# Measurement of Direct CP-Violation in the Neutral Kaon System

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## Outline

1. Introduction
2. The KTeV Detector
3. Data Collection and Analysis Technique
4. Study of Systematic Uncertainties
5. Experimental Results
6. Conclusions

## CP Violation in Long-lived $K_L^0 \longrightarrow \pi^+\pi^-$ decay

$$\Downarrow$$

Weak eigenstates

Short-lived $K_S^0 \equiv K_{even}^0 + \epsilon K_{odd}^0$

Long-lived $K_L^0 \equiv K_{odd}^0 + \epsilon K_{even}^0$

Direct $\Downarrow$ $\Downarrow$ Indirect

$2\pi$ $2\pi$

CP even final state

Direct CP Violation ( $\varepsilon'$)

$$\Longrightarrow \frac{\Gamma(K_L^0 \longrightarrow \pi^+\pi^-)}{\Gamma(K_S^0 \longrightarrow \pi^+\pi^-)} \neq \frac{\Gamma(K_L^0 \longrightarrow \pi^0\pi^0)}{\Gamma(K_S^0 \longrightarrow \pi^0\pi^0)}$$

Indirect CP Violating Parameter:

$|\epsilon| \sim 10^{-3}$

# Kaons at the TeVatron (KTeV)

## KTeV Collaboration

Arizona, UCLA, UCSD, Chicago, Colorado, Elmhurst, Fermilab,
Osaka, Rice, Rutgers, Virginia, Wisconsin

## ULTIMATE Goal of E832 at KTeV

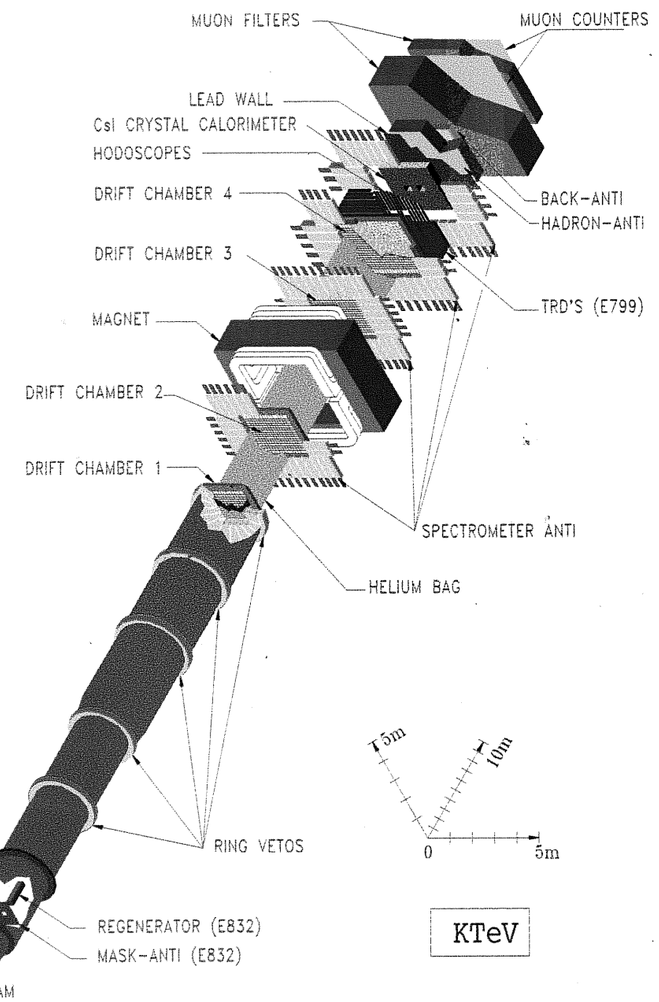
To measure $Re(\frac{\epsilon'}{\epsilon})$ at the $1 \times 10^{-4}$ level.

$$Re(\frac{\epsilon'}{\epsilon}) \sim \frac{1}{6} \left(\frac{\Gamma(K_L^0 \longrightarrow \pi^+\pi^-)/\Gamma(K_S^0 \longrightarrow \pi^+\pi^-)}{\Gamma(K_L^0 \longrightarrow \pi^0\pi^0)/\Gamma(K_S^0 \longrightarrow \pi^0\pi^0)} - 1\right)$$

### Challenges faced in E832

1. Reduction of measurement biases during data-taking
2. Understanding the Detector
3. Understanding of Acceptances
4. Minimization and Determination of Systematic Errors
5. Large Event Sample

# The KTeV Detector




"Vacuum" beam $\rightarrow K_L$ beam

"Regenerator" beam $\rightarrow K_L + \rho K_S$ beam

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

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

96-1128

A $K^0_{L,S} \rightarrow \pi^0\pi^0$ event

$\rightarrow \gamma\gamma$

$\rightarrow \gamma\gamma$

KTEV Event Display

/usr/kpasa/data32/valp/raw2pi0.dat

Run Number: 9730
Spill Number: 1
Event Number: 85227
Trigger Mask: 8
All Slices

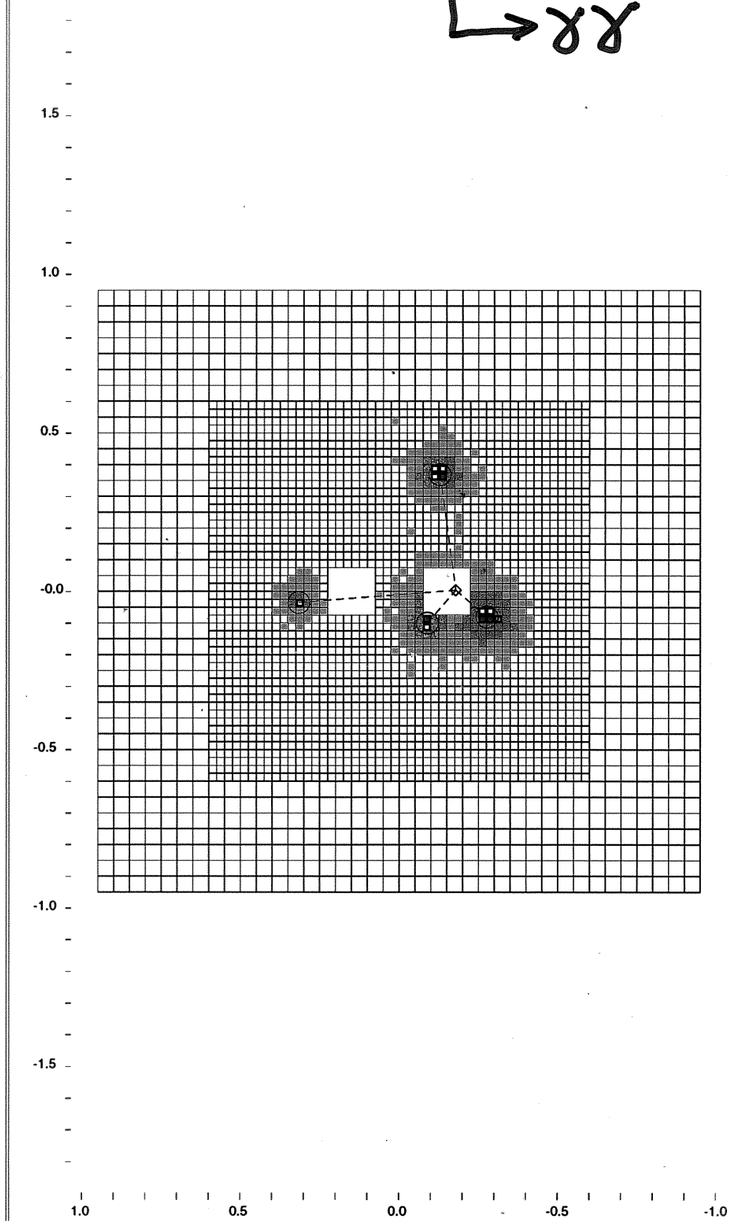
Track and Cluster Info
HCC cluster count: 4

| ID | Xcsi | Ycsi | P or E |
|---|---|---|---|
| C 1: | 0.3160 | -0.0347 | 6.69 |
| C 2: | -0.1291 | 0.3692 | 22.24 |
| C 3: | -0.0886 | -0.1003 | 22.57 |
| C 4: | -0.2761 | -0.0803 | 65.40 |

Vertex: 4 clusters

| X | Y | Z |
|---|---|---|
| -0.1264 | 0.0027 | 132.169 |

Mass=0.4976
Pairing chisq=1.42




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

# A $K^0_L \rightarrow \pi^+\pi^-$ event

KTEV Event Display

/usr/kpasa/data05/shawhan/kzc074_some.dat

Run Number: 9097
Spill Number: 210
Event Number: 40474649
Trigger Mask: 1
All Slices

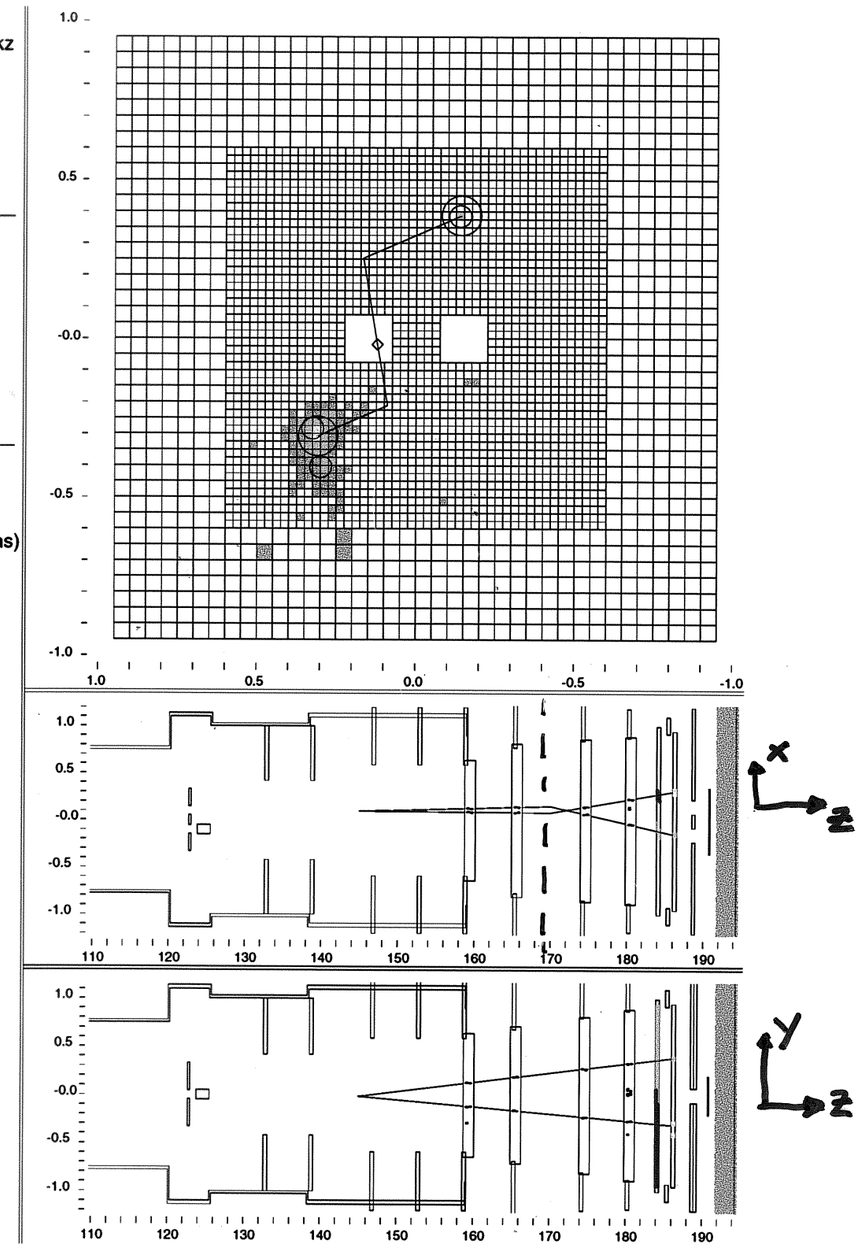
Track and Cluster Info
HCC cluster count: 4

| ID | Xcsi | Ycsi | P or E |
|---|---|---|---|
| T 1: | -0.1418 | 0.3870 | -20.05 |
| C 3: | -0.1379 | 0.3855 | 0.36 |
| T 2: | 0.3079 | -0.3072 | +28.25 |
| C 2: | 0.3248 | -0.2828 | 7.83 |
| C 1: | 0.2993 | -0.4046 | 1.84 |

Vertex: 2 tracks

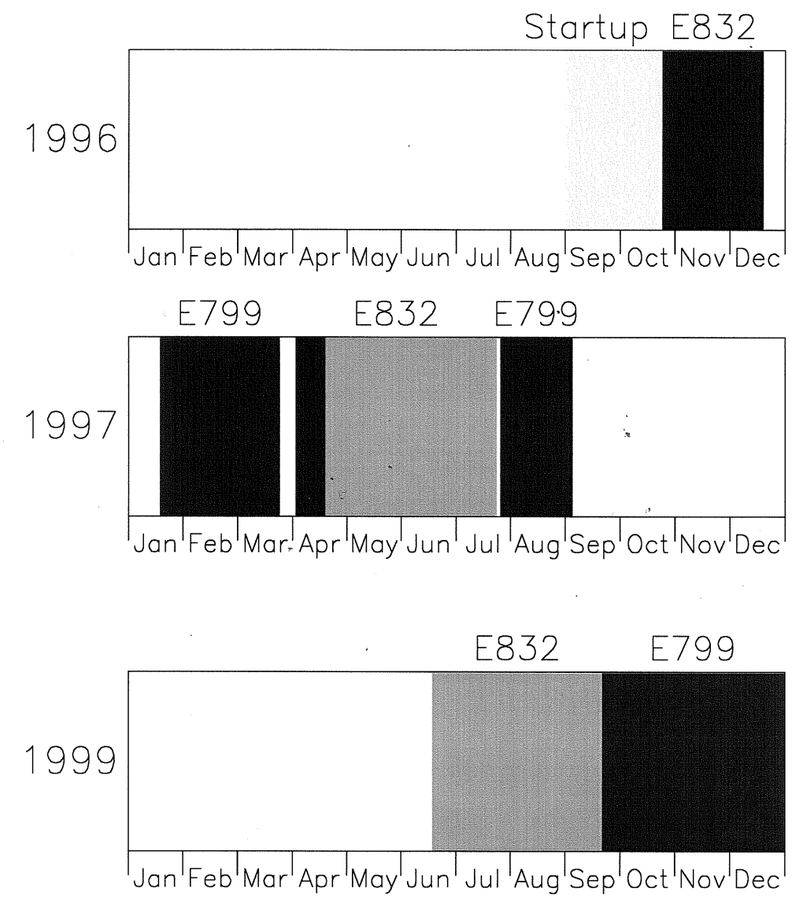
| X | Y | Z |
|---|---|---|
| 0.0952 | -0.0146 | 144.934 |

Mass=0.4970 (assuming pions)
Chisq=0.58 Pt2v=0.000001




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

# Data Taking Periods at the KTeV Experiments

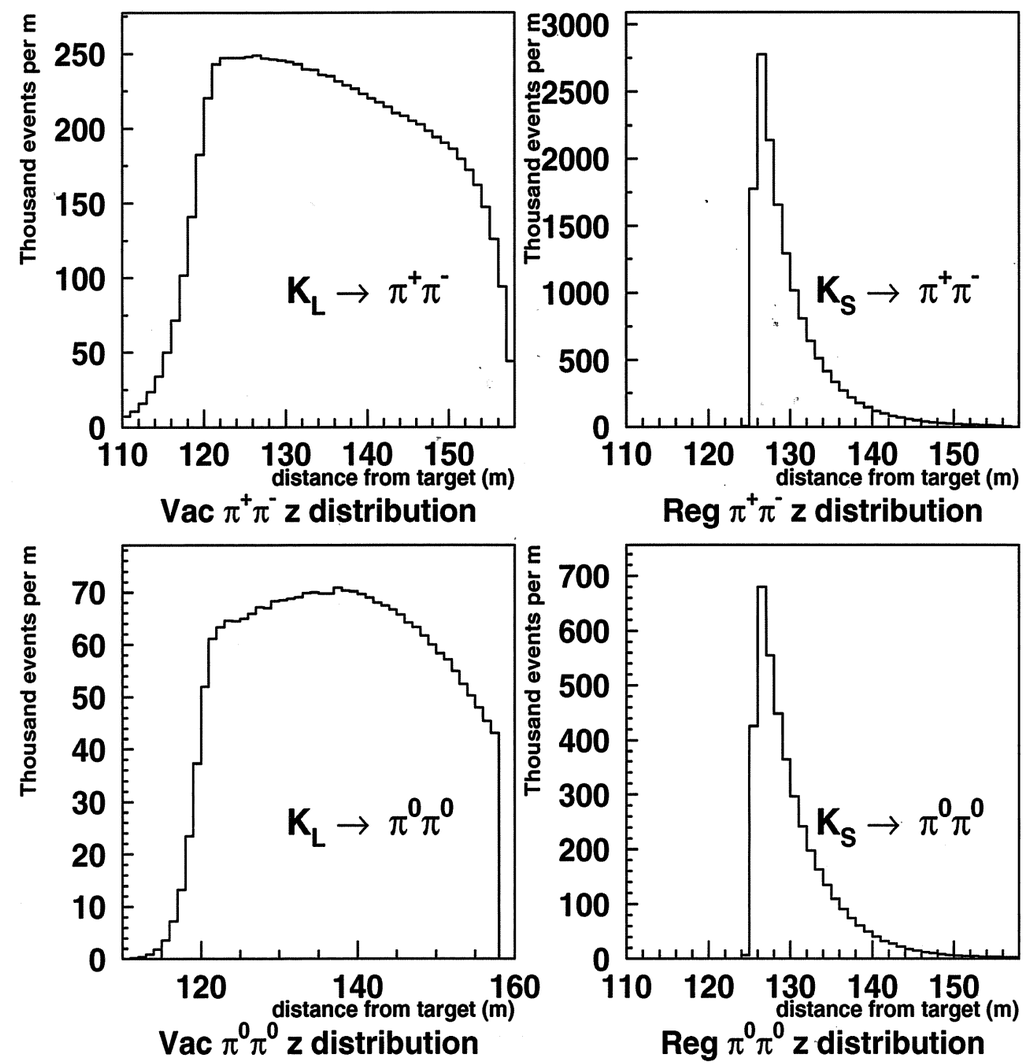



## Published Result (PRD 67, 012005 (2003))

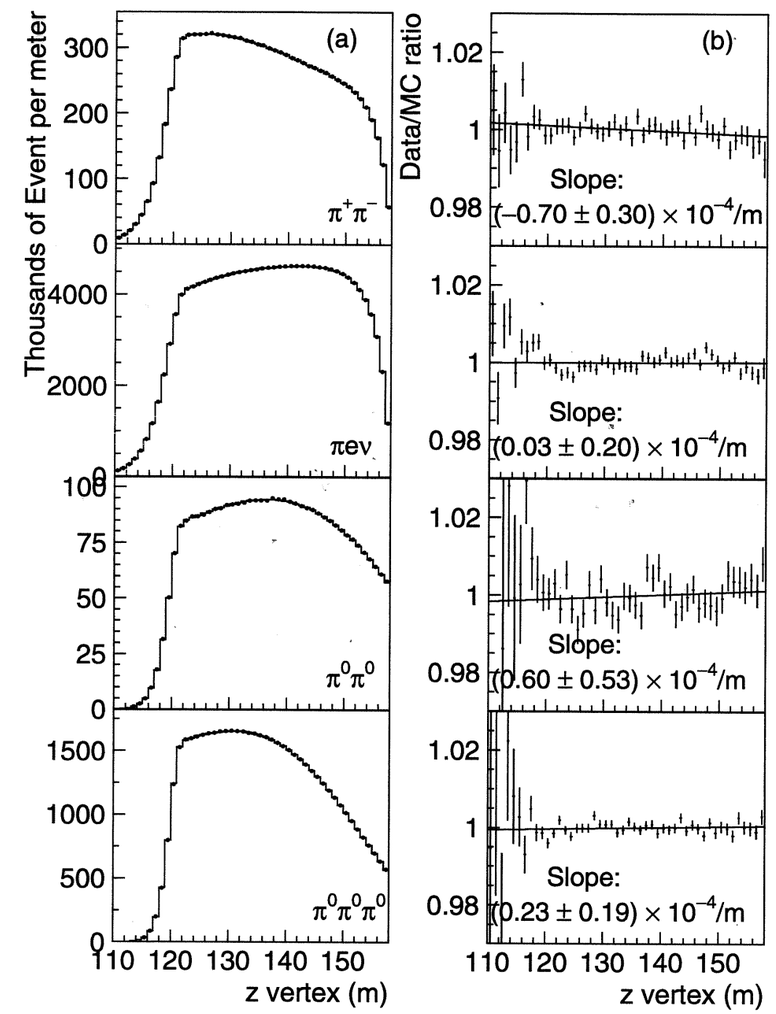
$\pi^+\pi^-$ analysis : 1997 E832 data

$\pi^0\pi^0$ analysis : 1996 and 1997 E832 data

# Reconstructed Vertex Z Distributions in 1997



# Data-MC Acceptance




- Data-MC Slope of
  $0.9 \times 10^{-4} \Rightarrow \Delta Re(\epsilon'/\epsilon) \sim 1 \times 10^{-4}$

## Systematic Uncertainties

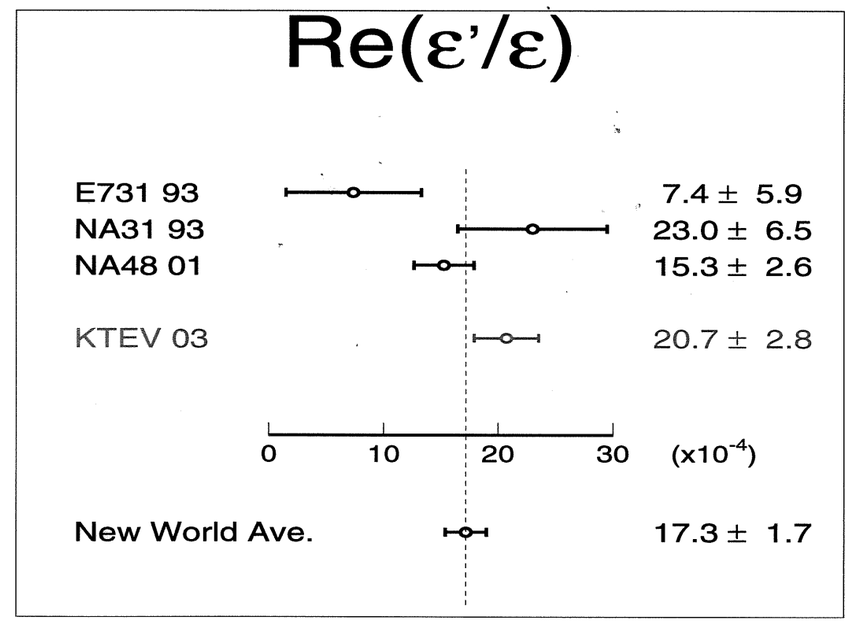
| Source of uncertainty | Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$ | from $\pi^0\pi^0$ |
|---|---|---|
| Class 1: Data collection | | |
| Trigger and level 3 filter | **0.58** | **0.18** |
| Class 2: Event reconstruction, selection, backgrounds | | |
| Energy/Resolution scale | **0.16** | **1.27** |
| Calorimeter nonlinearity | — | **0.66** |
| Detector calib, align | **0.28** | **0.35** |
| Analysis cut variations | **0.25** | **0.37** |
| Background subtraction | **0.20** | **1.07** |
| Class 3: Detector acceptance | | |
| Limiting apertures | **0.30** | **0.48** |
| Detector resolution | **0.15** | **0.08** |
| Drift chamber simulation | **0.37** | — |
| $z$ dependence | **0.79** | **0.39** |
| Class 4: Kaon flux and physics parameters | | |
| Reg-beam attenuation | **0.19** | |
| $\Delta m$, $\tau_S$ | **0.11** | |
| Reg phase screening | **0.22** | |
| TOTAL | **2.32** | |

# KTeV Measurement of $Re(\epsilon'/\epsilon)$

$$
\begin{aligned}
Re(\epsilon'/\epsilon) &= (20.7 \pm 1.5(stat) \pm 0.6(MC) \pm 2.3(syst)) \times 10^{-4} \\
&= (20.7 \pm 2.8) \times 10^{-4}
\end{aligned}
$$

## Comparison of KTeV Result to Other $Re(\epsilon'/\epsilon)$ Measurements

$$\text{KTeV}: \quad Re(\epsilon'/\epsilon) = \quad (20.7 \pm 2.8) \times 10^{-4}$$
$$\text{NA48}: \quad Re(\epsilon'/\epsilon) = \quad (15.3 \pm 2.6) \times 10^{-4}$$




$$\text{World Ave. } Re(\epsilon'/\epsilon) \quad = \quad 17.3 \pm 1.7 \times 10^{-4}$$
$$\text{Probability} \quad = \quad 13\%$$

## Some Theoretical Predictions of $Re(\frac{\epsilon'}{\epsilon})$

| | |
|---|---|
| Munich 2000 | $7.7^{+6.0}_{-3.5} \times 10^{-4}$ |
| Rome 2001 | $4.6^{+7.7}_{-7.2} \times 10^{-4}$ |
| Trieste 2001 | $22 \pm 8 \times 10^{-4}$ |
| Valencia 2001 | $17 \pm 9 \times 10^{-4}$ |
| RIKEN-BNL 2001 | $-4.0 \pm 2.3 \times 10^{-4}$ |

# Current $\varepsilon'/\varepsilon$ Analysis

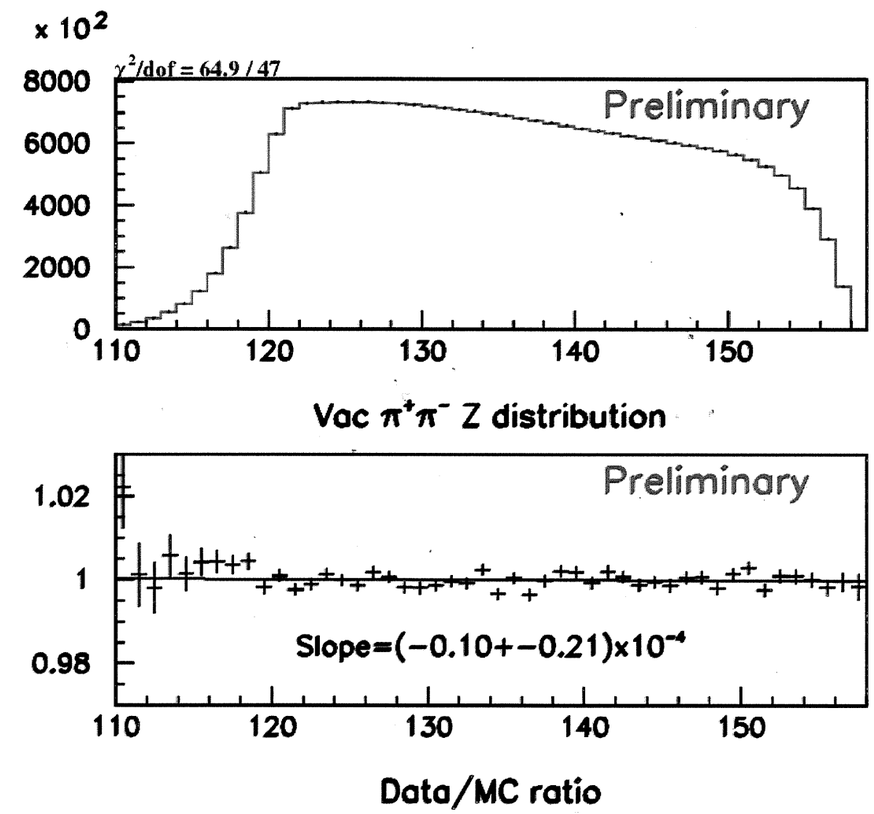
| | Vacuum beam ($K_L$) | | Reg. Beam ("$K_S$") | | |
|---|---|---|---|---|---|
| | $\pi^+\pi^-$ ($\times 10^6$) | $\pi^0\pi^0$ ($\times 10^6$) | $\pi^+\pi^-$ ($\times 10^6$) | $\pi^0\pi^0$ ($\times 10^6$) | $\sigma(\varepsilon'/\varepsilon)_{stat}$ ($\times 10^{-4}$) |
| 96+97 | 11.2 | 3.4 | 19.4 | 5.6 | 1.5 |
| ~ 1999 | 14.9 | 3.7 | 25.8 | 6.1 | 1.4 |
| ~ 96-99 | 26.1 | 7.1 | 45.2 | 11.7 | 1.0 |

Improvement in systematics needed to take advantage of increase in statistics.

- Full treatment of photon angles in simulation and reconstruction: E scale, E nonlinearity
- Better treatment of nearby and overlapping clusters: E scale, E nonlinearity
- √ Better modeling of fringe field: calorimeter calibration, E nonlinearity
- √ Improved drift chamber alignment: calorimeter calibration, E nonlinearity
- √ Improved simulation of delta rays: $p_t$ distribution, neutral background estimate
- √ Better drift chamber performance (99) and track reconstruction: mass resolution improved by ~10%.

# $K_L \rightarrow \pi^+\pi^-$ Data / Monte Carlo Comparison

(full KTeV data sample)



## Conclusions

$$\mathrm{Re}(\epsilon'/\epsilon) \quad = \quad (20.7 \pm 1.6(stat) \pm 2.3(syst)) \times 10^{-4}$$

- Combined with CERN results, $Re(\epsilon'/\epsilon)$ has been measured at the 10% level.
- Direct CP-Violation has been unambiguously observed by both experiments.
- Matter and Antimatter **DO** decay differently!
- Still exciting times ahead in the study of CP Violation.