31st INTERNATIONAL CONFERENCE ON
HIGH ENERGY PHYSICS AMSTERDAM

KTEV
Kaons at the Tevatron

Recent Results from KTeV

Tony Barker
University of Colorado, Boulder

Outline

- ▷ Overview of KTeV Experiments
- ▷ Re(ϵ'/ϵ) Results and Status
- ▷ $K_L \to \gamma^*\gamma^*$ Modes
- ▷ Lepton Flavor Violation Limits
- ▷ Rare Decays and CP Violation

KTeV Project Overview

- Two related experiments collected data in 1996–1997 and again in 1999–2000:

▷ E832: Precision Measurement of Re(ϵ'/ϵ)

▹ This experiment uses two parallel kaon beams. K-short mesons are produced by an Active Regenerator consisting of about two meters of scintillating plastic, which moves back and forth periodically between the two beams. K-long and K-short decays are detected simultaneously to reduce systematic errors.

▹ The analysis searches for two-pion decays in each beam. Epsilon-prime is extracted by comparing the two CP-violation parameters η_{+-} and η_{00}, which are determined from $\pi^+\pi^-$ and $\pi^0\pi^0$ decays, respectively.

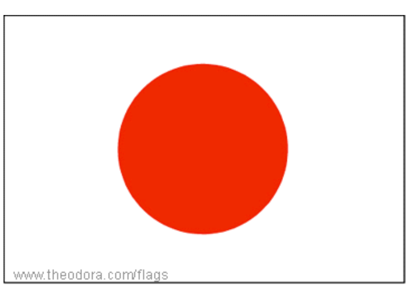
▷ E799-II: Search for Rare K_L^0 Decays

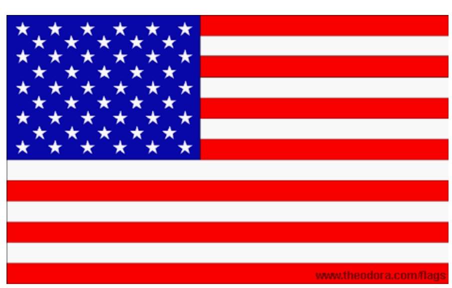
▹ In this experiment, there is no regenerator. The beam intensity is increased, and the analysis searches for a variety of interesting rare decays. Backgrounds from particle misidentification are more important than in E832; these are greatly suppressed by adding a set of Transition Radiation Detectors to the apparatus.

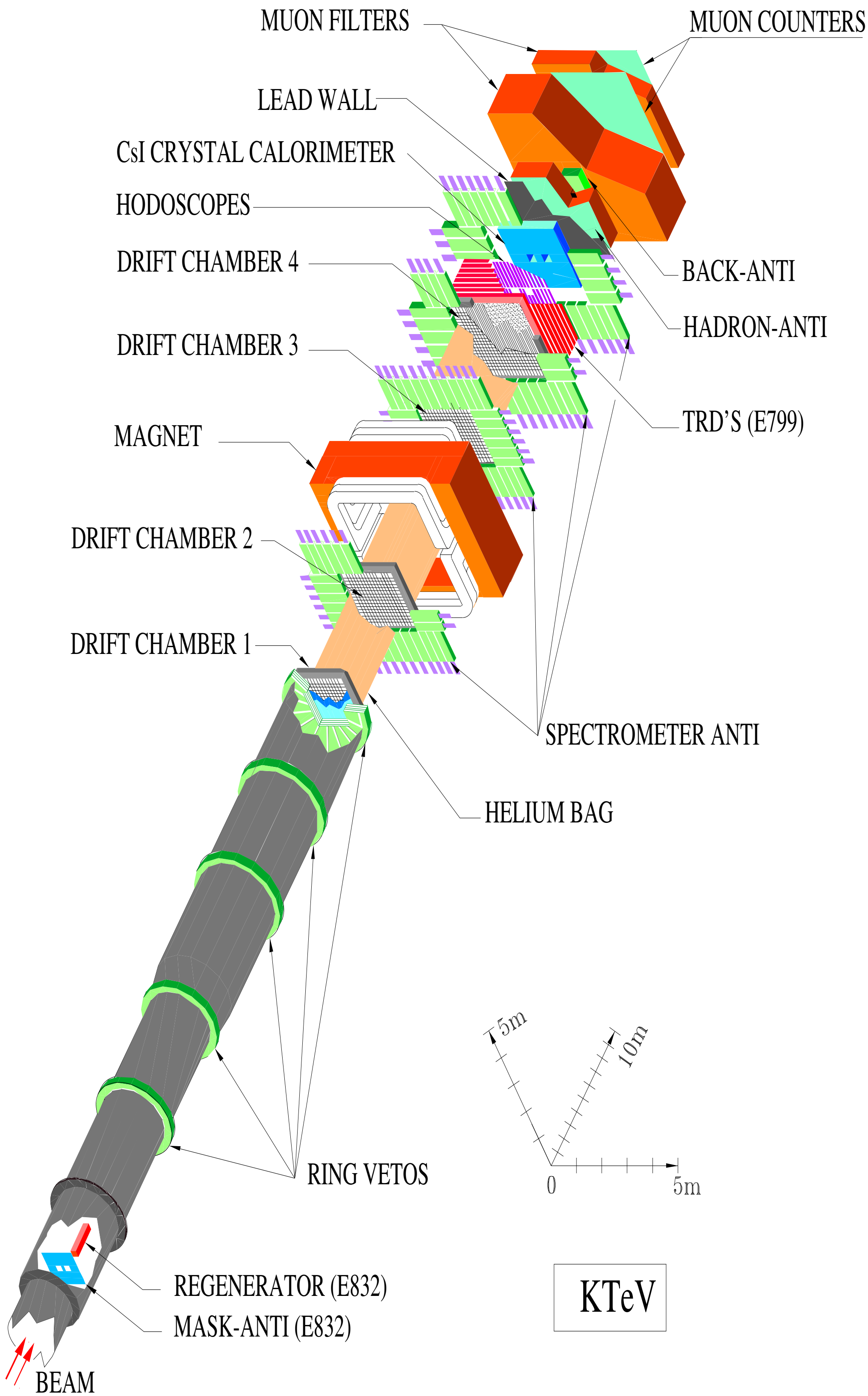
▹ Of particular interest are the decays $K_L^0 \to \pi^0 l\bar{l}$, where $l\bar{l}$ represents a lepton pair: either electrons, muons, or neutrinos. In the Standard Model, the rates for these decays are sensitive to direct CP-Violating amplitudes related to those responsible for a non-zero value of epsilon-prime.

KTeV Collaborating Institutions in 2000

- ▷ University of Arizona
- ▷ University of California, Los Angeles
- ▷ University of California, San Diego
- ▷ University of Campinas, Brazil
- ▷ The University of Chicago
- ▷ University of Colorado, Boulder
- ▷ Elmhurst College
- ▷ Fermi National Accelerator Laboratory
- ▷ Osaka University, Japan
- ▷ Rice University
- ▷ University of Sao Paulo, Brazil
- ▷ University of Virginia
- ▷ University of Wisconsin, Madison






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

Measurement of Re(ϵ'/ϵ)

▷ Assuming CPT symmetry, the mixing between K^0 and $\overline{K}^0$ is described by a single complex parameter ϵ:

$$\begin{aligned} |\, K_S^0\rangle &= \frac{1}{\sqrt{(1+|\epsilon|^2)}}\Big(|\, K_1^0\rangle + \epsilon\,|\, K_2^0\rangle\Big) \\ |\, K_L^0\rangle &= \frac{1}{\sqrt{(1+|\epsilon|^2)}}\Big(|\, K_2^0\rangle + \epsilon\,|\, K_1^0\rangle\Big) \end{aligned}$$

▷ The best present measurements give

$$\begin{aligned} |\epsilon| &= (2.269 \pm 0.023) \times 10^{-3} \\ \phi_\epsilon &= (44.3 \pm 0.8)^\circ \end{aligned}$$

▷ CP violation in $\pi\pi$ decays of the K_L can be *indirect* (through CP-conserving decays of its small K_1 component) or *direct* (through CP-violating decays of its large K_2 component).

▷ The signal for direct CPV is a difference between the ratio of $\pi^0\pi^0$ to $\pi^+\pi^-$ decays for the K_L compared to that for the K_S.

Measurement of Re(ϵ'/ϵ)

▷ By fitting the acceptance-corrected distributions of K_L and K_S decays as a function of momentum and decay vertex position in E832, the amplitude ratios η_{00} and η_{+-} can be extracted:

$$\eta_{00} = \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)}$$
$$\eta_{+-} = \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)}$$

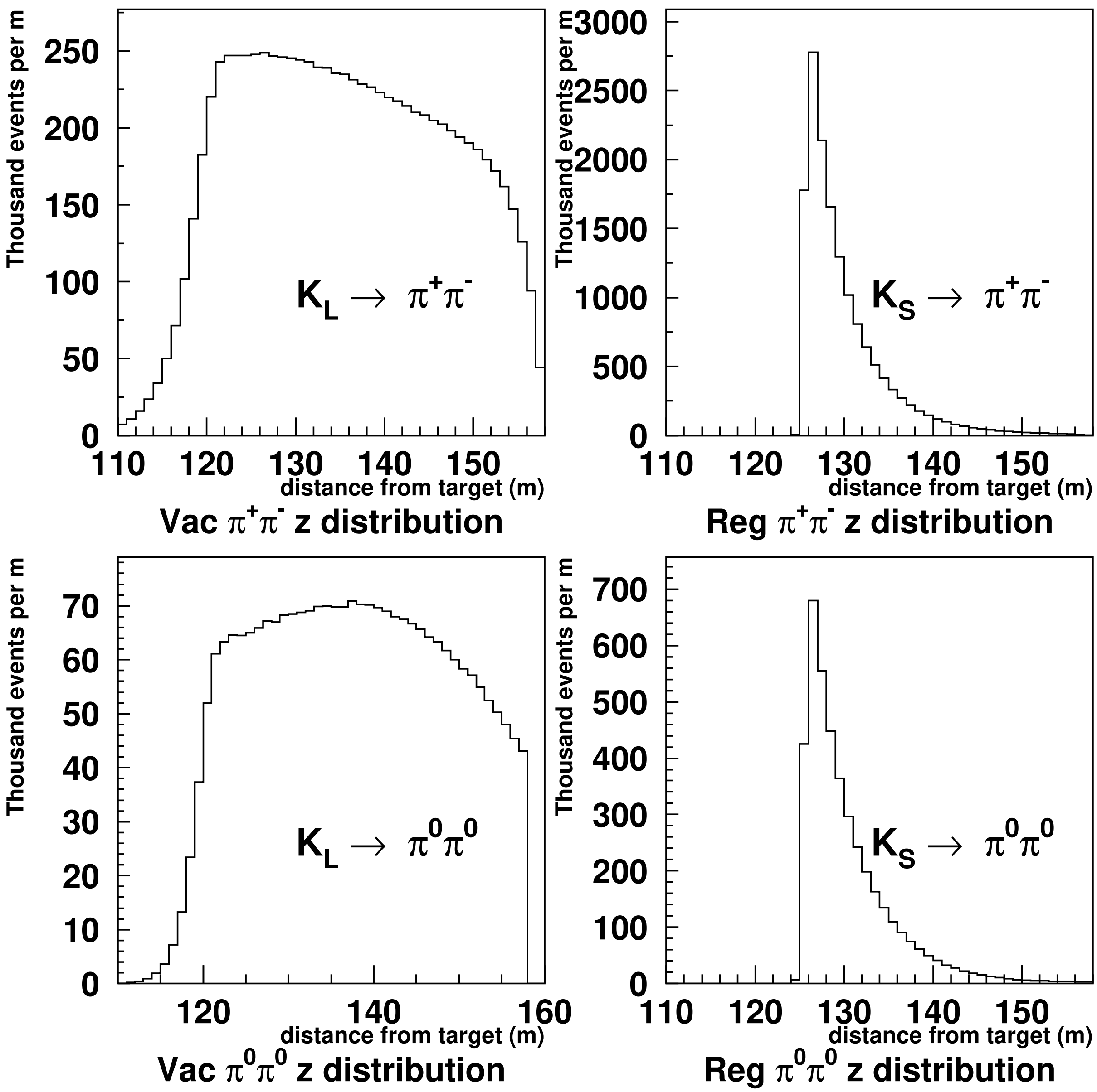
▷ These ratios are related to the direct CPV parameter ϵ' by the (approximate) relations

$$\eta_{00} \approx \epsilon - 2\,\epsilon'$$
$$\eta_{+-} \approx \epsilon + \epsilon'$$

▷ Thus we obtain

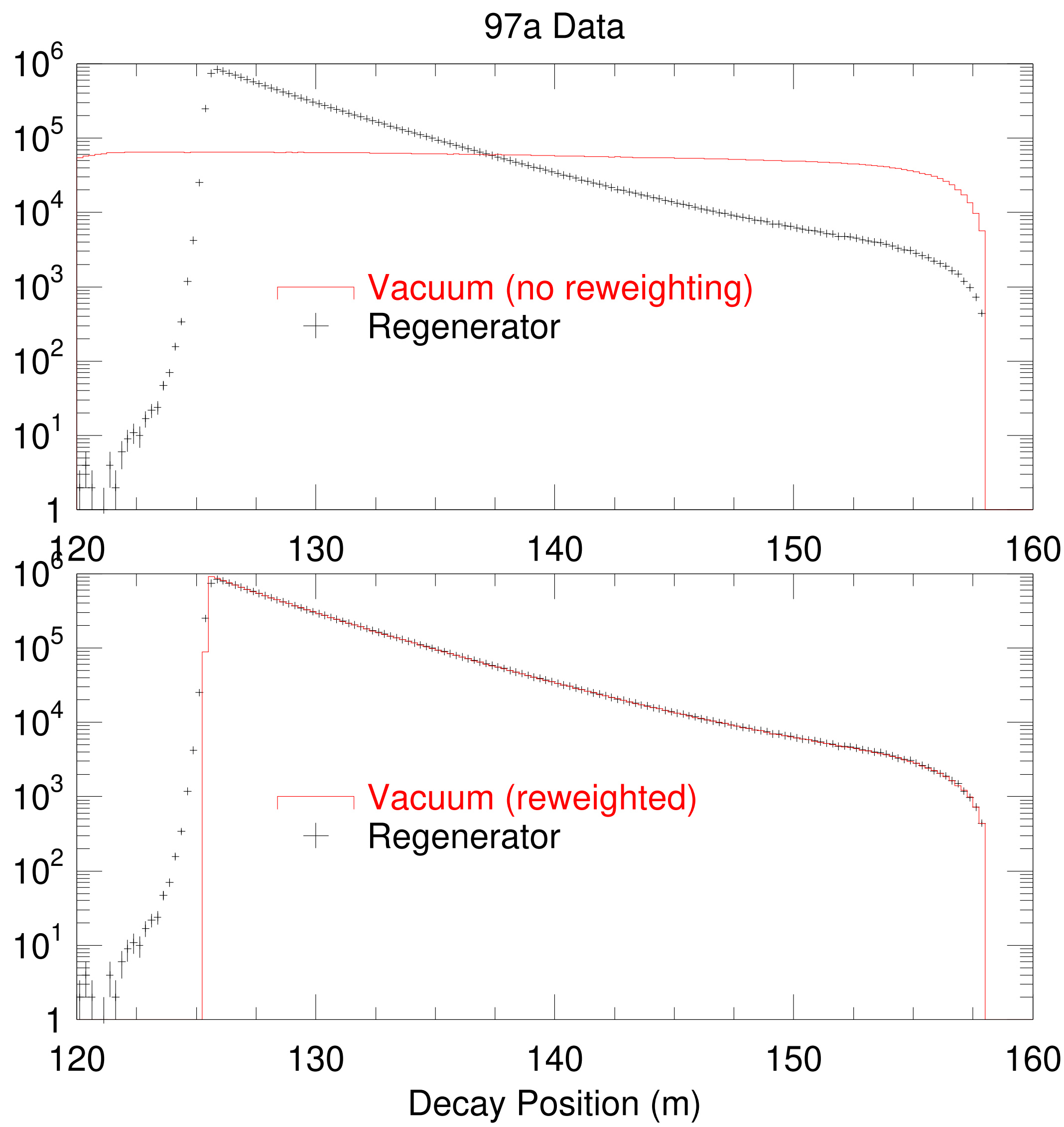
$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \approx \frac{1}{6}\left(1 - \frac{|\eta_{00}|^2}{|\eta_{+-}|^2}\right)$$

Measurement of Re(ϵ'/ϵ)



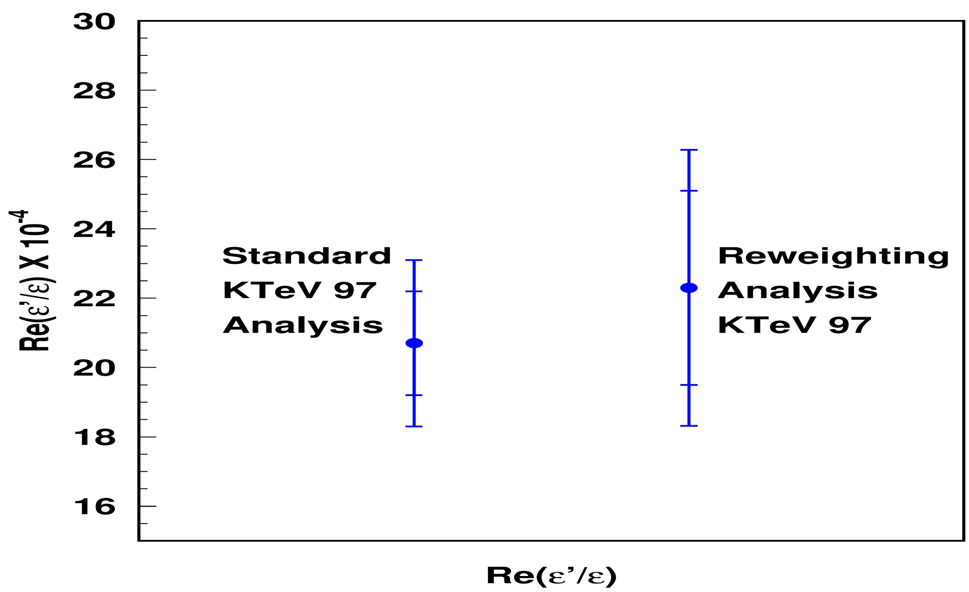
The observed decay vertex distributions for the four $K_{L,S} \to \pi\pi$ modes. The regenerator is at approximately 125 meters.

Measurement of Re(ϵ'/ϵ)



As a cross-check of our primary result, we have recently performed the extraction of Re(ϵ'/ϵ) using the NA48-style z-reweighting technique. This eliminates acceptance corrections at the cost of reduced statistical power.

Comparison of Results for $\mathrm{Re}(\epsilon'/\epsilon)$



Result of the KTeV Standard Analysis of all 1996-97 E832 data:

$$(20.7 \pm 1.5(\mathrm{stat}) \pm 2.4(\mathrm{syst}) \pm 0.5(\mathrm{MC\ stat})) \times 10^{-4}$$

Uncorrelated difference vs Reweighting Analysis:

$$\Delta = (1.5 \pm 2.1(\mathrm{stat}) \pm 3.0(\mathrm{syst})) \times 10^{-4}$$

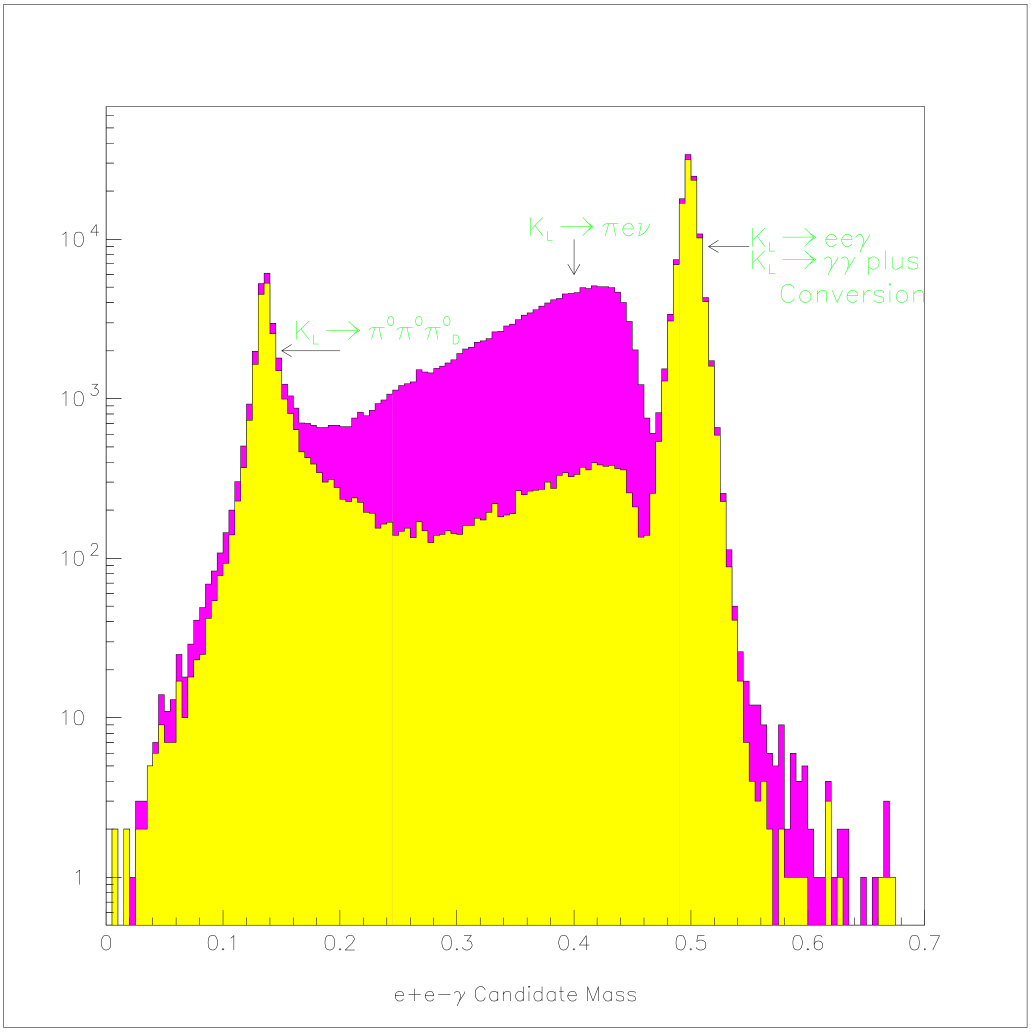
Current NA48 Overall Result (Blois 2002):

$$(14.7 \pm 2.2) \times 10^{-4}$$

Difference NA48 vs KTeV: $(6.0 \pm 3.6) \times 10^{-4}$

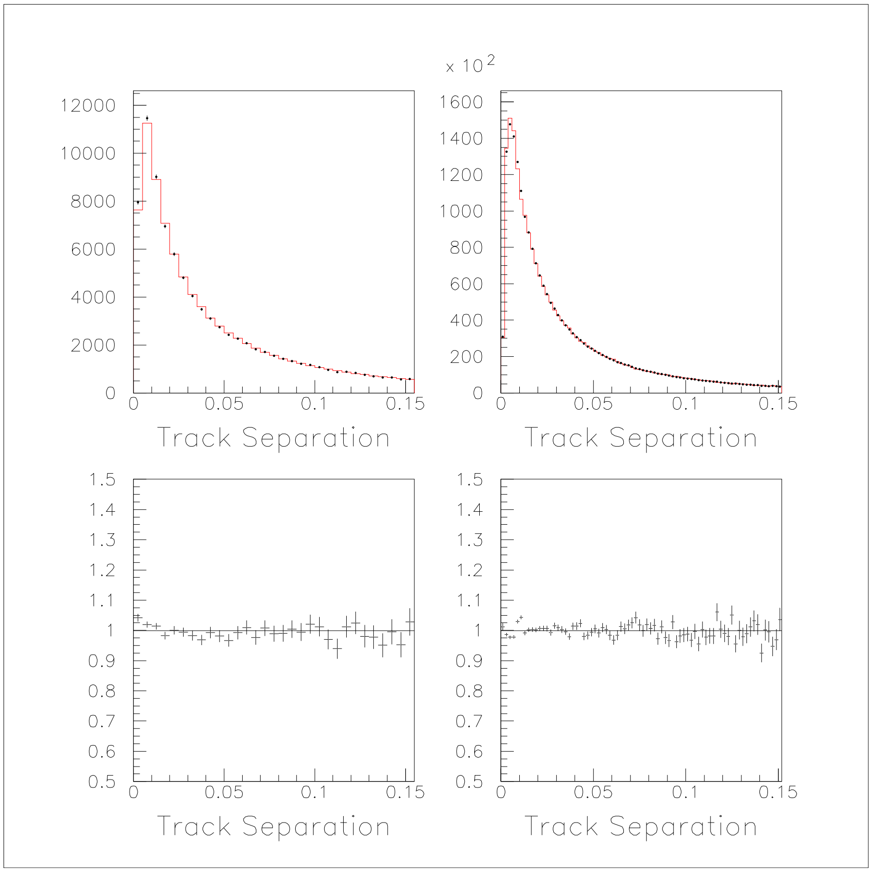
2002 World Avg: $\mathrm{Re}(\epsilon'/\epsilon) = (16.6 \pm 1.6) \times 10^{-4}$

Measurement of $K_L \to e^+e^-\gamma$



- ▷ TRD particle identification is used to reject backgrounds involving misidentified charged pions.
- ▷ A cut requiring track separation of 1.5 mm rejects essentially all external conversion backgrounds.
- ▷ In the 1997 data, KTeV has identified 93,383 $K_L \to e^+e^-\gamma$ candidate events, over a background estimated to be less than 0.1% after these cuts.

Measurement of $K_L \to e^+e^-\gamma$



Signal Channel Normalization Channel

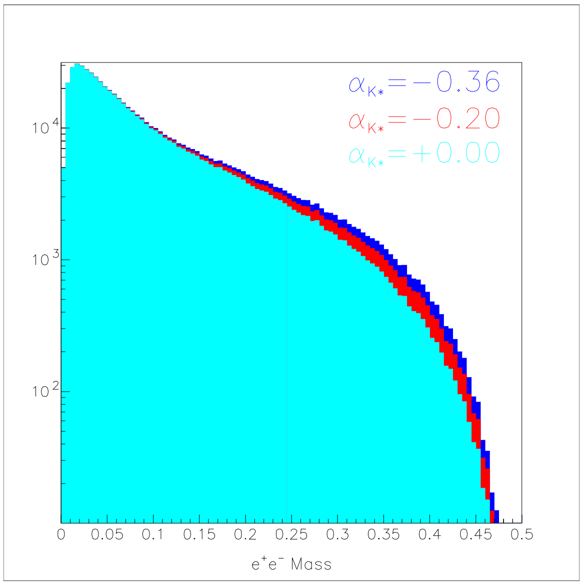
- It is critical to have a good understanding of tracking performance for close pairs of tracks to accurately determine the acceptance for $K_L \to e^+e^-\gamma$.

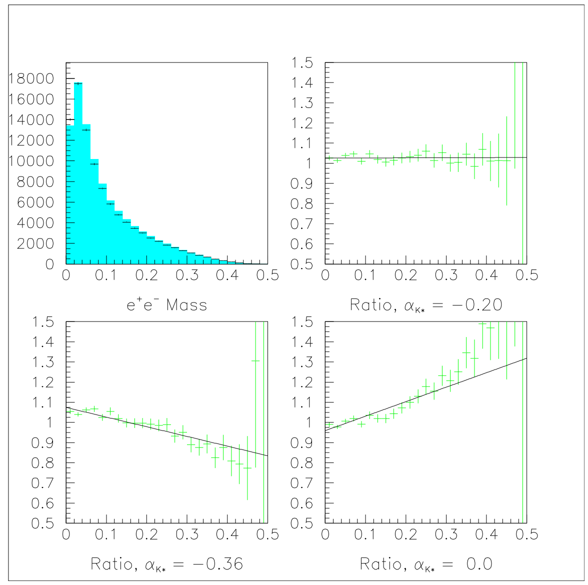
- The branching ratio is determined to be

$$B(K_L \to e^+e^-\gamma) = (10.13 \pm 0.04(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \pm 0.29(\mathrm{norm})) \times 10^{-6}$$

- The uncertainty is dominated by the uncertainty in the branching fraction for the normalization mode, $K_L \to \pi^0\pi^0\pi^0$ with two $\pi^0 \to e^+e^-\gamma$ decays.

Measurement of $K_L \to e^+e^-\gamma$

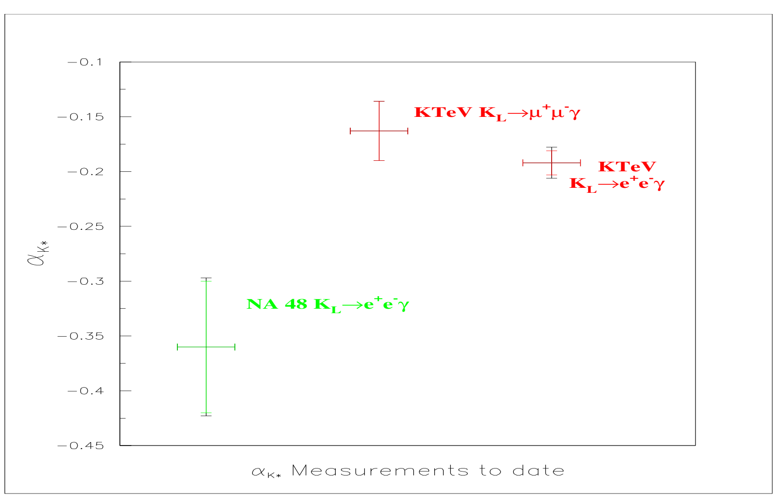




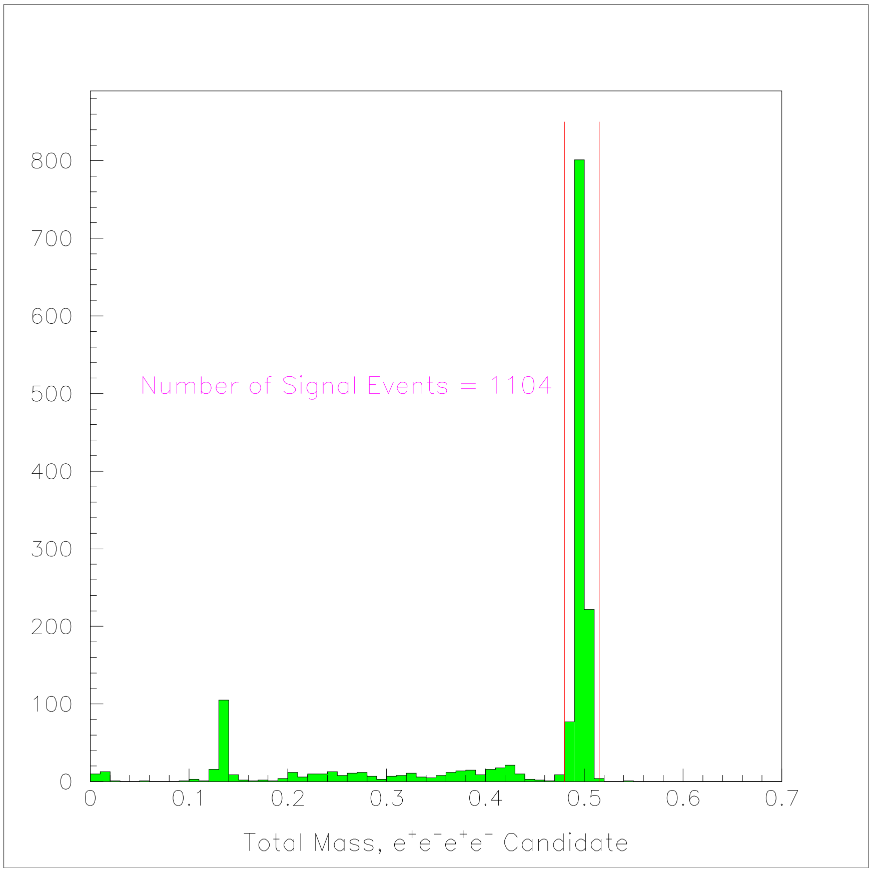
- The M_{ee} spectrum can be used to extract a fit for the $K_L\gamma\gamma^*$ form factor shape. We find for the BMS parameter α_{K^*} the value

$$\alpha_{K^*} = -0.192 \pm 0.011 \pm 0.009$$

- This result is in mild disagreement with the previous NA48 result of -0.36 ± 0.06 but agrees with the value -0.160 ± 0.027 found in the KTeV analysis of $K_L \to \mu^+\mu^-\gamma$.



Measurement of $K_L \to e^+e^-e^+e^-$

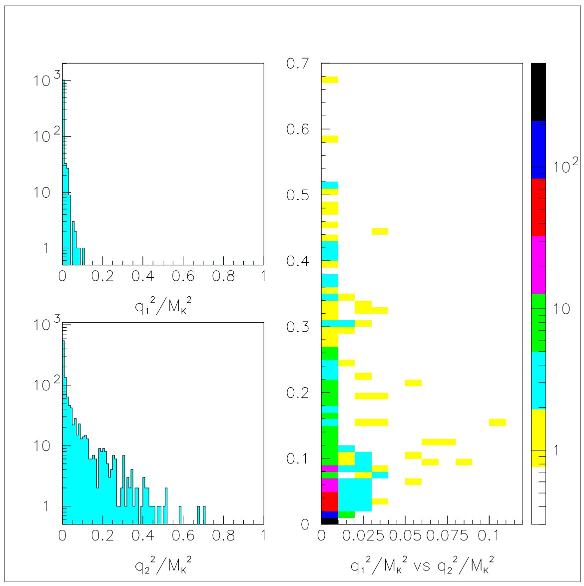


- ▷ We have published an analysis of the 441 $K_L \to e^+e^-e^+e^-$ events observed in the 1997 KTeV data. We determined

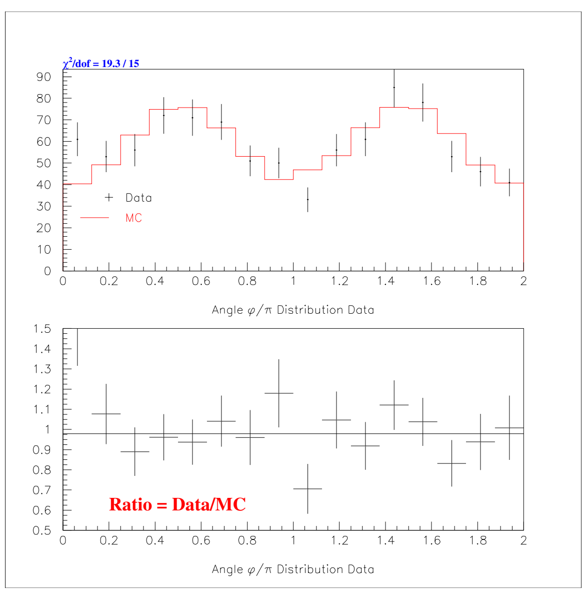
$$BR(K_L \to e^+e^-e^+e^-) = (3.72 \pm 0.18 \pm 0.23) \times 10^{-8}$$

- ▷ In the full KTeV dataset, we have over 1100 examples of this decay, with negligible background. Analysis of these data is underway.

Measurement of $K_L \to e^+e^-e^+e^-$

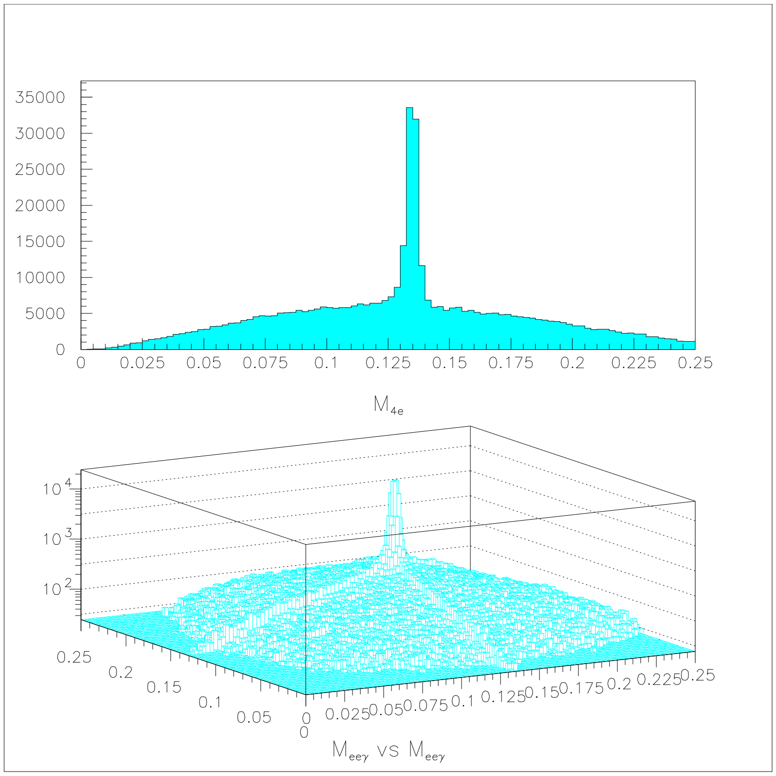


▷ We will extract the $K_L\gamma^*\gamma^*$ form factor from the M_{ee} distributions for this sample of 1,100 K_L Double Dalitz decays.



▷ We can also place a limit on CP-violating $K_L\gamma^*\gamma^*$ decays by studying the distribution of the angle ϕ between the two e^+e^- planes in the K_L rest frame.

Measurement of $\pi^0 \to e^+e^-e^+e^-$

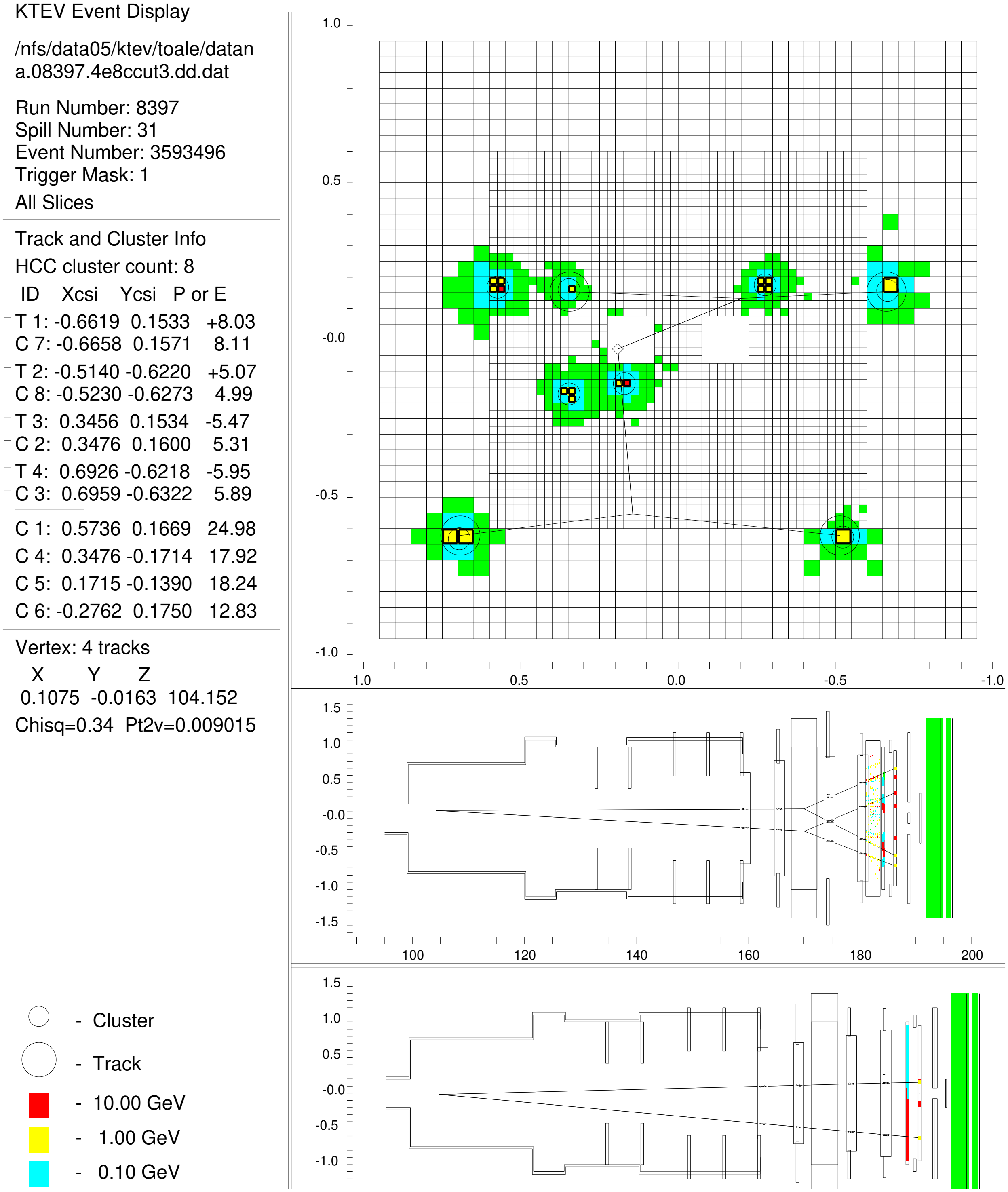


- In a sample of $e^+e^-e^+e^-\gamma\gamma\gamma\gamma$ events, we find both $K_L \to \pi^0\pi^0\pi^0$ with one $\pi^0 \to e^+e^-e^+e^-$ and with two $\pi^0 \to e^+e^-\gamma$ decays.
- These are separated using a kinematic χ^2, and conversions are eliminated with a track-separation cut.
- We find 27,954 $\pi^0 \to e^+e^-e^+e^-$ decays and normalizes them to the sample of 132,086 double-$\pi^0 \to e^+e^-\gamma$ events.
- The result is

$$\frac{BR(\pi^0 \to e^+e^-e^+e^-)}{BR(\pi^0 \to e^+e^-\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0059$$

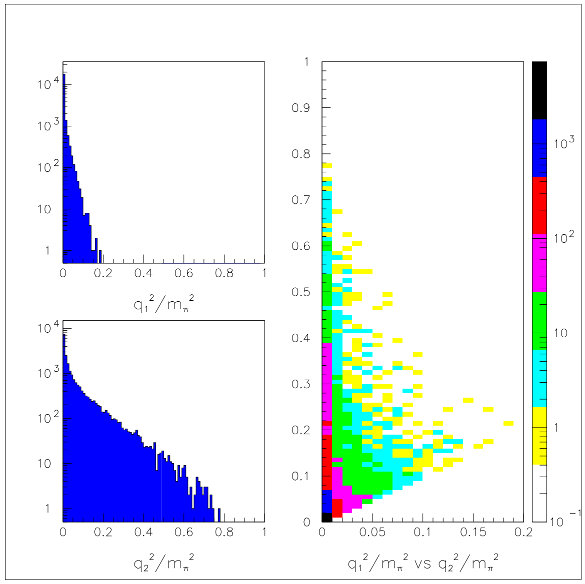
which implies

$$\frac{BR(\pi^0 \to e^+e^-e^+e^-)}{BR(\pi^0 \to \gamma\gamma)} = (3.274 \pm 0.022 \pm 0.197) \times 10^{-5}$$

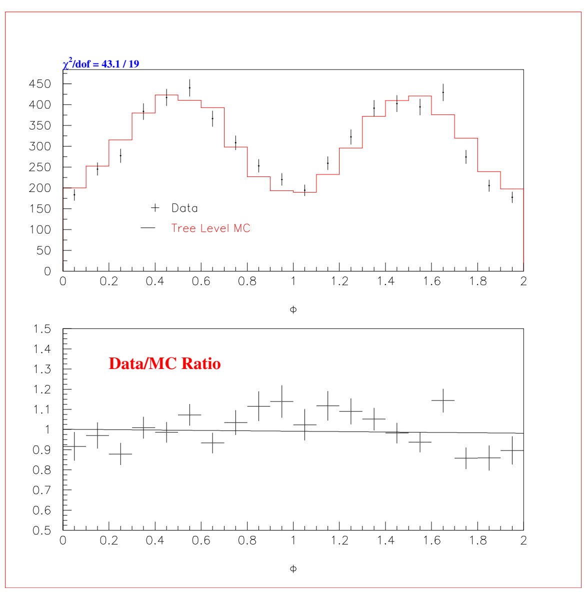


Event display for a $K_L \to \pi^0\pi^0\pi^0$ event with a $\pi^0 \to e^+e^-e^+e^-$ decay.

Measurement of $\pi^0 \to e^+e^-e^+e^-$

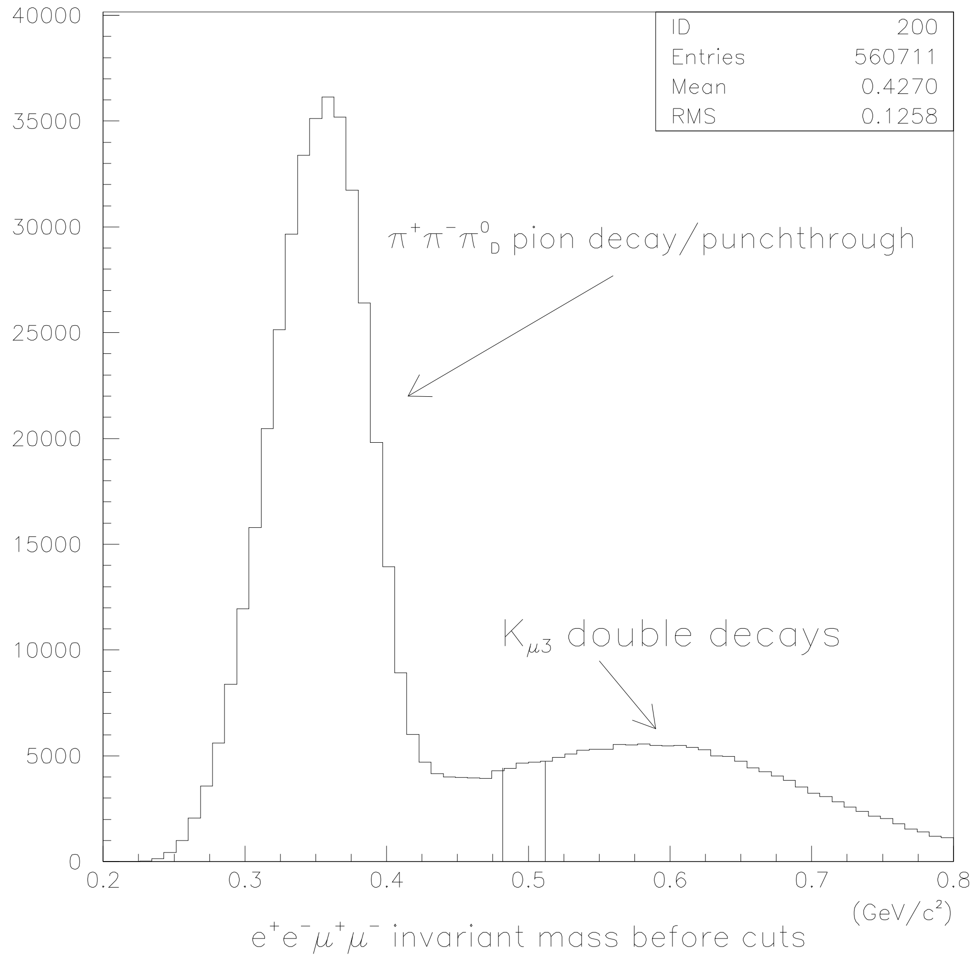


▷ We will extract the $\pi^0\gamma^*\gamma^*$ form factor from the M_{ee} distributions for this sample of 28,000 π^0 Double Dalitz decays.



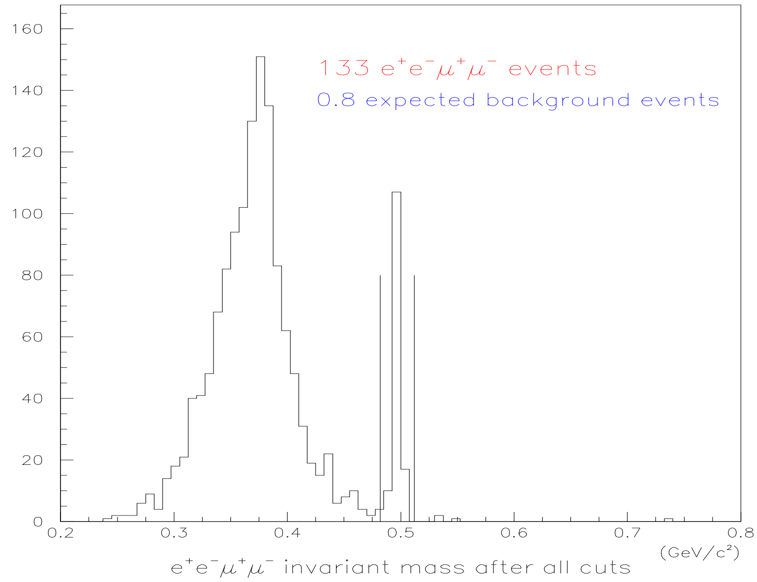
▷ We can also place a limit on CP-violating $\pi^0\gamma^*\gamma^*$ decays by studying the distribution of the angle ϕ between the two e^+e^- planes in the π^0 rest frame.

Measurement of $K_L \to e^+e^-\mu^+\mu^-$



- The backgrounds to the this mode are mostly from $K_L \to \pi^+\pi^-\pi^0$ and double (simultaneous) semileptonic decays.
- The backgrounds are largely eliminated by cutting on $P_\perp^2$ and rejecting events with extra clusters in the CsI or poor vertex-reconstruction quality.

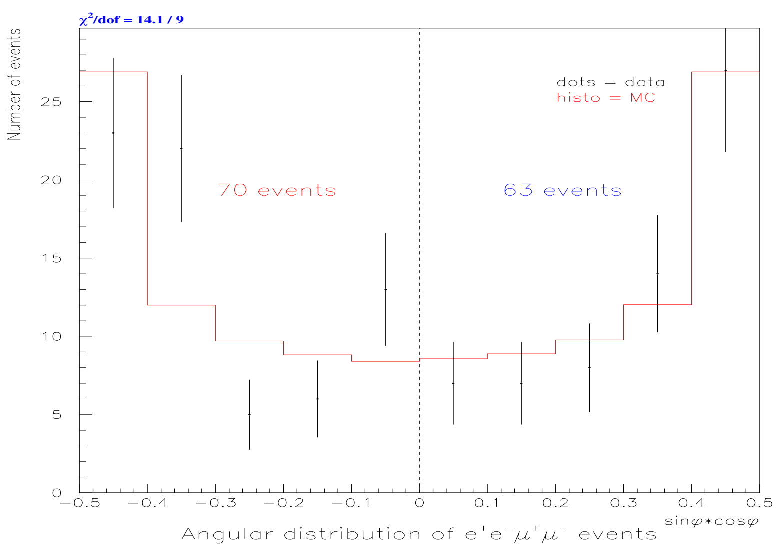
Measurement of $K_L \to e^+e^-\mu^+\mu^-$



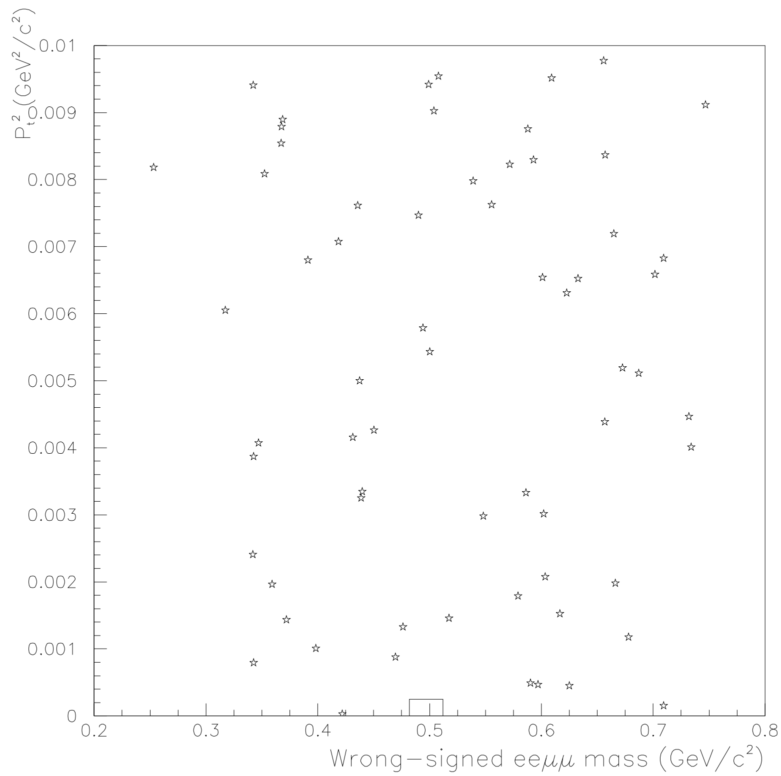
- A total of 133 candidate events remain after all cuts, with a background estimated at 0.82 events.
- The branching fraction is measured to be

$$BR(K_L \to e^+e^-\mu^+\mu^-) = (2.63 \pm 0.23 \pm 0.18) \times 10^{-9}$$

- No CP-violating asymmetry is seen in the distribution of $\sin\phi\cos\phi$, where ϕ is the angle between the e^+e^- and $\mu^+\mu^-$ planes in the kaon rest frame.



Search for $\Delta L = 2$ Lepton Flavor Violation



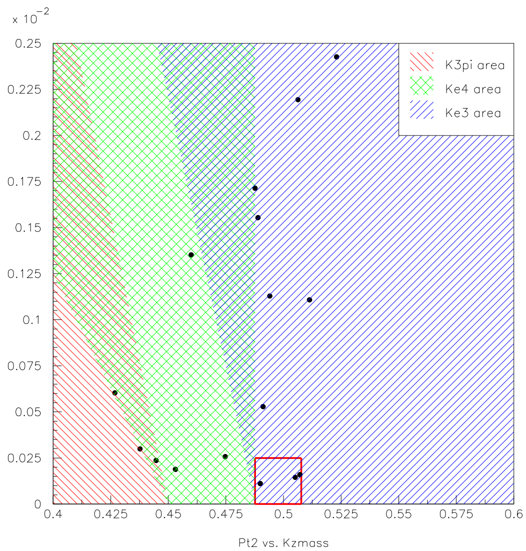
- As a byproduct of the measurement of $K_L \rightarrow e^+e^-\mu^+\mu^-$, we have search for the lepton-flavor-violating decay $K_L \rightarrow e^+e^+\mu^-\mu^-$ and its charge conjugate.

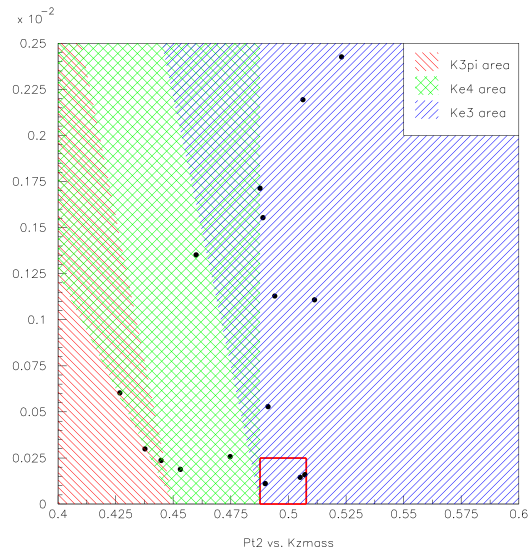
- No events are seen in the search region in the $P_\perp^2$ vs $M(\mu\mu ee)$ plane, leading to an upper limit

$$BR(K_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp) < 4.12 \times 10^{-11}$$

at the 90% confidence level.

Search for $K_L \to \pi^0 \mu^\pm e^\mp$

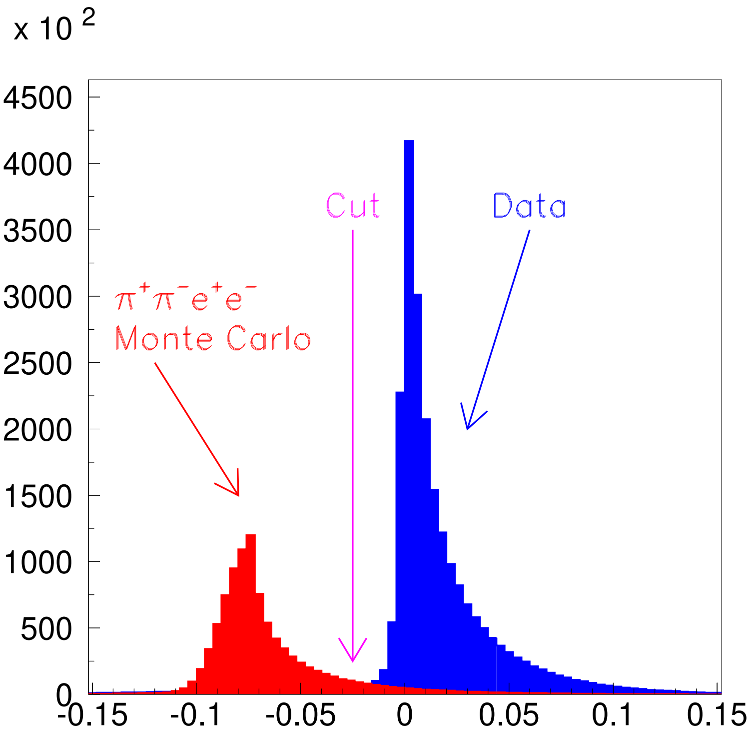




- KTeV has searched for the lepton-flavor-violating decay mode $K_L \to \pi^0 \mu^\pm e^\mp$. The backgrounds in this search are dominated by semileptonic decays with accidental activity, and have proven difficult to simulate.
- In the 1997 data, 2 events were observed in the signal region, compared to an expected background of about 0.6 events.
- In the 1999 data, 3 events were observed in the signal region, compared to an expected background of about 0.5 events.
- We believe that the five events are background, albeit one not yet understood or correctly predicted.
- We therefore quote a 90% confidence level upper limit, treating these events as though they were a signal:

$$BR(K_L \to \pi^0 \mu^\pm e^\mp) < 3.31 \times 10^{-10}$$

Measurement of $K_L \to \pi^+\pi^-e^+e^-$



- KTeV has observed CP-violating angular correlations in the decay $K_L \to \pi^+\pi^-e^+e^-$.
- The main background in this channel is

$$K_L \to \pi^+\pi^-\pi^0(\pi^0 \to e^+e^-\gamma)$$

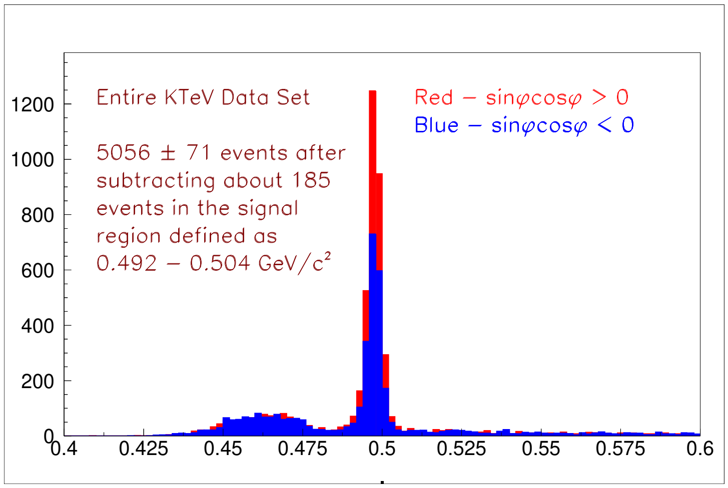
with a missing photon.

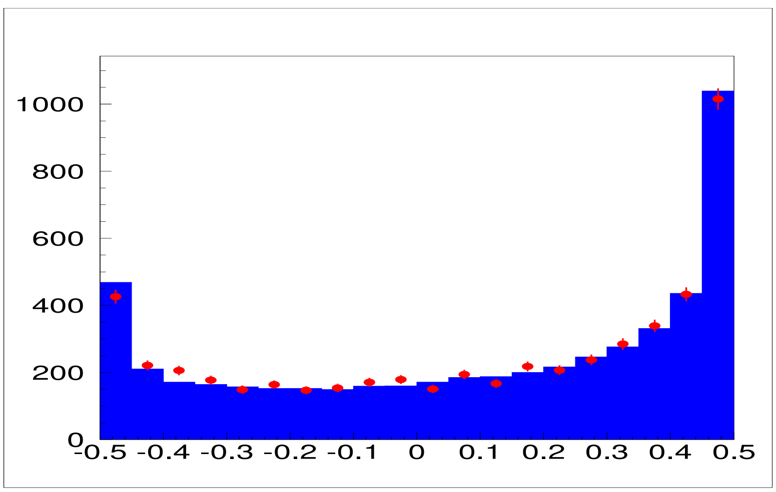
- To suppress this background, we calculate the kinematic quantity $P^2_{\pi^0}$, defined by

$$P^2_{\pi^0} \equiv \frac{M_K^2 - M_{\pi^0}^2 - M_{\pi\pi}^2 - 4M_{\pi^0}^2 M_{\pi\pi}^2 - 4M_K^2 P_\perp(\pi\pi)^2}{4[(P_\perp(\pi\pi)^2 + M_{\pi\pi}^2]}$$

- As the plot above shows, this quantity efficiently distinguishes between the $K_L \to \pi^+\pi^-e^+e^-$ signal and the background.

Measurement of $K_L \to \pi^+\pi^-e^+e^-$





- The CP-odd and T-odd asymmetry is defined by

$$\mathcal{A}_{\pi\pi ee} \equiv \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

- With the full KTeV dataset, we have a new preliminary measurement of the acceptance-corrected asymmetry with reduced uncertainties:

$$\mathcal{A}_{\pi\pi ee} = (13.4 \pm 1.4 \pm 1.0)\%$$

in agreement with the published result for the 1997 data only.

Selected E799 Rare Decay Results
(1997 Data Only)

Decay Mode	Events	Br. Fraction or 90% CL Limit
$K_L \to \pi^0 e^+ e^-$	2 (bkgd)	$< 5.1 \times 10^{-10}$
$K_L \to \pi^0 \mu^+ \mu^-$	2 (bkgd)	$< 3.8 \times 10^{-10}$
$K_L \to \pi^0 \nu \bar{\nu}$	0	$< 5.9 \times 10^{-7}$
$K_L \to \pi^0 \mu^\pm e^\mp$	2 (bkgd)	$< 4.4 \times 10^{-10}$
$K_L \to \pi^+ \pi^- e^+ e^-$	1508	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$
$K_L \to \pi^0 \pi^0 e^+ e^-$	1 (bkgd)	$< 5.4 \times 10^{-9}$
$K_L \to \pi^0 e^+ e^- \gamma$	48	$(2.34 \pm 0.15 \pm 0.13) \times 10^{-8}$
$K_L \to \mu^+ \mu^- \gamma$	9327	$(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$
$K_L \to e^+ e^- \mu^+ \mu^-$	38	$(2.50 \pm 0.41 \pm 0.17) \times 10^{-9}$
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$	0	$< 1.36 \times 10^{-10}$
$K_L \to e^+ e^- e^+ e^-$	441	$(3.72 \pm 0.18 \pm 0.23) \times 10^{-8}$
$K_L \to e^+ e^- \gamma\gamma$	1543	$(5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$
$K_L \to \mu^+ \mu^- \gamma\gamma$	4	$(10.4^{+7.5}_{-5.9} \pm 0.7) \times 10^{-9}$

Summary and Prospects

- ▷ The final KTeV analysis of Re(ϵ'/ϵ) from the 1996-97 data will be submitted for publication this summer.
- ▷ A new NA48-style reweighting analysis of KTeV data yields results consistent with the standard analysis.
- ▷ The 1999 E832 data will double the ϵ'/ϵ statistics, reducing the statistical error to about 1.0×10^{-4}.
- ▷ Improvements in systematic uncertainties are also anticipated before KTeV is finished.

- ▷ The rare decay experiment E799 has observed or set limits on numerous K_L decays. Most analyses of 1997 data are now published.
- ▷ The 1999 data will increase total statistics for most modes by a factor between 2.3 and 2.7.
- ▷ No results including 1999 data have yet been published, but the first paper will be submitted this summer.
- ▷ Expect many new KTeV results between now and ICHEP 2004.