

Recent Results from KTeV

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Outline

- Kaons at the TeVatron
- CP Violating Effects in KTeV
 - Indirect CP Violation:
 - The $K_L \rightarrow \pi e \nu$ Charge Asymmetry and
The $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ Angular Asymmetry
 - Direct CP Violation: $K \rightarrow \pi\pi$ and $Re(\epsilon'/\epsilon)$
 - Mixed CP Violation: $K_L \rightarrow \pi^0 l \bar{l}$
- Other Interesting Results
 - Electromagnetic Decays of the K_L and π^0
 - Lepton Flavor Violation

The KTeV Experiment

Two Goals:

E832 Precision Measurement of $Re(\epsilon'/\epsilon)$:

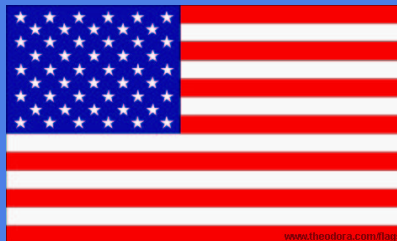
Measure K_L and K_S decays to both $\pi^+\pi^-$ and $\pi^0\pi^0$ to extract η_{+-} and η_{00} .

E799-II Search for Rare K_L Decays:

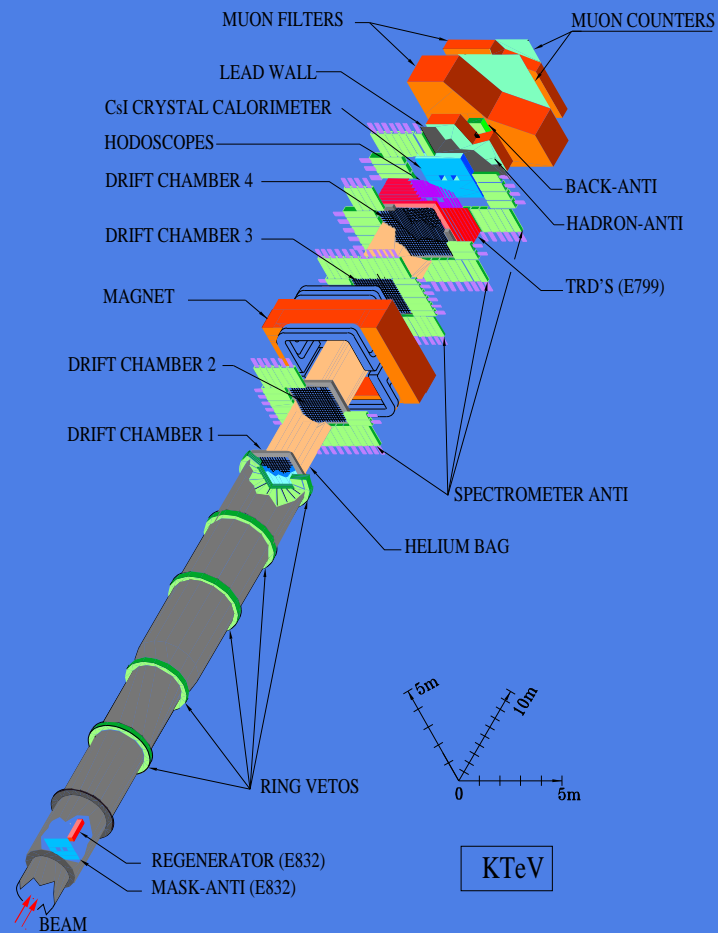
Searches for rare K_L modes with significant CPV contributions are complementary to E832.

The KTeV Collaboration

- Univ of Arizona
- UCLA
- UCSD
- Univ of Campinas
- Univ of Chicago
- Univ of Colorado
- Elmhurst College
- FNAL
- Osaka Univ
- Rice Univ
- Univ of São Paulo
- Univ of Virginia
- Univ of Wisconsin



The KTeV Detector



- CsI Calorimeter:

Energy resolution $< 1\%$ at $E \sim 10$ GeV

- Drift Chambers:

Position resolution $\sim 100 \mu\text{m}$

- Transition Radiation Detectors:

π/e rejection > 200

- For $E_K \sim 70$ GeV:

$$\gamma\beta c\tau \sim \begin{cases} 3.5 \text{ m} & K_S \\ 2.2 \text{ km} & K_L \end{cases}$$

The KTeV Event Display

KTeV Event Display

/disks/gammadisk/crunch/dat/
4E8C.08088.dat

Run Number: 8088
Spill Number: 1
Event Number: 39315
Trigger Mask: 1
All Slices

Track and Cluster Info

HCC cluster count: 0

ID Xcsi Ycsi P or E

[T 1: -0.5369 0.1606 +9.57
C 1: -0.5452 0.1618 9.37

[T 2: 0.8034 0.1609 -3.31
C 7: 0.8149 0.1391 3.32

[T 3: 0.1006 0.3400 +11.40
C 4: 0.1013 0.3398 11.29

[T 4: 0.9038 0.3402 -6.39
C 8: 0.9100 0.3361 6.50

C 2: 0.3857 -0.2240 10.80

C 3: 0.2120 -0.1295 23.82

C 5: 0.0537 0.0575 37.19

C 6: 0.4344 -0.1471 17.36

Vertex: 4 tracks

X Y Z
0.1266 0.0093 122.694

Chisq=6.61 Pt2v=0.015405

○ - Cluster

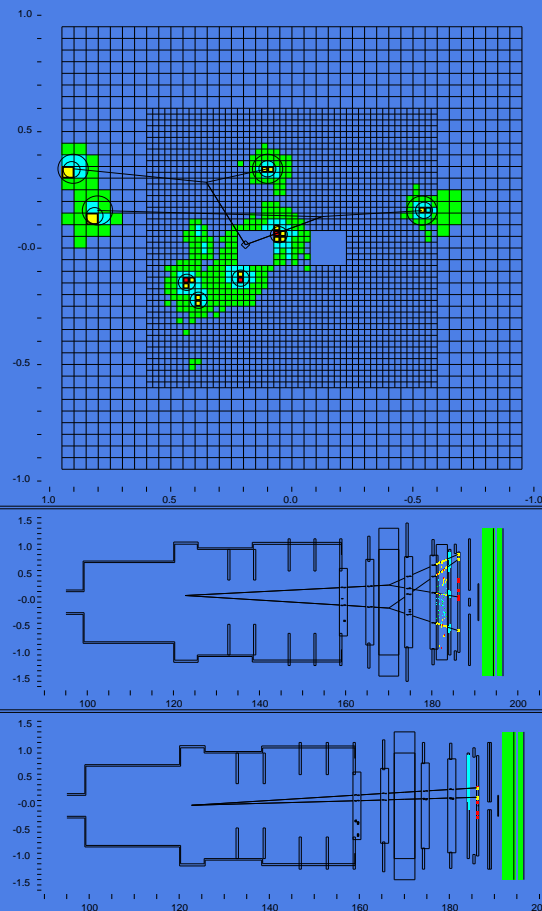
○ - Track

■ - 10.00 GeV

■ - 1.00 GeV

■ - 0.10 GeV

■ - 0.01 GeV



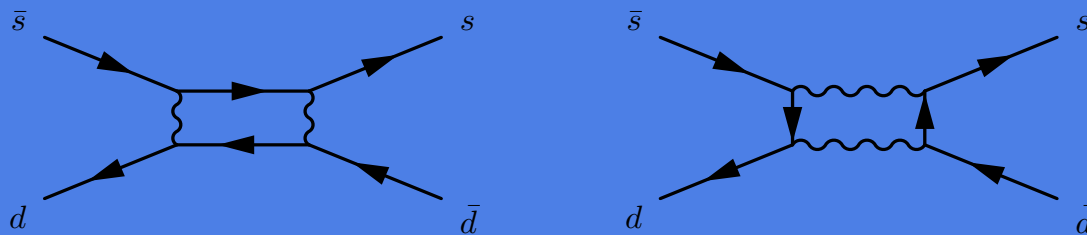
- 8 clusters: clean calorimeter (log scale)
- 4 tracks: very close together, good 4-track vertex
- $E/p \sim 1$: 2 electrons and 2 positrons
- Candidate $K_L \rightarrow 3\pi^0$ with $\pi^0 \rightarrow e^+e^-e^+e^-$

Indirect CP Violation

The K_S and K_L are very nearly CP eigenstates, with the difference parameterized by the small quantity ϵ :

$$|K_S\rangle \sim |K_1\rangle + \epsilon |K_2\rangle \quad (\text{nearly even}) \quad |K_L\rangle \sim |K_2\rangle + \epsilon |K_1\rangle \quad (\text{nearly odd})$$

Non-zero ϵ in the SM is due to $\Delta S = 2$ box diagrams which mix the strong states, K^0 and \bar{K}^0 :



The current values of the magnitude and phase of ϵ are:

$$|\epsilon| = (2.269 \pm 0.023) \cdot 10^{-3} \quad \phi_\epsilon = (44.3 \pm 0.8)^\circ$$

Ke3 Charge Asymmetry

The Charge Asymmetry in $K_L \rightarrow \pi e \nu$ decays is a measure of the real part of ϵ :

$$\delta_L = \frac{B(K_L \rightarrow \pi^- e^+ \nu) - B(K_L \rightarrow \pi^+ e^- \bar{\nu})}{B(K_L \rightarrow \pi^- e^+ \nu) + B(K_L \rightarrow \pi^+ e^- \bar{\nu})} = 2\text{Re}(\epsilon) + \text{CPT violating terms}$$

KTeV has found, using 298 M Ke3 events:

$$\delta_L = (3.322 \pm 0.074) \cdot 10^{-3}$$

Columbia 69

Columbia-Harvard
-Cern 70

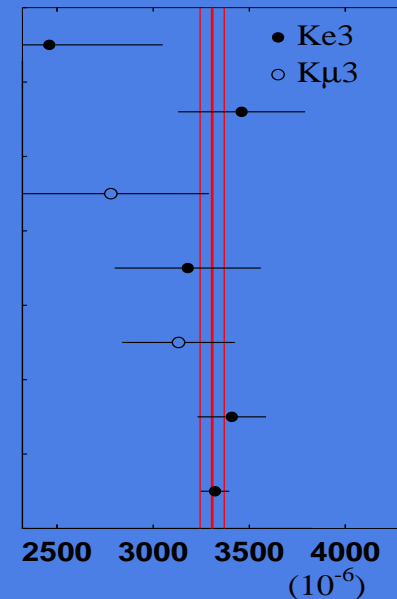
SLAC 72

Princeton 73

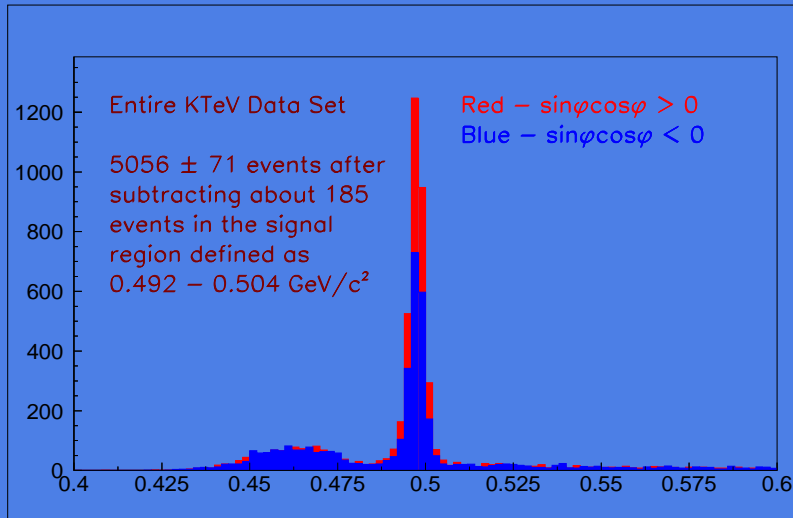
Cern-Heidelberg 74

Cern-Heidelberg 74

KTeV



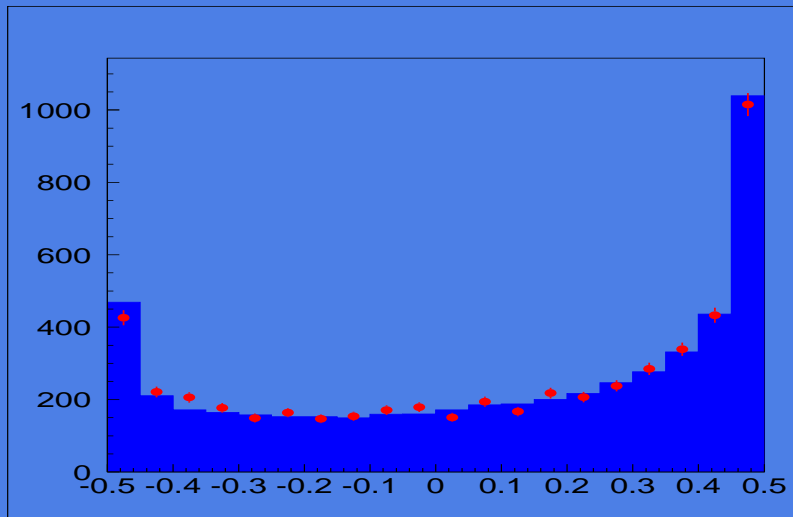
$K_L \rightarrow \pi^+ \pi^- e^+ e^-$ Angular Asymmetry



The asymmetry in the angle ϕ between the $\pi\pi$ plane and the ee plane in the K_L rest frame is defined as:

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

With 5056 events in the combined 97+99 dataset, KTeV measures an acceptance-corrected asymmetry of:



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

Direct CP Violation

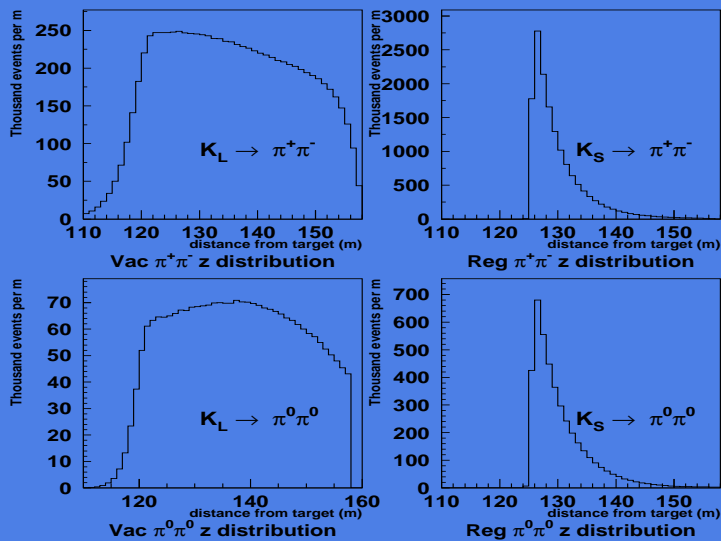
Direct CP violation in the SM is a consequence of the one imaginary phase in the CKM matrix. The effect is observable as a slight difference between the ratios of the charged and neutral $K \rightarrow \pi\pi$ decay amplitudes:

$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \approx \epsilon + \epsilon' \qquad \eta_{00} = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} \approx \epsilon - 2\epsilon'$$

The ratio of Direct to Indirect CPV is then:

$$\begin{aligned} \text{Re}(\epsilon'/\epsilon) &\approx \frac{1}{6} \left(1 - |\eta_{+-}/\eta_{00}|^2 \right) \\ \text{Im}(\epsilon'/\epsilon) &\approx \frac{1}{3} (\phi_{00} - \phi_{+-}) \end{aligned}$$

The $K \rightarrow \pi\pi$ Analysis



96+97 KTeV dataset

Mode	Vac Beam	Reg Beam
$\pi^+\pi^-$	11.1 M	19.3 M
$\pi^0\pi^0$	3.3 M	5.6 M

- The analysis of the 96+97 $K \rightarrow \pi\pi$ data is complete. KTeV published new results on ϵ'/ϵ , Δm , τ_S , and $\Delta\phi$.
- The inclusion of the 99 data will more than double the statistics. We anticipate that reductions in systematic uncertainties will accompany the reduced statistical errors.

The 96+97 $K \rightarrow \pi\pi$ Results

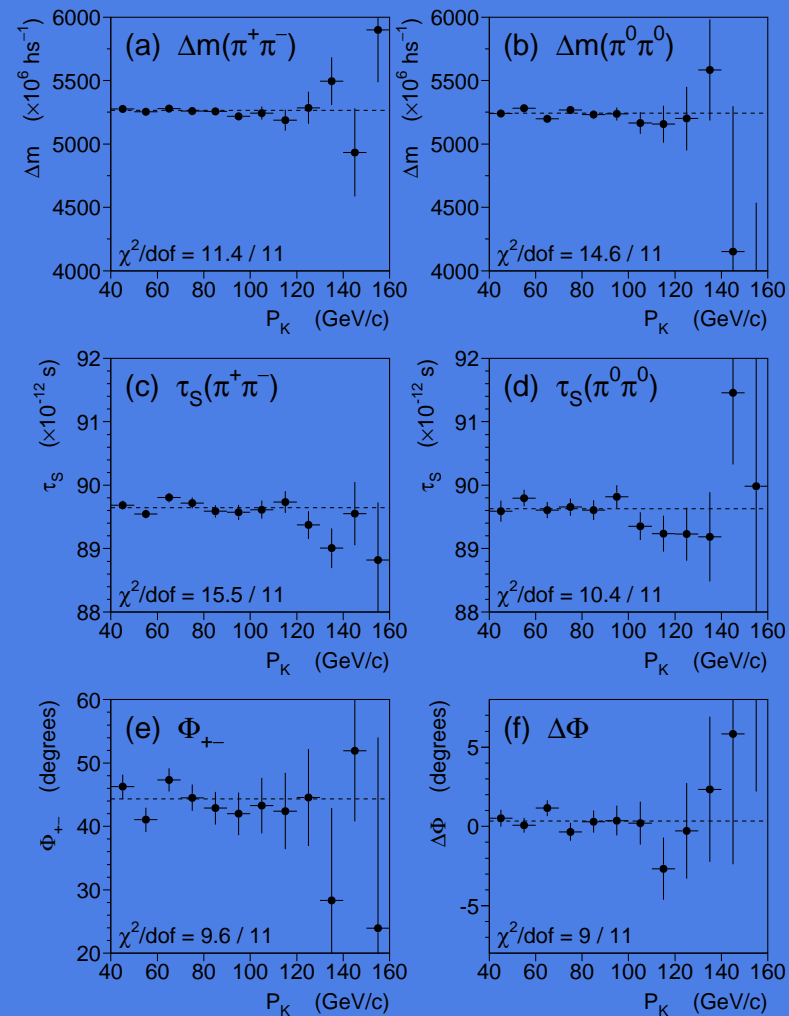
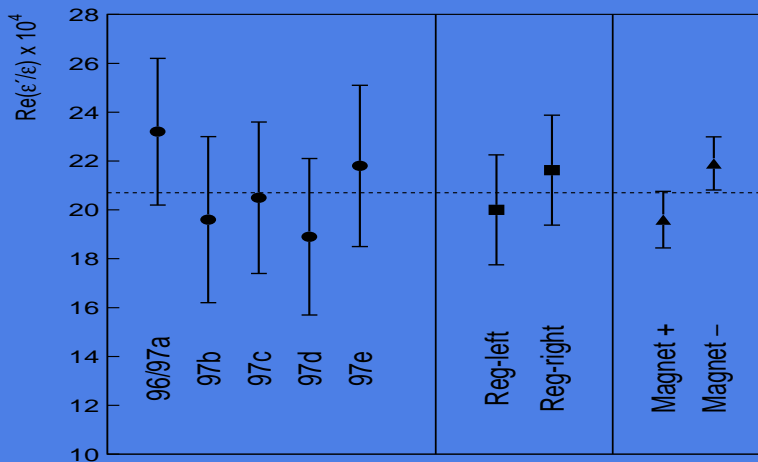
$$\text{Re}(\epsilon'/\epsilon) = (20.7 \pm 1.48 \pm 2.39) \cdot 10^{-4}$$

$$\Delta m = (5261 \pm 15) \cdot 10^6 \hbar/s$$

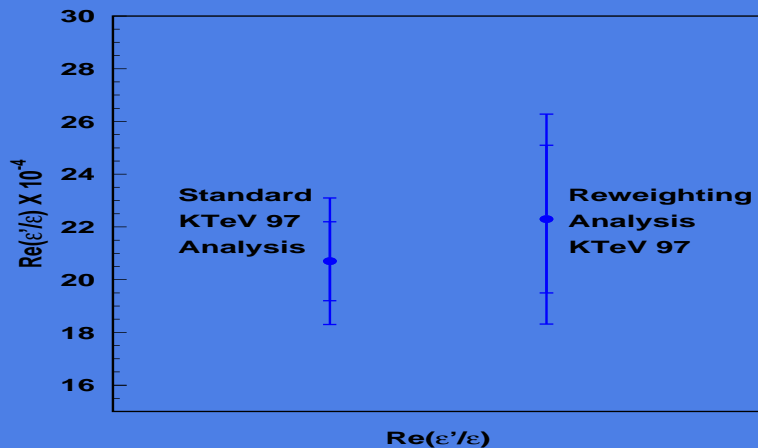
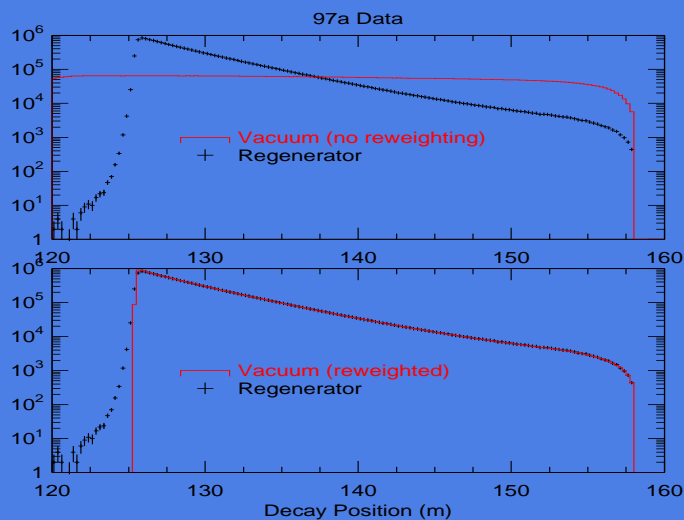
$$\tau_S = (89.65 \pm 0.07) \cdot 10^{-12} \text{ s}$$

$$\Delta\phi = (0.39 \pm 0.50)^\circ$$

$$\text{Im}(\epsilon'/\epsilon) = (-22.9 \pm 29.1) \cdot 10^{-4}$$



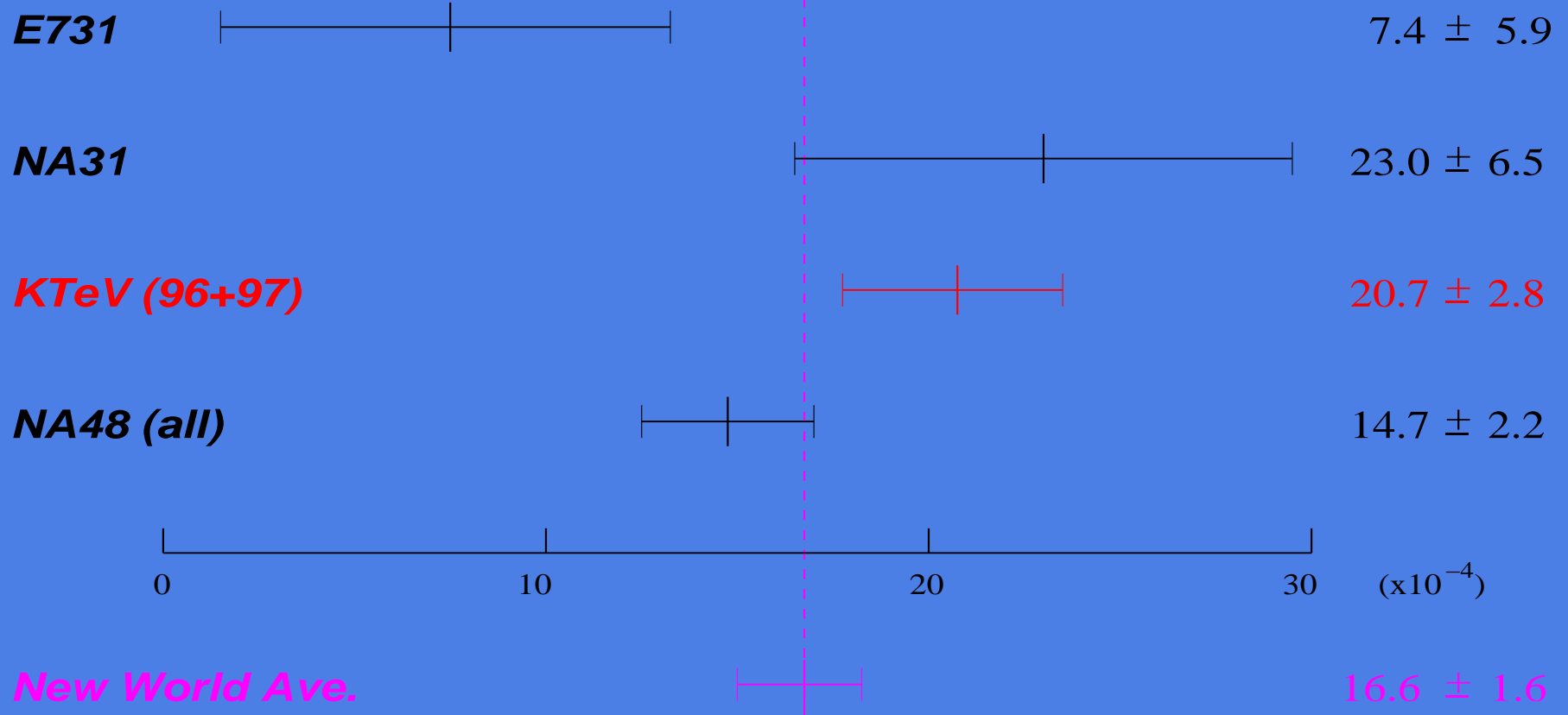
$Re(\epsilon'/\epsilon)$ Reweighting Technique



- KTeV has performed a z–vertex reweighting analysis as a cross–check of the traditional technique
- The method does not require an acceptance correction but has less statistical power
- The result is in excellent agreement with the primary result. The uncorrelated difference between the two is:

$$\Delta = (1.5 \pm 2.1 \pm 3.0) \cdot 10^{-4}$$

$Re(\epsilon'/\epsilon)$ Comparison of Measurements

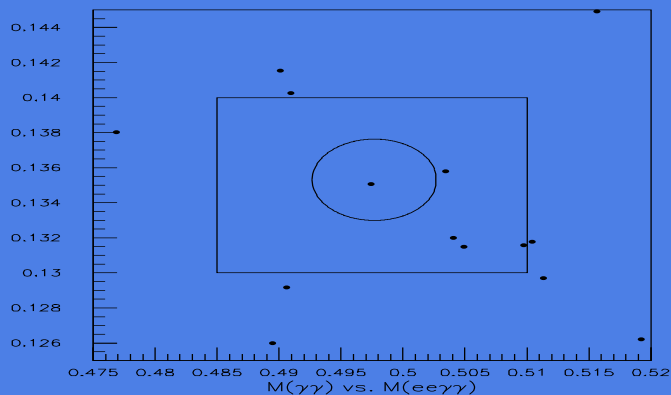
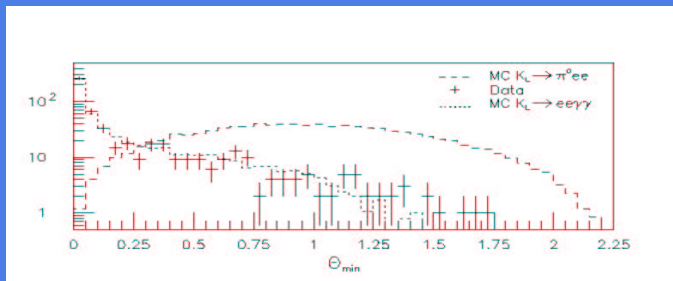
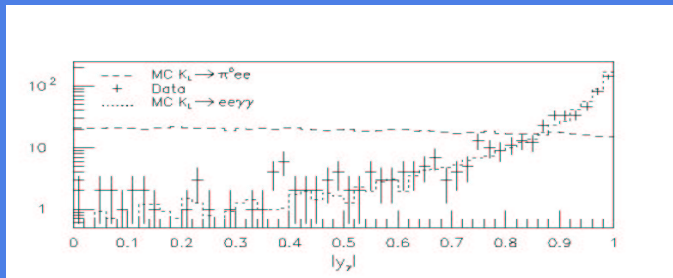


The $K_L \rightarrow \pi^0 l \bar{l}$ Decays

- The amplitudes for these modes contain direct CPV, indirect CPV, and CP-conserving contributions
- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is dominated by direct CPV, is theoretically clean, but experimentally challenging
- The decays to charged leptons are experimentally accessible, but are theoretically messy
- KTeV results from the 97 data:

Mode	# Evts	90% CL Limit	Predicted
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	0	$< 5.9 \cdot 10^{-7}$	$(2.0 - 4.0) \cdot 10^{-11}$
$K_L \rightarrow \pi^0 e^+ e^-$	2 (BG)	$< 5.1 \cdot 10^{-10}$	$\sim 3 \cdot 10^{-11}$
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	2 (BG)	$< 3.8 \cdot 10^{-10}$	$(0.4 - 1.0) \cdot 10^{-11}$

The New $K_L \rightarrow \pi^0 e^+ e^-$ Result



- The blind search for $K_L \rightarrow \pi^0 e^+ e^-$ in the 99 data is complete
- The main background is from $K_L \rightarrow e^+ e^- \gamma \gamma$ with $M_{\gamma\gamma} \sim M_{\pi^0}$
- The most effective cuts are on $|y_\gamma|$ and θ_{min} : reduces BG by factor of 40 while removing only 27% of signal
- 1 event was observed with an expected background of 1 event
- Combined KTeV result (3 BG):

$$BR < 2.8 \cdot 10^{-10} (90\% \text{ CL})$$

K_L Electromagnetic Decays

The electromagnetic decays of the K_L proceed through a two-photon intermediate state, with a coupling strength described by the electromagnetic form factor. One parameterization of the form factor (due to Bergström, Massó, and Singer) is:

$$f_{BMS}(q^2, 0) = \frac{1}{1 - q^2/M_\rho^2} + \frac{2.5\alpha_{K^*}}{1 - q^2/M_{K^*}^2} \left(\frac{4}{3} - \frac{1}{1 - q^2/M_\rho^2} - \frac{1}{9(1 - q^2/M_\omega^2)} - \frac{2}{9(1 - q^2/M_\phi^2)} \right)$$

Another (due to D'Ambrosio, Isidori, and Portolès) is:

$$f_{DIP}(q_1^2, q_2^2) = 1 + \alpha \left(\frac{q_1^2}{q_1^2 - M_\rho^2} + \frac{q_2^2}{q_2^2 - M_\rho^2} \right) + \beta \frac{q_1^2 q_2^2}{(q_1^2 - M_\rho^2)(q_2^2 - M_\rho^2)}$$

The $K_L \rightarrow e^+e^-\gamma$ Analysis

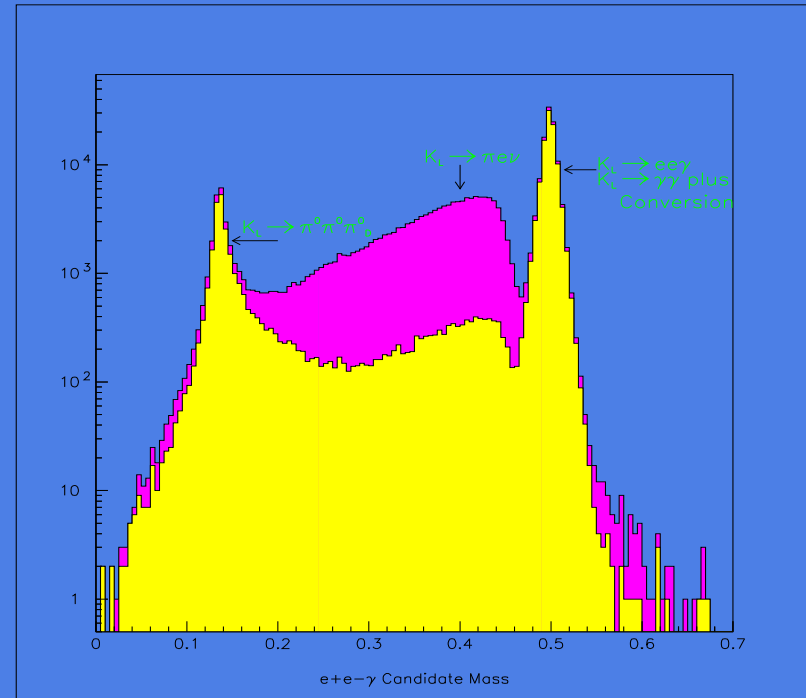
Main backgrounds are:

- $K \rightarrow \pi e \nu + \text{extra } \gamma$
- $K \rightarrow \gamma\gamma + \text{conversion}$

BG's are eliminated by:

- TRD's remove events with pions
- A cut on the track separation at DC1 removes events with conversions

In the 97 dataset there are 93,383 events with a residual background $< 0.1\%$



Preliminary BR result:

$$B(K_L \rightarrow ee\gamma) = (10.13 \pm 0.04(\text{stat}) \pm 0.06(\text{syst}) \pm 0.29(\text{norm})) \cdot 10^{-6}$$

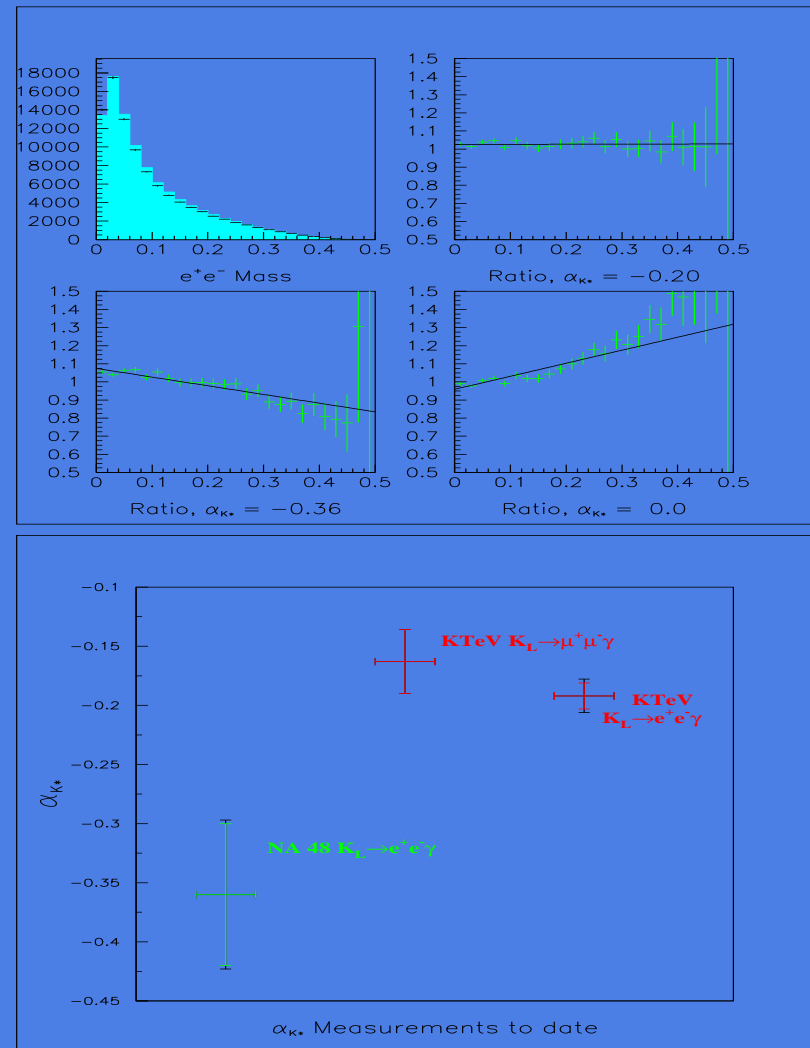
The $K_L \rightarrow e^+e^-\gamma$ Form Factor

The shape of the ee mass distribution is sensitive to the K_L form factor with one off-shell photon. The preliminary result for the BMS model is:

$$\alpha_{K^*} = -0.186 \pm 0.011 \pm 0.009$$

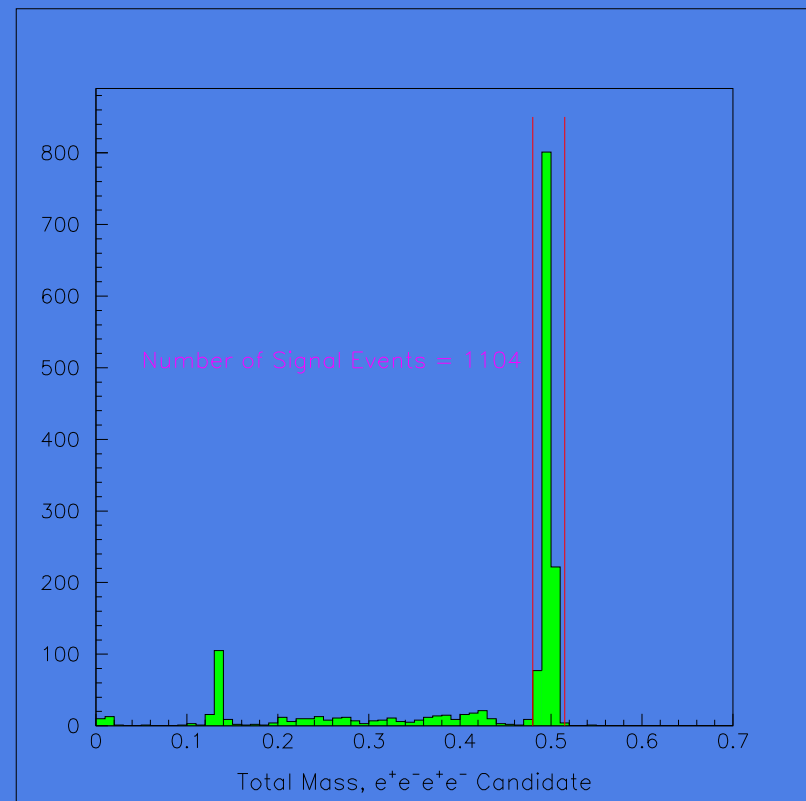
For the DIP model, we find:

$$\alpha = -1.630 \pm 0.038 \pm 0.028$$



The $K_L \rightarrow e^+e^-e^+e^-$ Analysis

- KTeV has a sample of over 1100 K_L double Dalitz decays with very little background
- This mode is sensitive to the form factor when both photons are off-shell
- We can also look for a CPV angular asymmetry as in $K \rightarrow \pi\pi ee$



The $K_L \rightarrow e^+e^-e^+e^-$ Results

The preliminary measurement of the branching ratio based on the full dataset is:

$$BR = (4.16 \pm 0.13 \pm 0.13 \pm 0.17) \cdot 10^{-8}$$

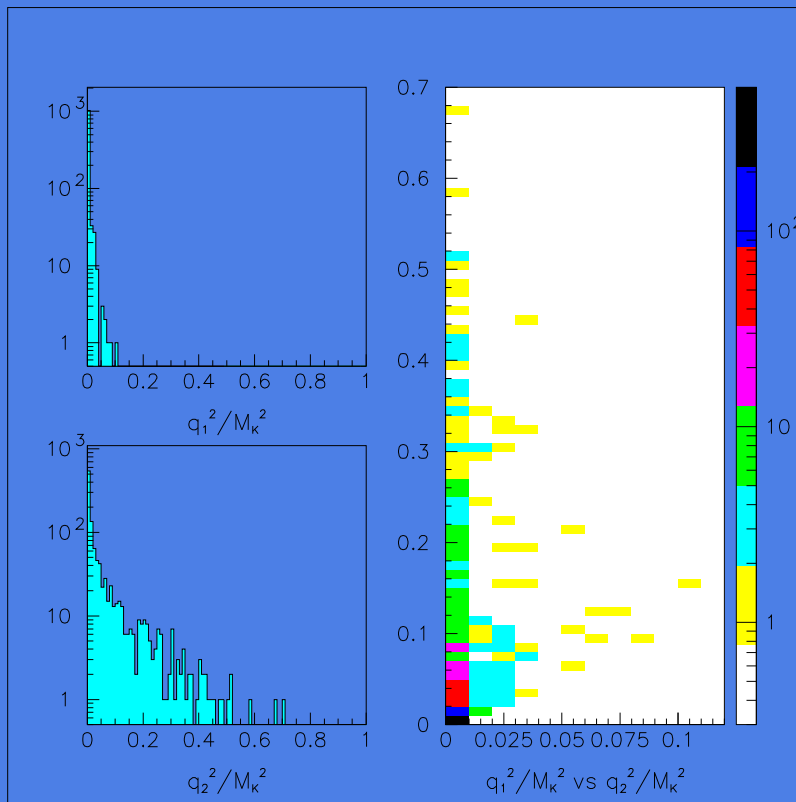
The value of the BMS form factor parameter is:

$$\alpha_{K^*} = -0.03 \pm 0.13 \pm 0.04$$

For the DIP model, we find:

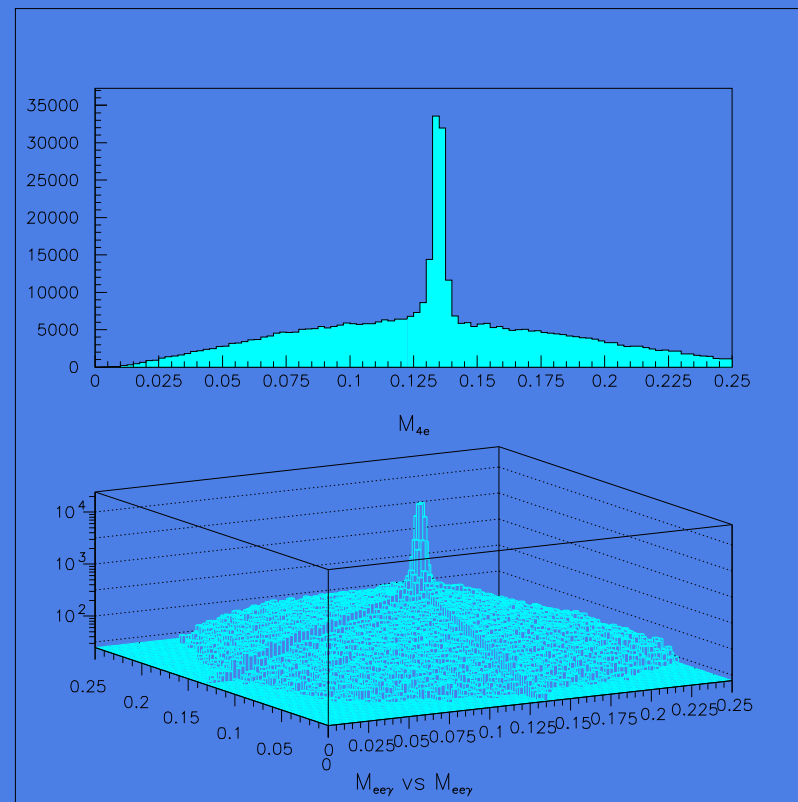
$$\alpha = -1.08 \pm 0.41 \pm 0.13$$

$$\beta = 13 \pm 54 \pm 43$$



The $\pi^0 \rightarrow e^+e^-e^+e^-$ Analysis

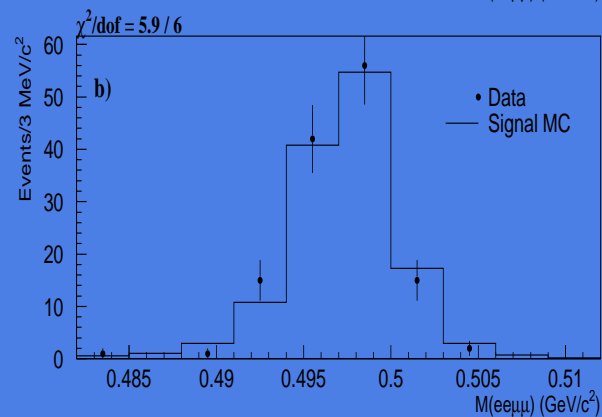
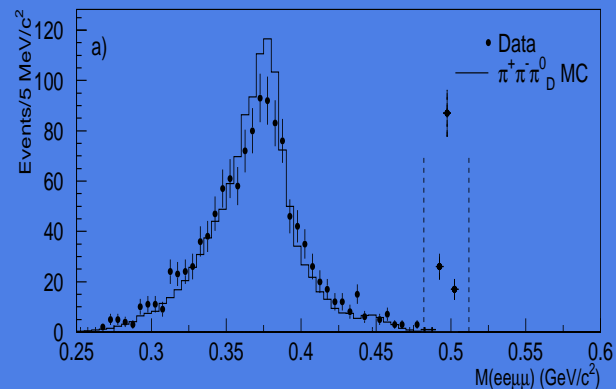
- Uses $K_L \rightarrow 3\pi^0$ as a source of π^0 's
- The normalization mode is $K_L \rightarrow 3\pi^0$ with two $\pi^0 \rightarrow e^+e^-\gamma$
- We have presented a preliminary measurement of the branching ratio based on 28,000 events in the combined dataset
- Measurements of the π^0 form factor and angular asymmetry are coming soon



$$\frac{B(\pi^0 \rightarrow eeee)}{B(\pi^0 \rightarrow ee\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0059$$

The $K_L \rightarrow e^+e^-\mu^+\mu^-$ Analysis

- The major backgrounds to this mode are $K_L \rightarrow \pi^+\pi^-\pi^0$ with $\pi^0 \rightarrow e^+e^-\gamma$, and double $Ke3$ decays
- These backgrounds typically have large P_{\perp}^2 , extra clusters in the CsI, or poor vertex χ^2
- After all cuts we observe 133 events in the combined 97+99 data with an expected BG of < 1 event
- This mode is sensitive to the K_L form factor through both the branching ratio and the dilepton mass distributions



The $K_L \rightarrow e^+e^-\mu^+\mu^-$ Results

The final results from the combined 97+99 dataset are:

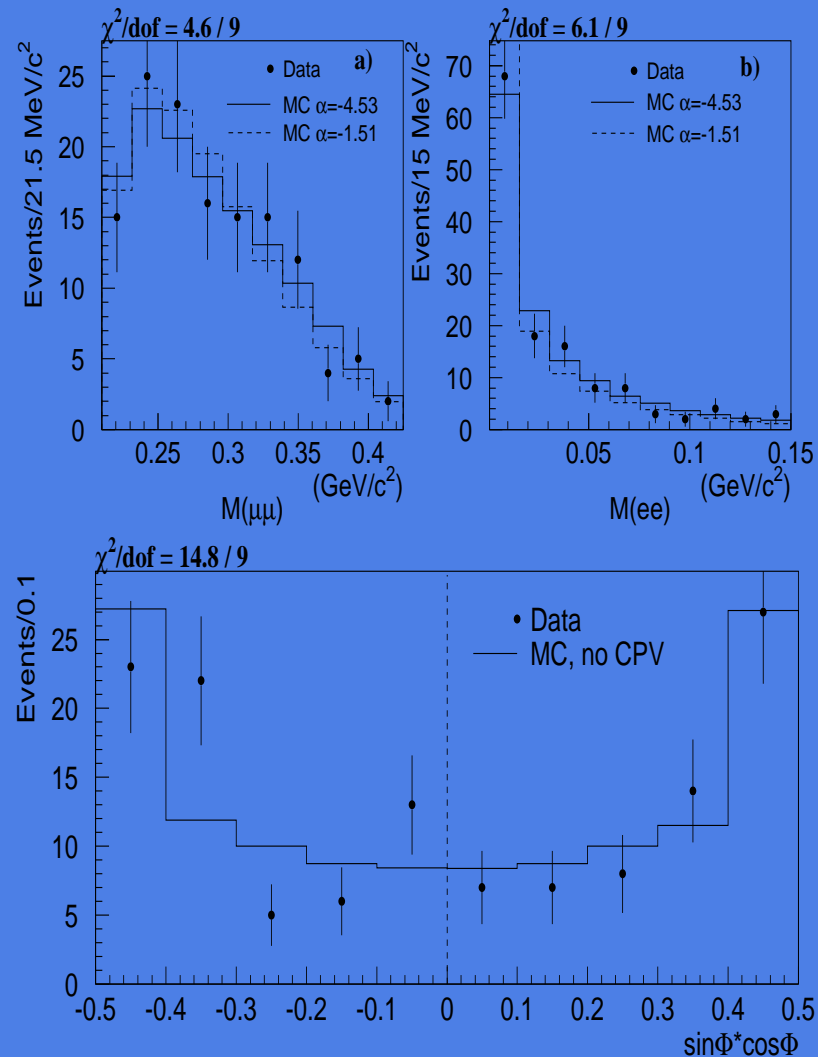
$$BR = (2.69 \pm 0.24 \pm 0.12) \cdot 10^{-9}$$

$$\alpha_{K^*} = -0.19 \pm 0.11$$

$$\alpha = -1.59 \pm 0.37$$

$$\mathcal{A}_{ee\mu\mu} < 25.5\% \text{ (90\% CL)}$$

There is no sensitivity to the quadratic DIP parameter β



K_L Form Factor Summary

Mode	α_{K^*}	α_{DIP}
$K_L \rightarrow \mu\mu\gamma$	-0.160 ± 0.027	-1.54 ± 0.10
$K_L \rightarrow ee\mu\mu$	-0.19 ± 0.11	-1.59 ± 0.37
$K_L \rightarrow ee\gamma$	-0.186 ± 0.014	-1.63 ± 0.05
$K_L \rightarrow eeee$	-0.03 ± 0.14	-1.08 ± 0.43

The average of the 4 KTeV results:

$$\alpha_{K^*} = -0.18 \pm 0.01 \quad \chi^2/\text{dof} \sim 1.9/3$$

$$\alpha_{DIP} = -1.61 \pm 0.04 \quad \chi^2/\text{dof} \sim 2.2/3$$

Lepton Family Violating Decays

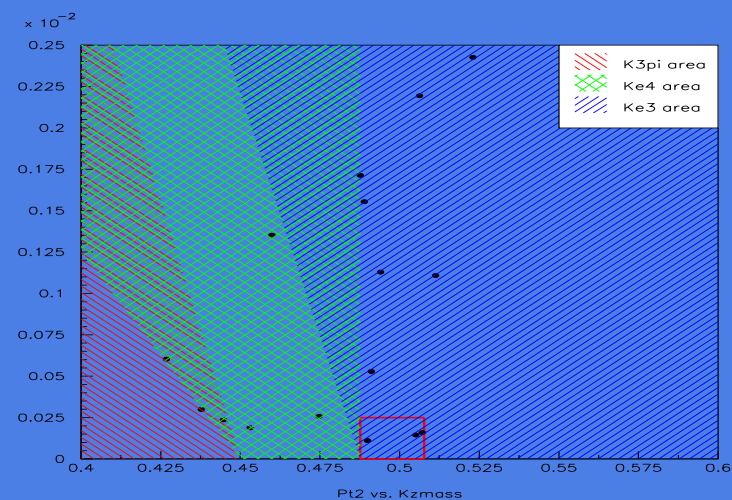
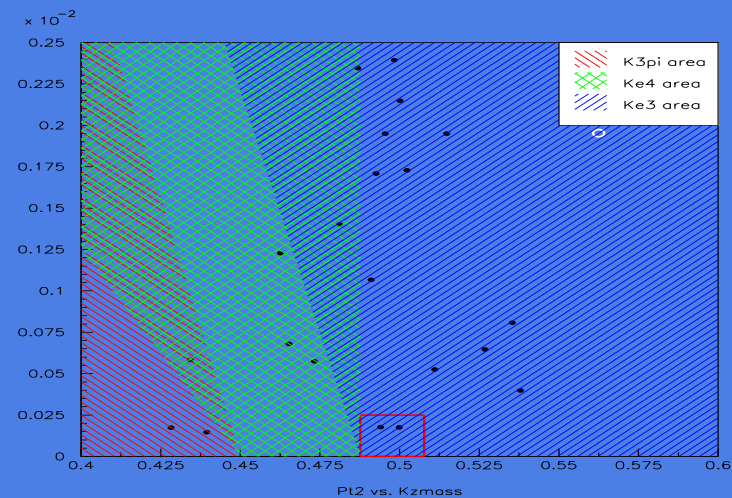
KTeV can search for a variety of lepton flavor violating decays, including:

Mode	90% CL Limit
$K_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp$	$< 4.12 \cdot 10^{-11}$
$K_L \rightarrow \pi^0 \mu e$	$< 3.31 \cdot 10^{-10}$
$K_L \rightarrow \mu e e e$	in progress
$\pi^0 \rightarrow \mu e$	in progress

The $K_L \rightarrow \pi^0 \mu e$ Analysis

- Main background is from semi-leptonic decays
- Found 2 events with an expected background of 0.6 in 97
- Found 3 events with an expected background of 0.5 in 99
- The five events are believed to be due to an unknown or misunderstood background
- The 90% CL limit is:

$$BR < 3.31 \cdot 10^{-10}$$



Summary

- KTeV is sensitive to a wide range of CP violating effects, in $K \rightarrow \pi\pi$ as well as in rare decays
- KTeV has made a precision measurement of the K_L electromagnetic form factor. Results from four different modes are consistent
- Results based on the 99 dataset are beginning to be presented (first published result was on $K_L \rightarrow ee\mu\mu$)
- We have also published results on a variety of rare hyperon and π^0 decays, and more are forthcoming