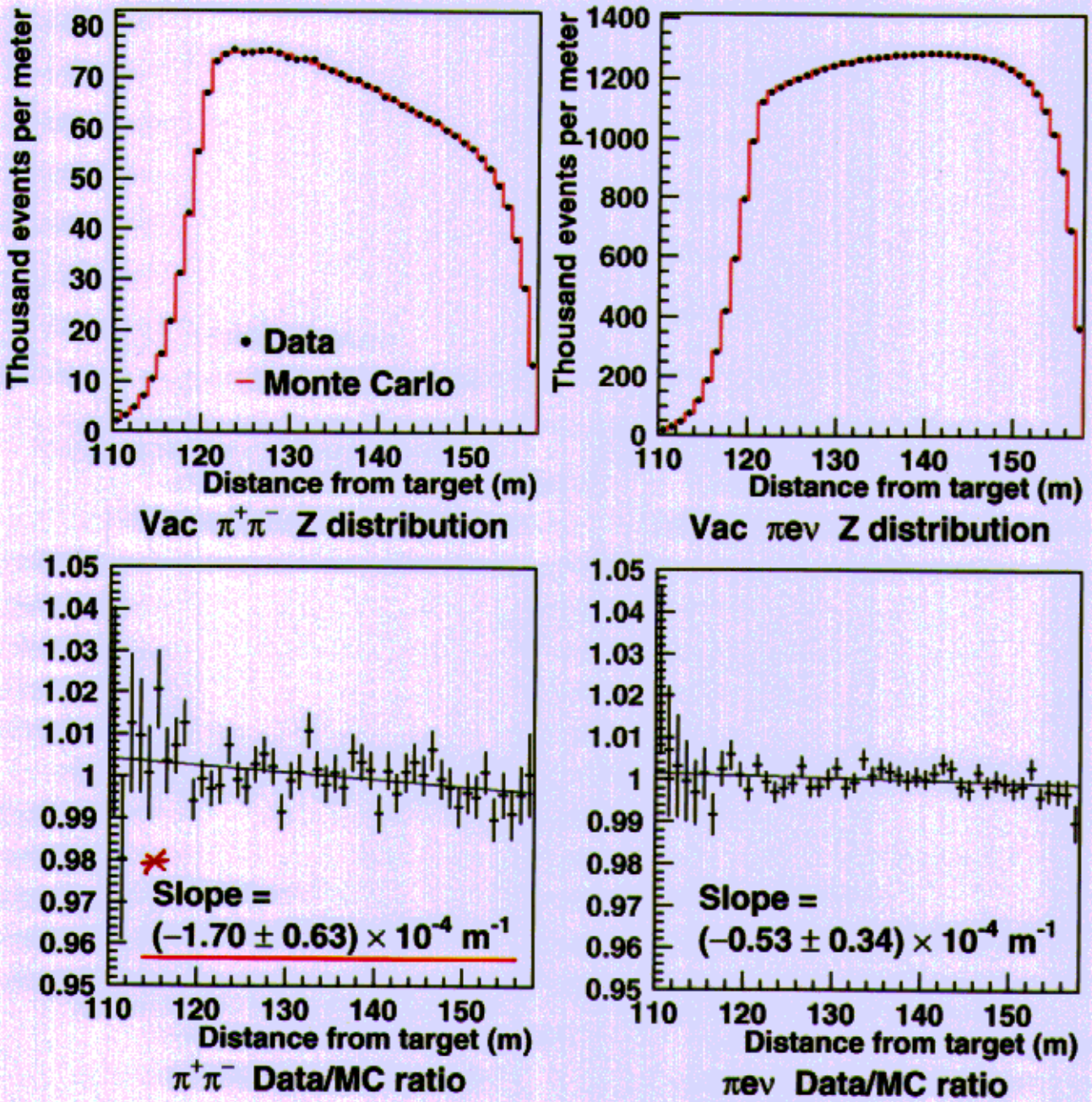
- Accidental overlays
- Full trigger simulation (L1,L2,L3)
- For $K \rightarrow \pi^0\pi^0$:
  - Geant-based shower library for CsI (showers cover 0.675×0.675 m^2)
  - Detail photon veto simulation
- For $K \rightarrow \pi^+\pi^-$:
  - Detailed drift chamber simulation
  - Magnetic field map
  - CsI pion shower library

High statistics decay modes (e.g., $K \rightarrow \pi e \nu$, $K \rightarrow 3\pi^0$) are used to check MC simulation.

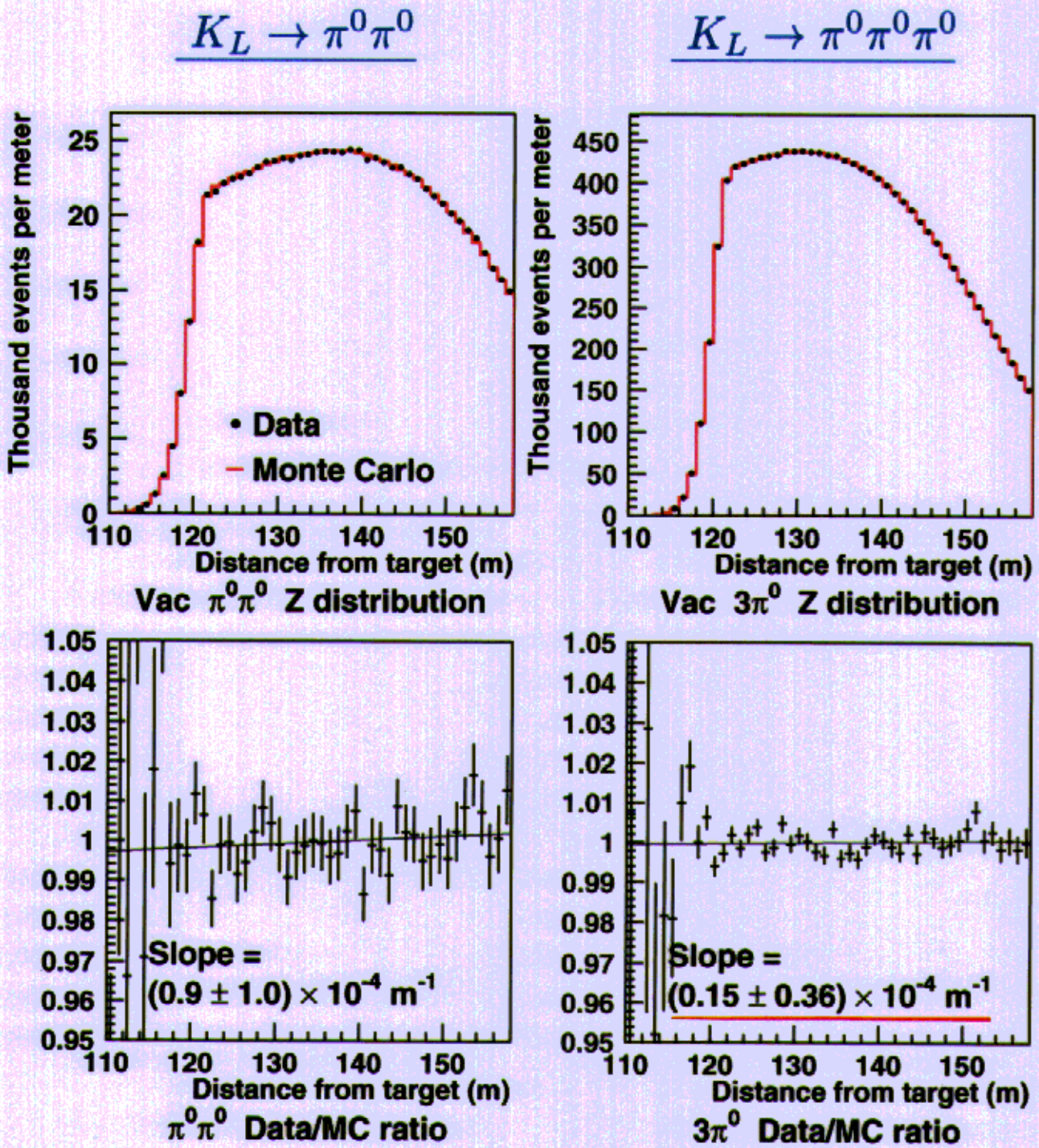
$\pi^+\pi^-$ Illumination Comparison



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



* Systematic error is based on this slope: largest systematic error.


$K_L \to \pi^0\pi^0$
$K_L \to \pi^0\pi^0\pi^0$
Thousand events per meter
• Data
– Monte Carlo
Distance from target (m)
Vac $\pi^0\pi^0$ Z distribution
Vac $3\pi^0$ Z distribution
Slope =
$(0.9 \pm 1.0) \times 10^{-4}$ m^{-1}
Slope =
$(0.15 \pm 0.36) \times 10^{-4}$ m^{-1}
$\pi^0\pi^0$ Data/MC ratio
$3\pi^0$ Data/MC ratio

Summary of Systematic Uncertainties

Source of uncertainty	Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$	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	

Value of ϵ'/ϵ was hidden until analysis + systematics were finalized.

Naive Double Ratio Analysis

$\pi^+\pi^-$, 40-160 GeV	VAC, 110-158m	REG, 124-132m
Data	2607274	3476114
MC Acceptance	0.231261(69)	0.318314(77)
Single Ratio	1.0320(09)	

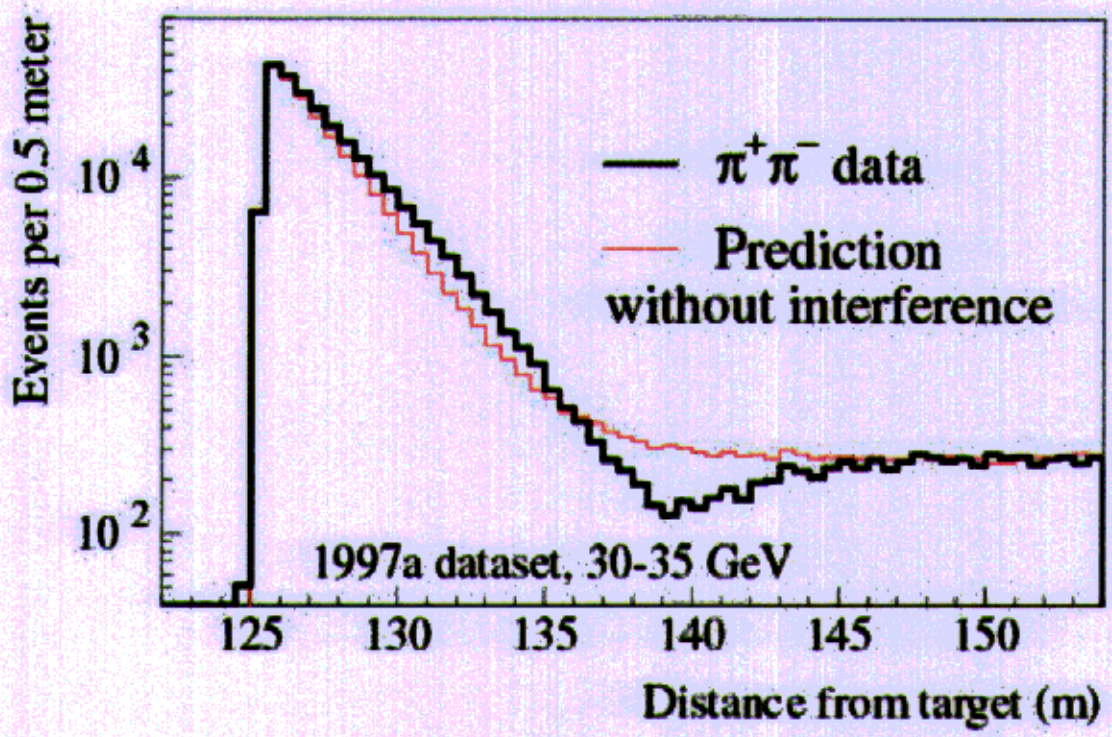
$\pi^0\pi^0$, 40-160 GeV	VAC, 110-158m	REG, 124-132m
Data	862254	1048347
MC Acceptance	0.103588(33)	0.127936(37)
Single Ratio	1.0158(15)	

$$Double\ Ratio = 1.0159 \pm 0.0018$$

$$Naive\ Re(\epsilon'/\epsilon) = (26.5 \pm 3.0) \times 10^{-4}$$

(assuming that the regenerator beam contains only K_S)

K_L - K_S Interference Downstream of Regenerator



KTeV Preliminary Results:

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

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

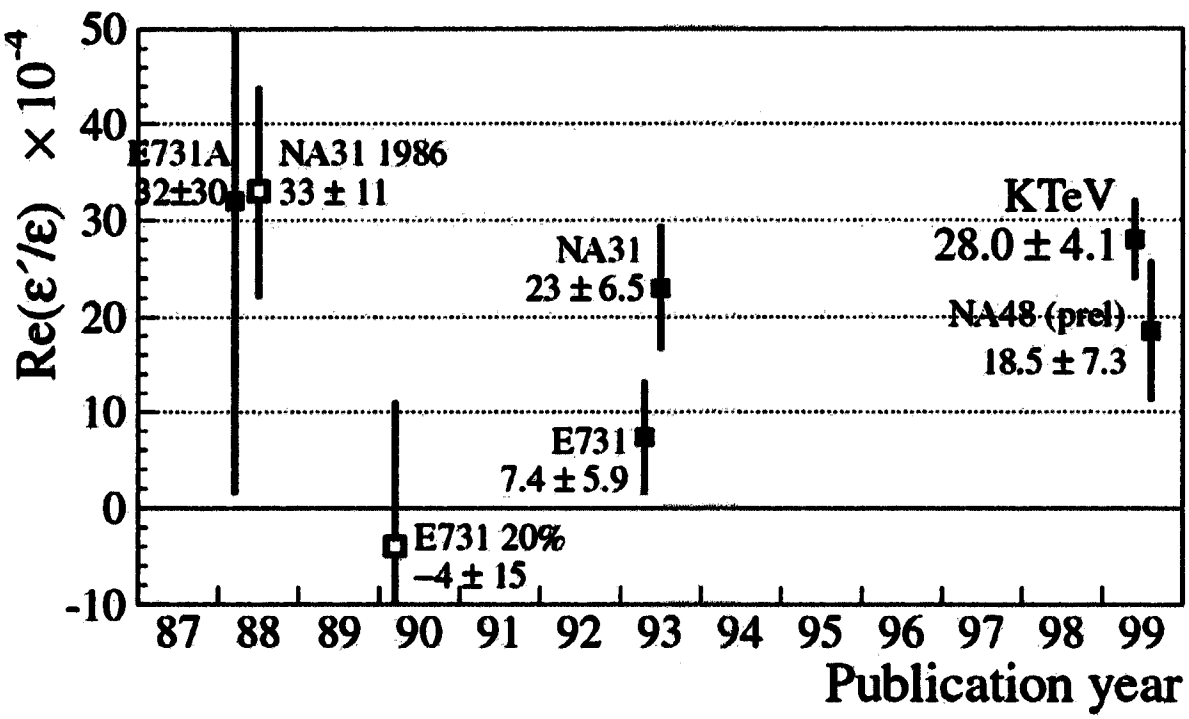
$$\Delta\Phi = \Phi_{00} - \Phi_{+-} = 0.09° \pm 0.46°$$

First ε'/ε Result from KTeV

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

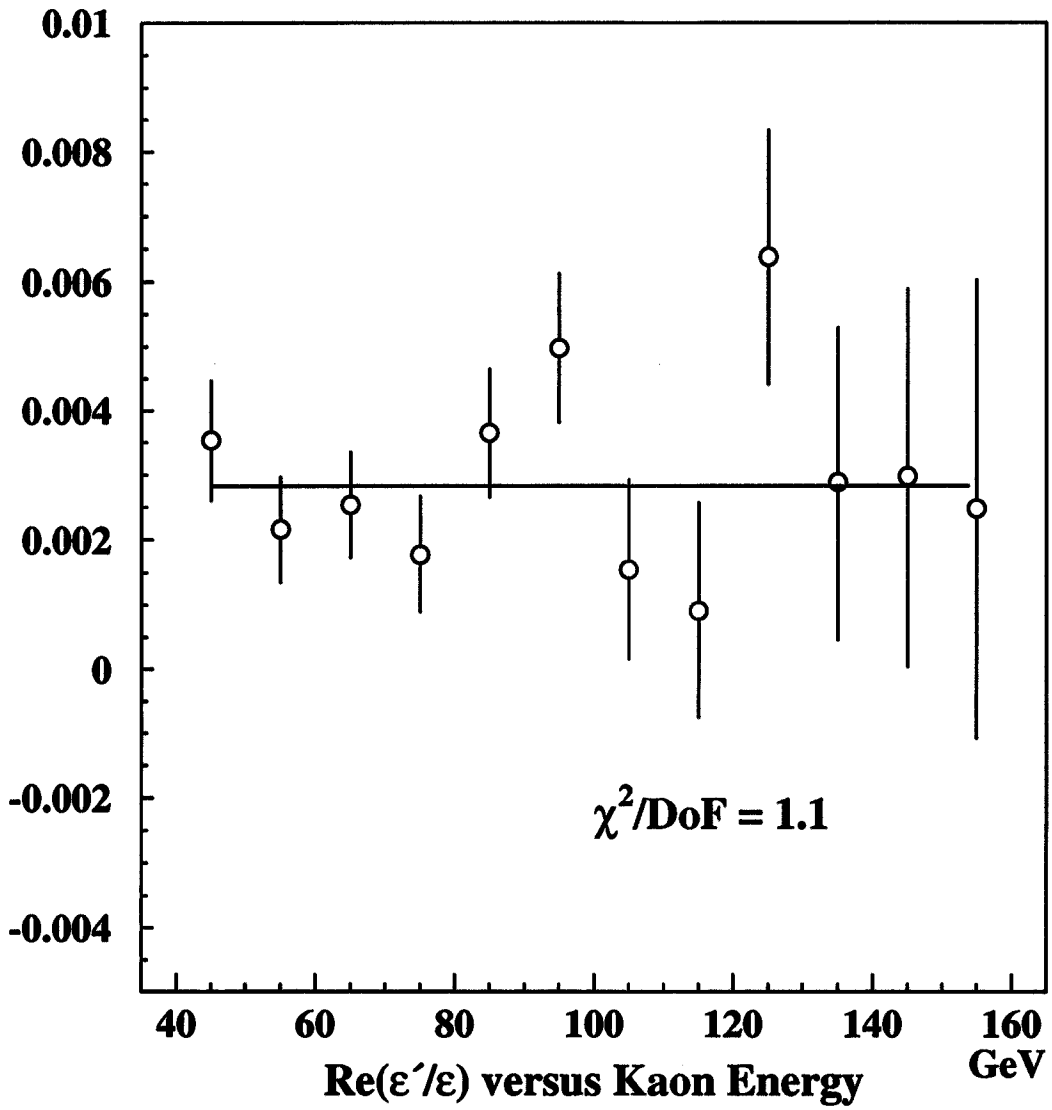
$$= (28.0 \pm 4.1) \times 10^{-4}$$

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

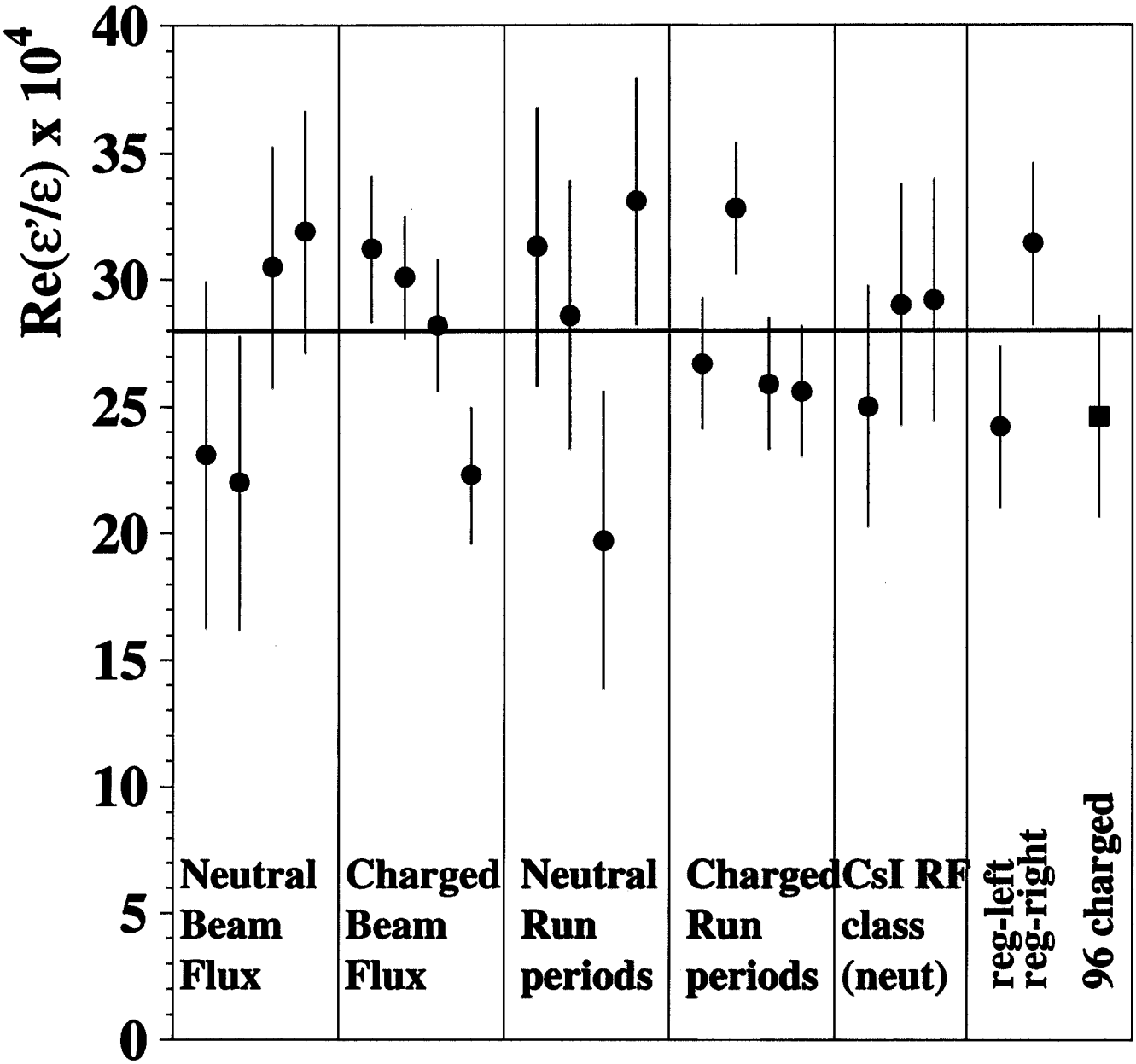


Average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (21.3 \pm 2.8) \times 10^{-4}$ (7.3% c.l.)

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



Cross Checks on Re(ε'/ε) Measurement



Ongoing analysis and datataking

Analysis of remaining ~3/4 of 96/97 data sample is in progress:

- Offline detector calibration almost complete
- Detailed data/Monte Carlo comparisons just beginning.

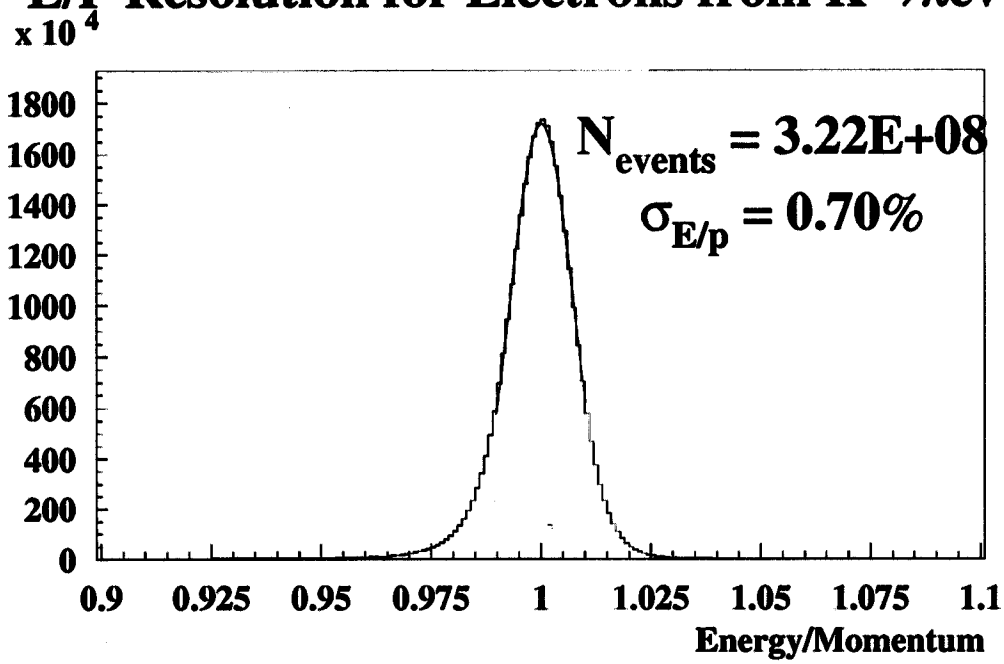
1999 run is going well:

By September, we should collect a data sample equal to the full 96/97 sample with improved systematics.

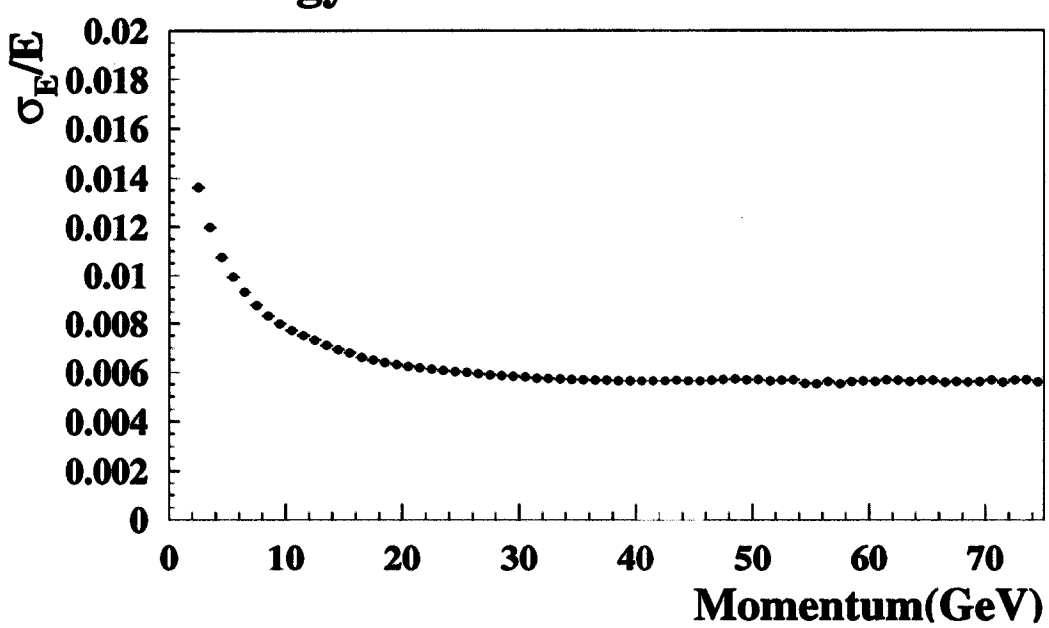
Full KTeV data sample (96+97+99) should reduce statistical uncertainty on $Re(\varepsilon'/\varepsilon)$ to 1×10^{-4}.

1997 CsI Calorimeter Performance

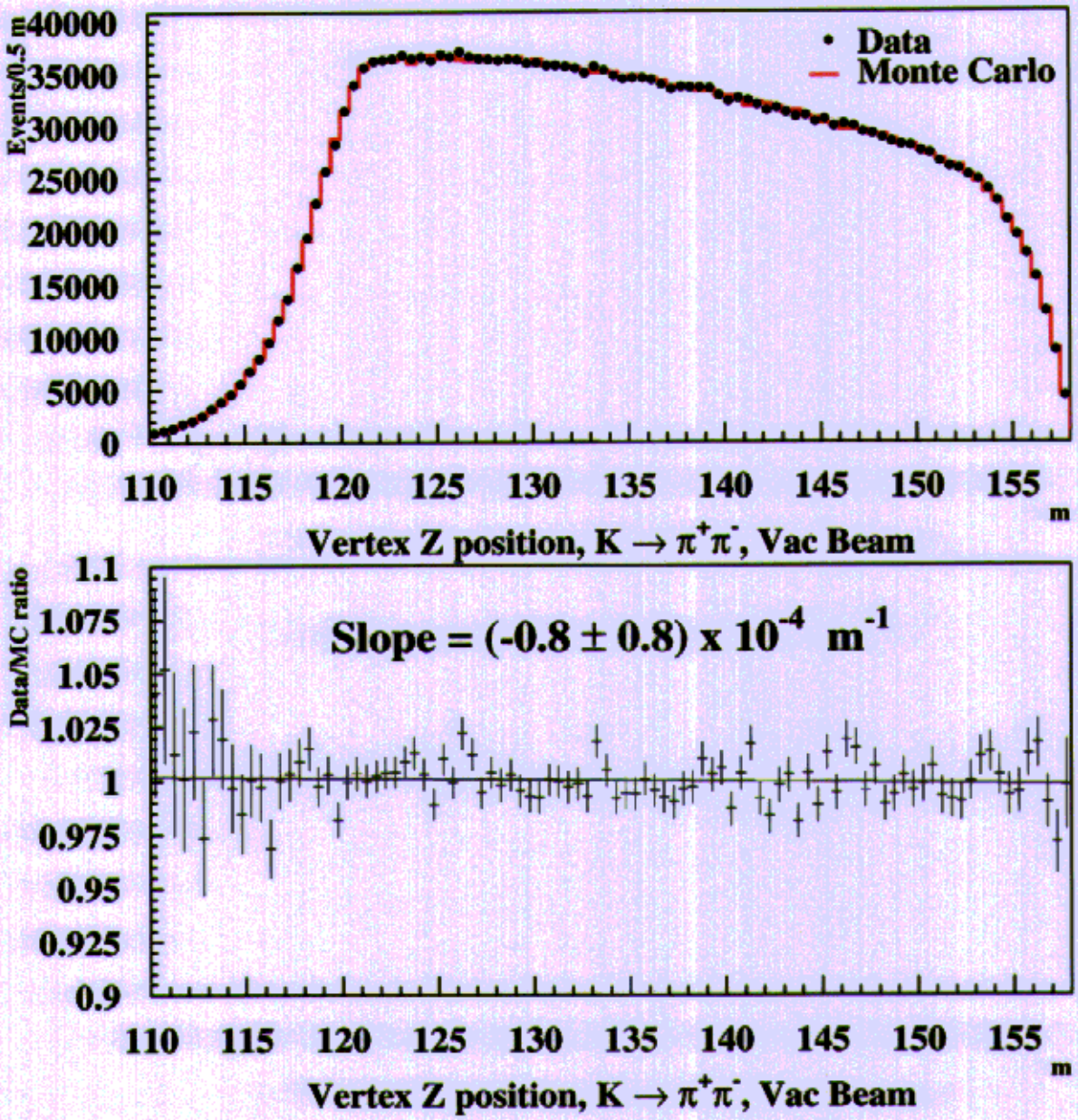
E/P Resolution for Electrons from $K \rightarrow \pi e \nu$

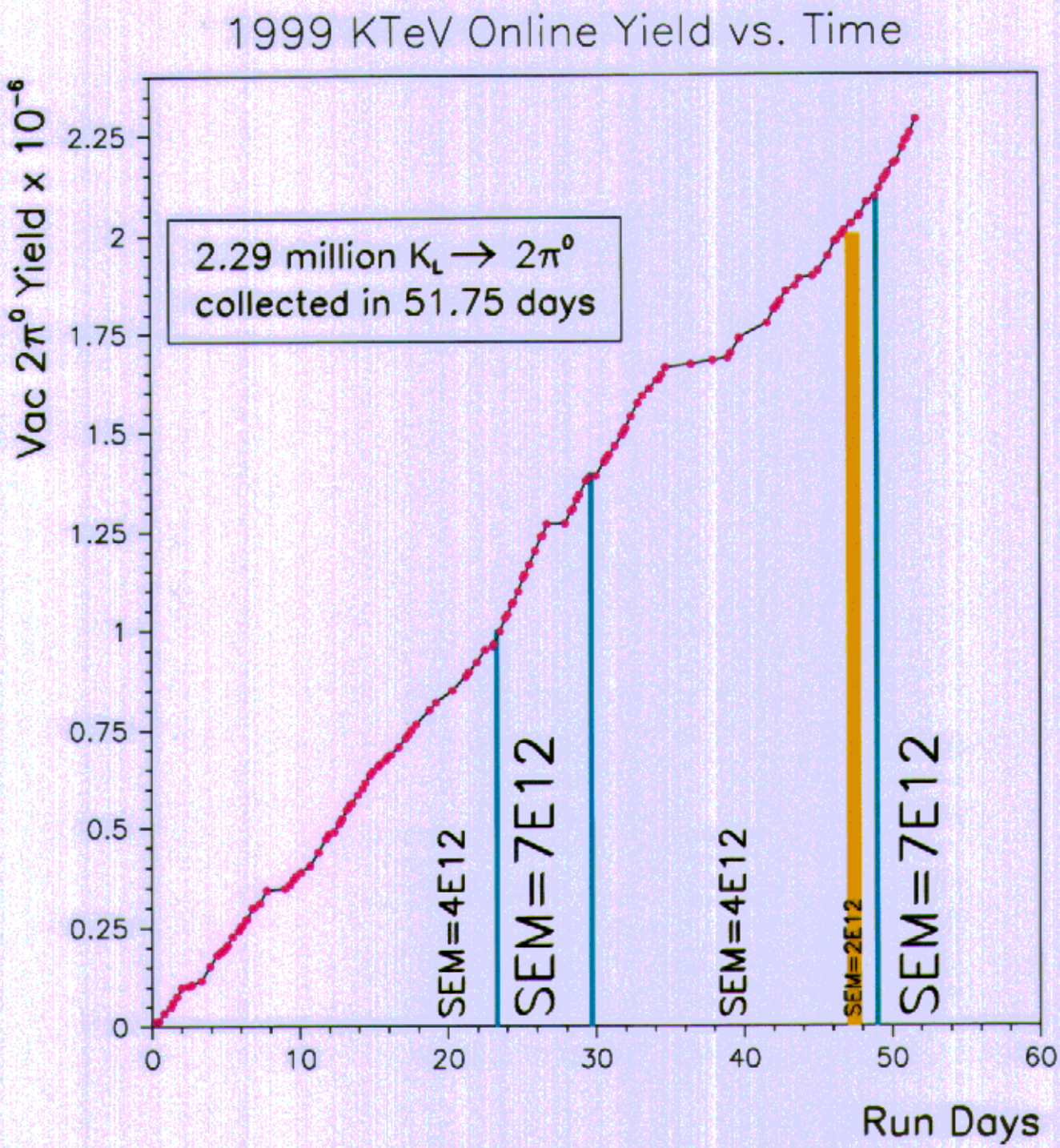


Energy Resolution vs. Momentum

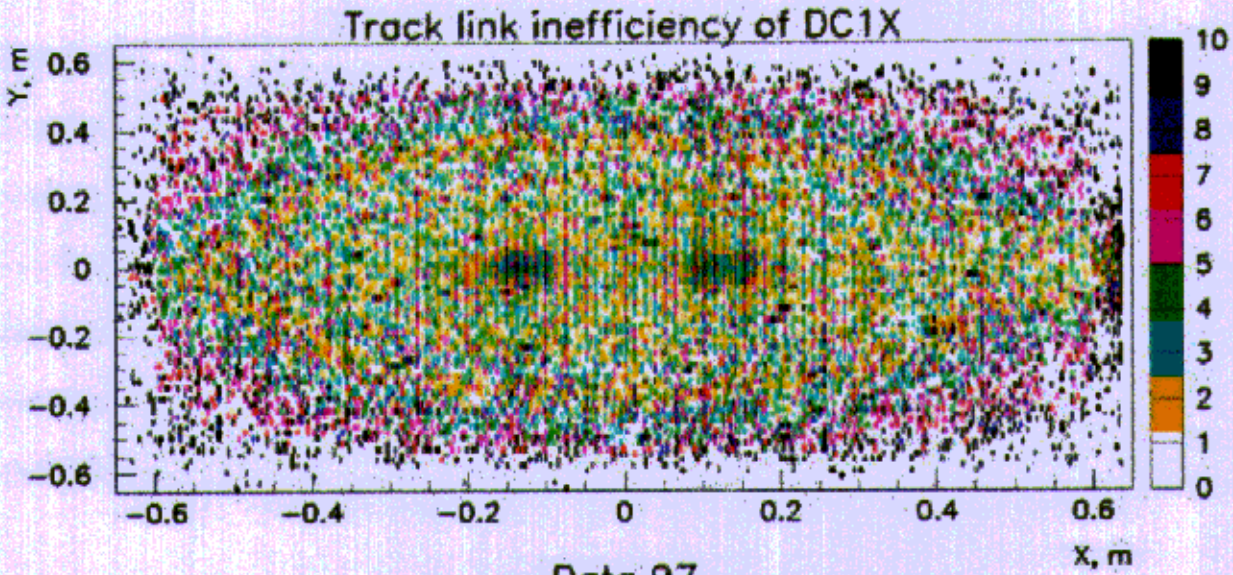


A first look at 1997b $K_L \to \pi^+\pi^-$ (prel.)

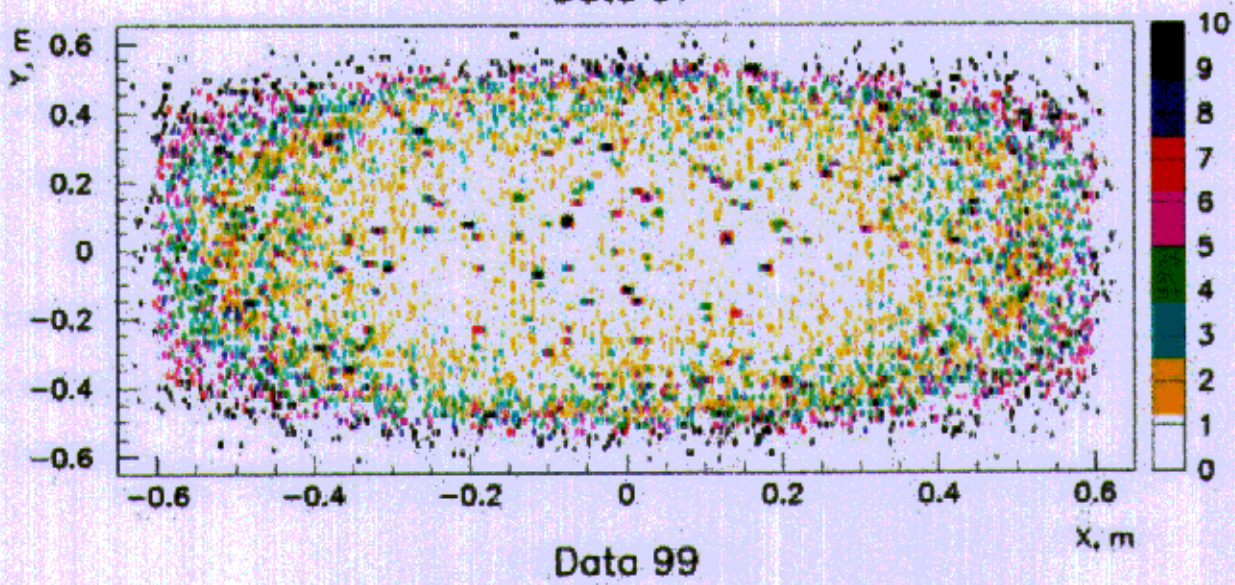



1999 KTeV Online Yield vs. Time
Vac 2π° Yield x 10⁻⁶
2.29 million K_L → 2π°
collected in 51.75 days
SEM=4E12
SEM=7E12
SEM=4E12
SEM=2E12
SEM=7E12
Run Days
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
0
10
20
30
40
50
60

Comparison of 1997 and 1999 Drift Chamber Performance



Data 97



Data 99

Conclusions

KTeV Result: $\mathrm{Re}(\varepsilon'/\varepsilon) = (28.0 \pm 4.1) \times 10^{-4}$

- $\varepsilon'/\varepsilon \neq 0 \Rightarrow$ direct CP violation occurs.
- Rules out Superweak Model as the sole source of CP violation; supports the Standard Model.
- Consistent with earlier evidence for direct CP violation from NA31.
- Full KTeV data sample will reduce the statistical error on ε'/ε to $\sim 1 \times 10^{-4}$

  $\Rightarrow \varepsilon'/\varepsilon$ may be measured to $\pm 5\%$!
- Theory improvement needed to take full advantage of this precision.

  $\Rightarrow$ There is optimism that next round(s) of lattice efforts could reach $\pm 10\%$ level.