Recent Results from KTeV

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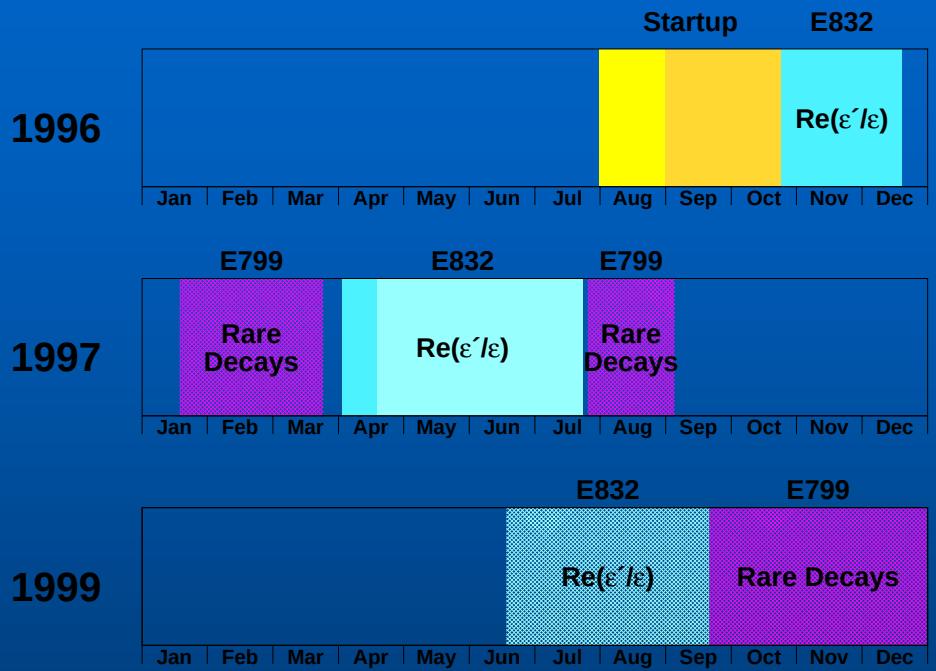
Moriond 2003

The KTeV Experiment

The KTeV Collaboration:

Arizona, Campinas (Brazil), Chicago, Colorado, Elmhurst, Fermilab, Osaka (Japan), Rice, Rutgers, San Paulo (Brazil), UCLA, UCSD, Virginia, Wisconsin



Two KTeV Goals:

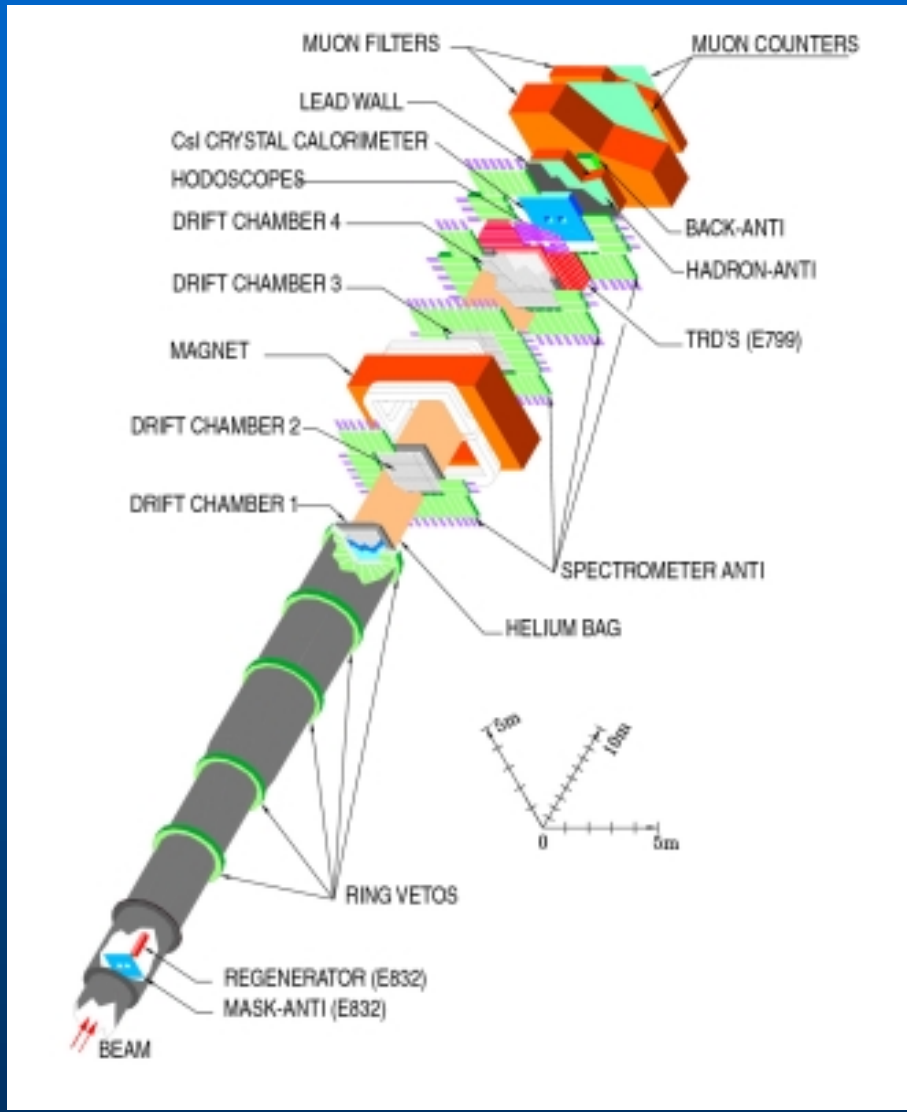
E832: Measure Re(ε′/ε) (Direct CP violation)

E799: Investigate rare decays

The KTeV Detector (E799)

- **Pure CsI Calorimeter: (Energy resolution < 1% at $\langle E_\gamma \rangle$ = 10GeV; π/e rejection of > 700)**
- **Four drift chambers: resolutions: ~100μm**
- **Transition radiation detectors: (π/e rejection of > 200) [E799]**
- **Intense beams: 5 x 10^{12} protons on target per spill → 5 x 10^9 kaons/spill**

- **For E_K ~ 70 GeV: K_S: $\gamma\beta c\tau$ ~ 3.5m**
  K_L: $\gamma\beta c\tau$ ~ 2.2 km



KTeV Result for Re(ε′/ε)

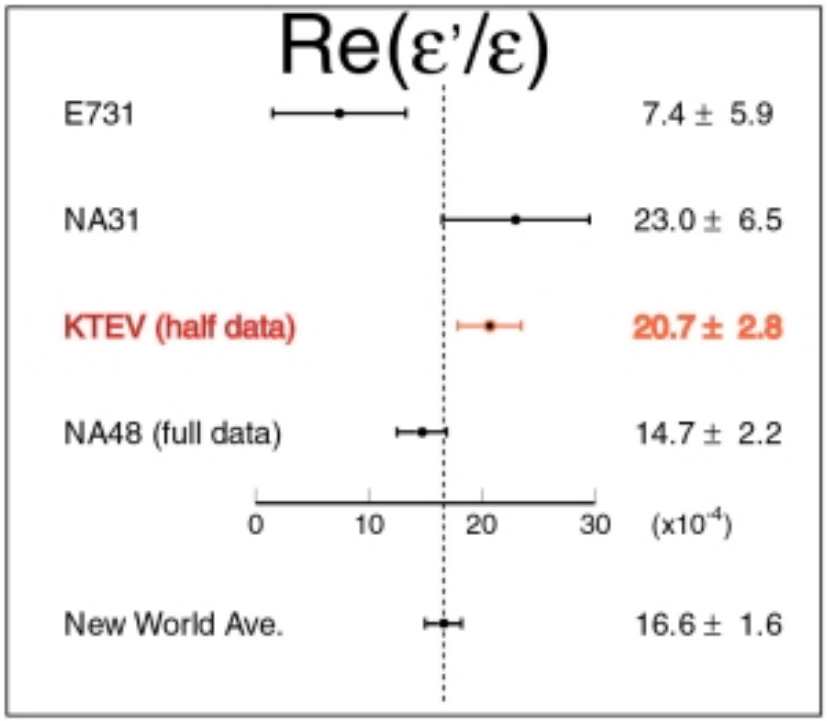
$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx 1/6 \left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1 \right]$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 1.5(\mathrm{stat}) \pm 2.4(\mathrm{syst})) \times 10^{-4}$$

$$= (20.7 \pm 2.8) \times 10^{-4} \text{ ('96+'97 data)}$$

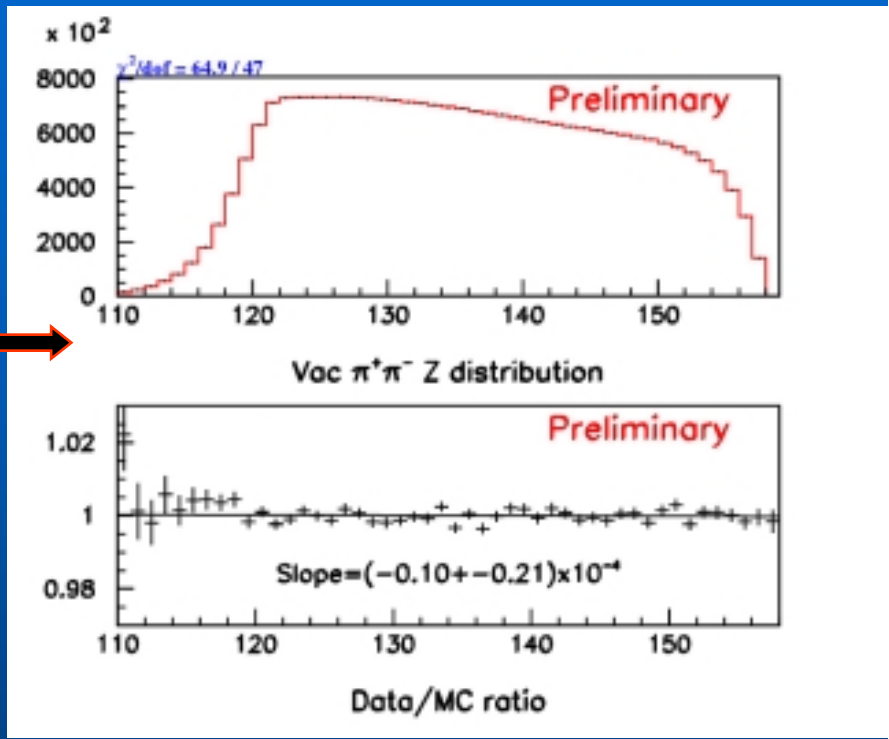
Published: *Measurements of direct CP violation, CPT symmetry, and other parameters in the neutral kaon system,* PRD 67, 012005 (2003).

Update on Re(ε′/ε): 1999 data sample is currently being analyzed (½ of the full data sample).



Analysis of Full E832 Data Sample

Data / Monte Carlo Comparison:
$K_L \to \pi^+\pi^-$ from the full E832 data sample including the 1999 data.



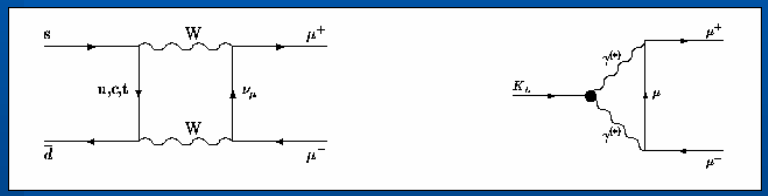
Improvements in systematics are needed to take advantage of the increase in statistics. (Numbers in the table are approximate.)

	Vacuum beam (K_L) $\pi^+\pi^-$ ($\times 10^6$)	Vacuum beam (K_L) $\pi^0\pi^0$ ($\times 10^6$)	Reg. Beam ("K_S") $\pi^+\pi^-$ ($\times 10^6$)	Reg. Beam ("K_S") $\pi^0\pi^0$ ($\times 10^6$)	$\sigma(\varepsilon'/\varepsilon)_{stat}$ ($\times 10^{-4}$)
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

$K_L \rightarrow e^+e^-\gamma$ branching ratio and form factor

$K_L\gamma\gamma^*$ form factor

- The form factor from $K_L \rightarrow e^+e^-\gamma$ decays can be used to calculate the "long-distance" contributions to the decay $K_L \rightarrow \mu^+\mu^-$.



- The Bergström, Massó and Singer (BMS) model is used to determine the form factor. The form factor is a function of the parameter α_{K^*}.

A typical signal event: $K_L \rightarrow e^+e^-\gamma$

KTEV Event Display

/disks/upsilondisk/jladue/eeg97.dat.10596.1

Run Number: 10596
Spill Number: 2
Event Number: 26988
Trigger Mask: 4
All Slices

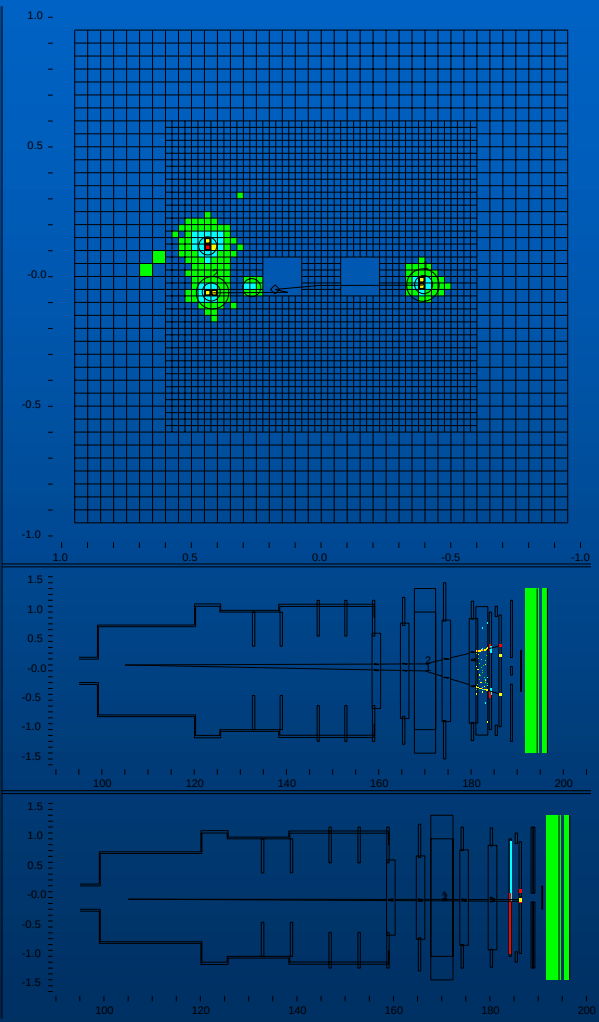
Track and Cluster Info
HCC cluster count: 3

ID	Xcsi	Ycsi	P or E
T 1:	-0.3915	-0.0335	+9.06
C 4:	-0.3945	-0.0317	8.88
T 2:	0.4193	-0.0631	-11.12
C 2:	0.4235	-0.0599	11.31
C 1:	0.4375	0.1178	34.09
C 3:	0.2677	-0.0432	1.19

Vertex: 2 tracks

X	Y	Z
0.1004	-0.0283	105.018

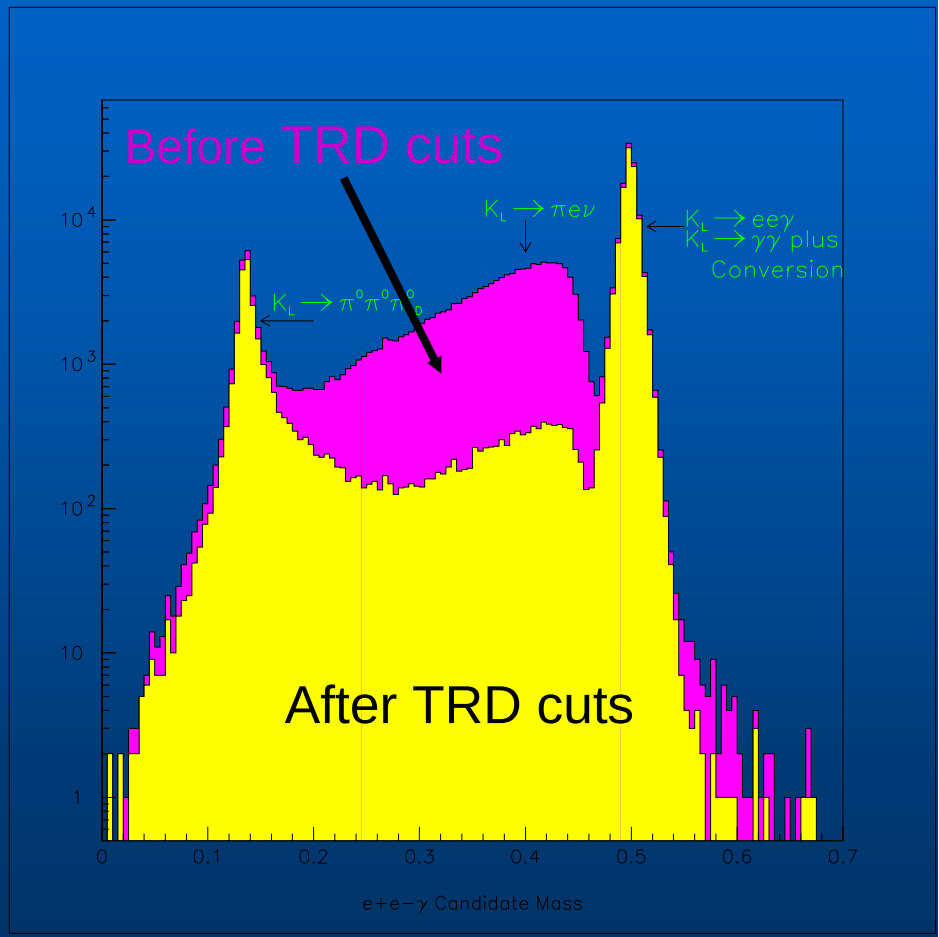
Mass=0.2812 (assuming pions)
Chisq=0.69 Pt2v=0.000930



$K_L \rightarrow e^+e^-\gamma$ event selection

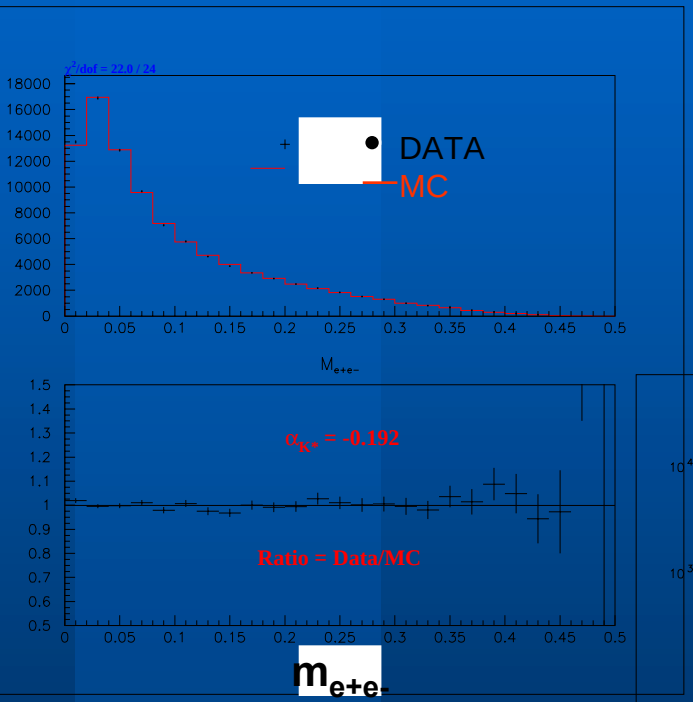
- A track separation cut of 1.5 mm rejects essentially all background from external conversions.
- The TRD particle identification is used to reject backgrounds from misidentified charge pions.

- In the 1997 data sample, 93,383 $K_L \rightarrow e^+e^-\gamma$ candidate events are observed.
- The background is estimated to be less than 0.1% after cuts.
- The normalization mode is $K_L \rightarrow \pi^0\pi^0\pi^0_D$. ($\gamma\gamma\ \gamma\gamma\ e^+e^-\gamma$)



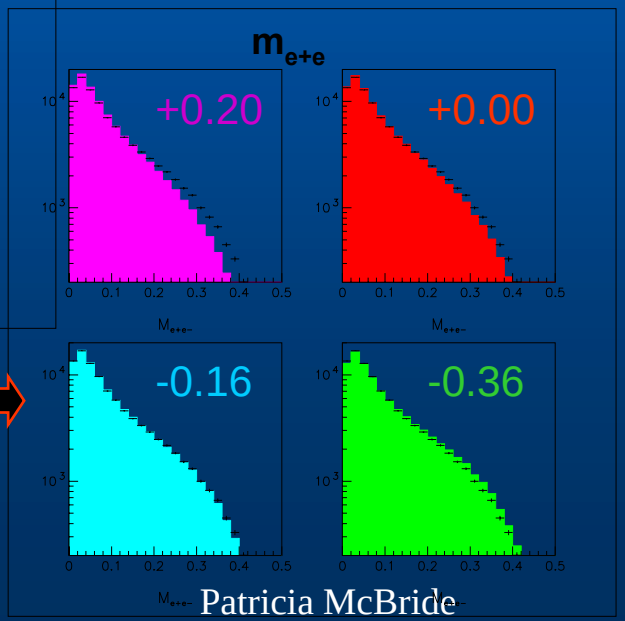
$K_L \rightarrow e^+e^-\gamma$ Results (1997, preliminary)

$BR(K_L \rightarrow e^+e^-\gamma) = (10.13 \pm 0.04(stat) \pm 0.06(sys) \pm 0.29(norm)) \times 10^{-6}$

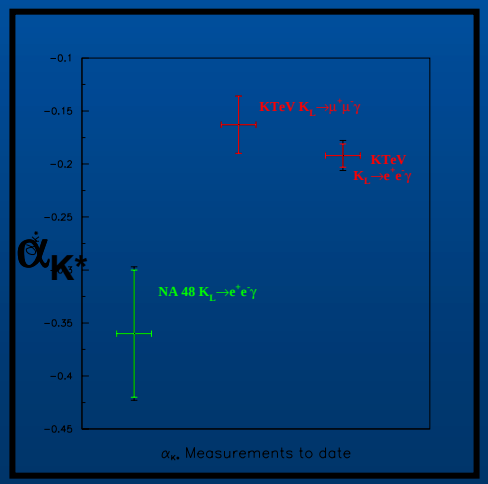


The mass of the e+e- system is sensitive to the BMS form factor parameter α_{K^*}.

$\alpha_{K^*} = -0.192 \pm 0.011(stat) \pm 0.009(sys)$



Comparisons to Monte Carlo with different form factor parameters α_{K^*}



Comparison to previous measurements

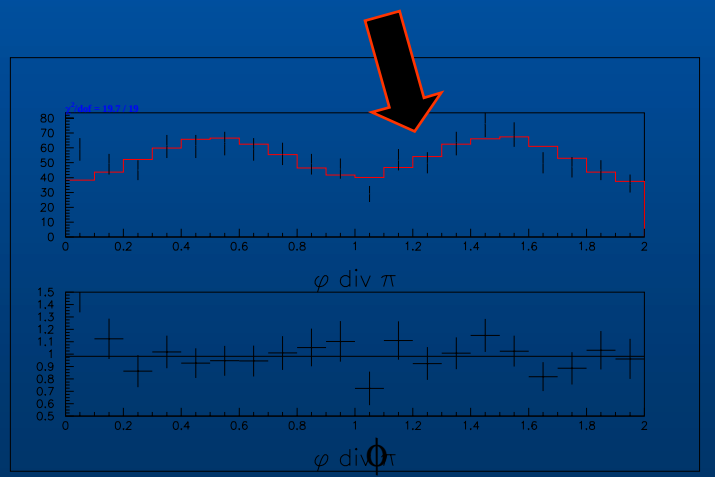
Measurement of $K_L \rightarrow e^+e^- e^+e^-$

Analysis of the Kaon Double-Dalitz Decay

- **Predicted rate: Br($K_L \rightarrow e^+e^- e^+e^-$) ≅ 3.5 x 10^{-8}**
- **Can extract the $K_L\gamma^*\gamma^*$ form factor from the M_{ee} distributions.**
- **The distribution of the angle ϕ between the two e^+e^- planes can be used to place a limit on CP-violating $K_L\gamma^*\gamma^*$ decays.**

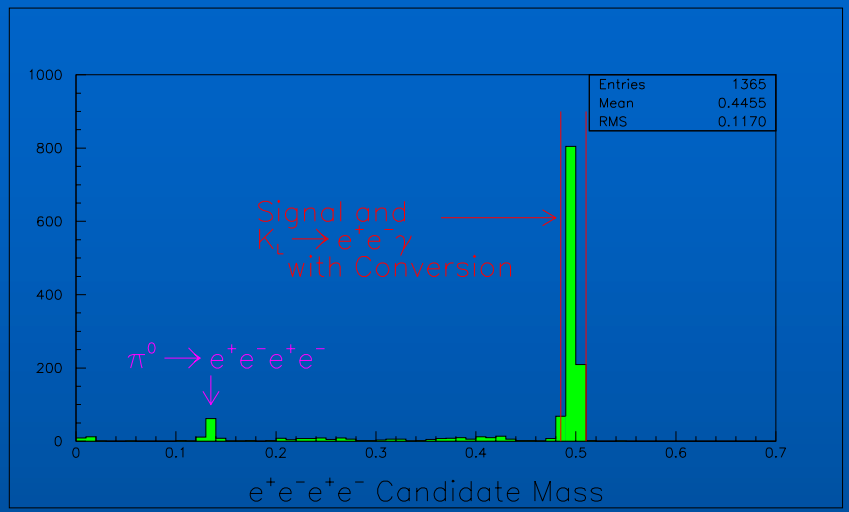
- KTeV has previously published an analysis of 441 events from the 1997 data sample:

  BR($K_L \rightarrow e^+e^- e^+e^-$) = (3.72 ± 0.18(stat) ± 0.23(sys)) X 10^{-8} (1997 data sample)



$K_L \rightarrow e^+e^- e^+e^-$ Branching Ratio

KTeV has analyzed the combined 1997 and1999 $K_L \rightarrow e^+e^- e^+e^-$ data sample and has made a preliminary measurement of the branching ratio.



$BR(K_L \rightarrow e^+e^- e^+e^-) = (4.07 \pm 0.12(stat) \pm 0.11(sys) \pm 0.16(norm)) \times 10^{-8}$

- 1056 events were observed with a background of 5 events.
- The normalization mode is $K_L \rightarrow \pi^0\pi^0_D\pi^0_D$. $(\gamma\gamma\, e^+e^-\gamma\, e^+e^-\gamma)$
- Backgrounds mainly from $e^+e^-\gamma$ plus a conversion.
- Form factor evaluation for the full data sample coming soon.

Search for $K_L \rightarrow \pi^0 e^+ e^-$

$$|K_L\rangle \cong |K_{ODD}\rangle + \varepsilon |K_{EVEN}\rangle$$

The decay $K_L \rightarrow \pi^0 e^+ e^-$ decay is of interest because it is expected to have a large CP-violating component.

The Standard Model prediction for the Branching Ratio is (3-10 x 10^{-12}).

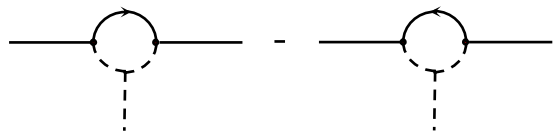
The major background is from the radiative Dalitz decay of the kaon $K_L \rightarrow ee\gamma\gamma$.

$\pi^0\gamma^* \rightarrow \pi^0 e^+ e^-$ **Indirect CP Violation**

$$Br(K_L \rightarrow \pi^0 e^+ e^-) = |\varepsilon|^2 \frac{\tau(K_L)}{\tau(K_S)} Br(K_S \rightarrow \pi^0 e^+ e^-)$$

$\pi^0\gamma^*$
$\pi^0 Z^*$ $\rightarrow \pi^0 e^+ e^-$ **Direct CP Violation**
$\pi^0 W^{+*} W^{-*}$

$$|K_{ODD}\rangle \propto |K^0\rangle - |\overline{K}^0\rangle$$



$$V_{td}V_{ts}^* - V_{td}^*V_{ts}$$

$$\propto \Im(V_{td}V_{ts}^*) \propto A^2\lambda^5\eta$$

$\pi^0\gamma^*\gamma^* \rightarrow \pi^0 e^+ e^-$ **CP conserving Helicity suppressed**

Backgrounds for $K_L \rightarrow \pi^0 e^+ e^-$

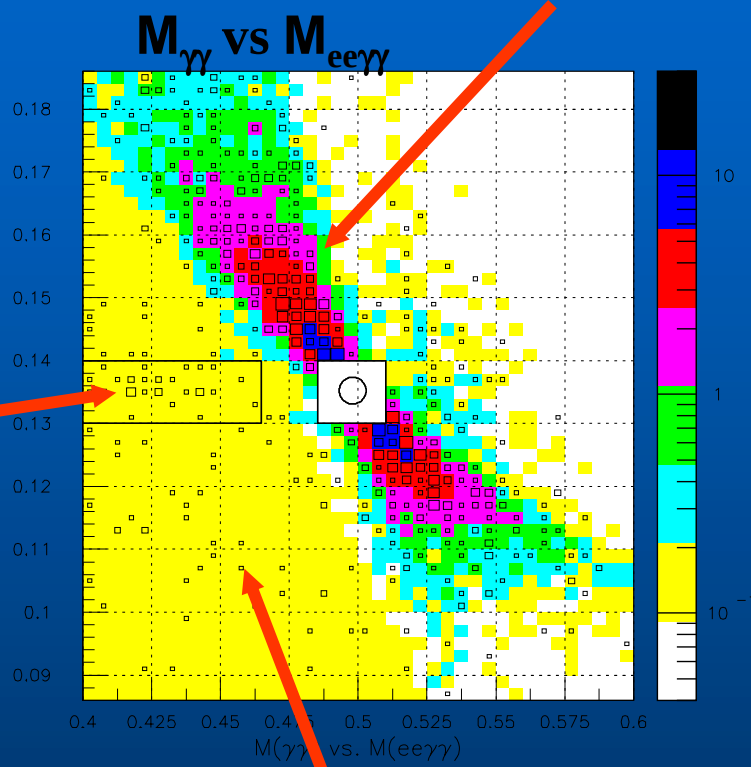
- Other backgrounds come from a kaon decay modes such as $K_L \rightarrow \pi^0\pi^0\pi^0_D$.
- The most significant and dangerous background comes from $K_L \rightarrow ee\gamma\gamma$ decays.

$K_L \rightarrow \pi^0\pi^0\pi^0_D$,

$\pi^{\pm}e^{\mp}\nu + \pi^0_{ACC}$

- The normalization mode is $K_L \rightarrow \pi^0\pi^0_D$

$K_L \rightarrow ee\gamma\gamma$

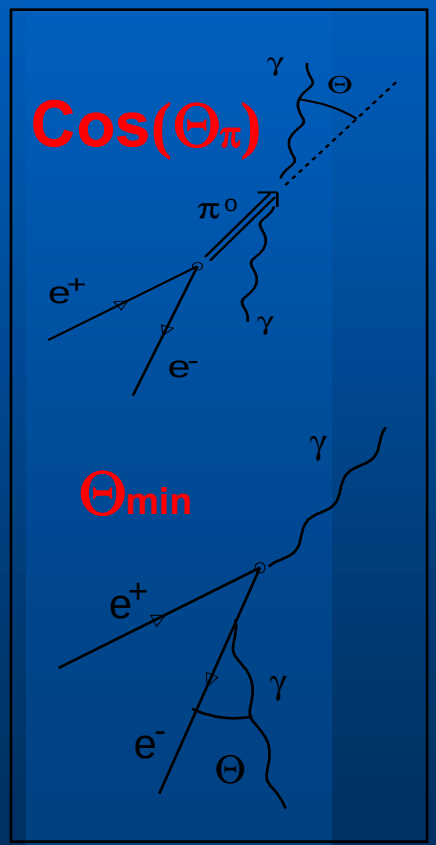


$K_L \rightarrow \pi^0\pi^0\pi^0$, $\pi^{\pm}e^{\mp}\gamma\nu + \gamma_{ACC}$

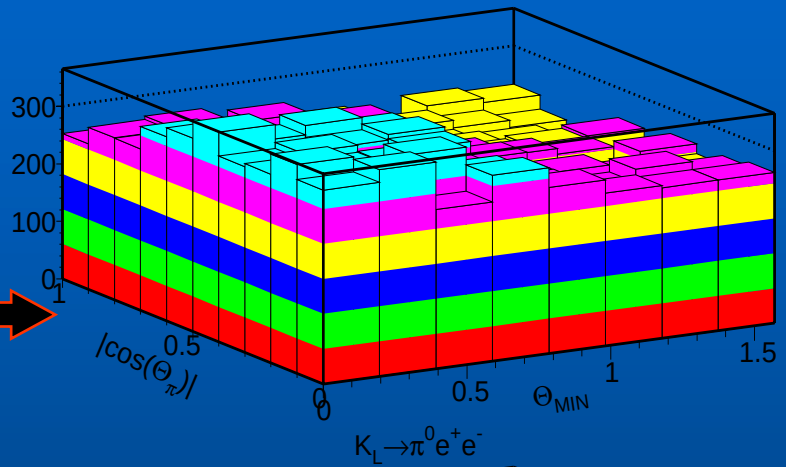
- $e^+\gamma X$
- $e^- X$
- γX

$K_L \to \pi^0 e^+ e^-$ *vs.* $K_L \to e^+ e^- \gamma\gamma$

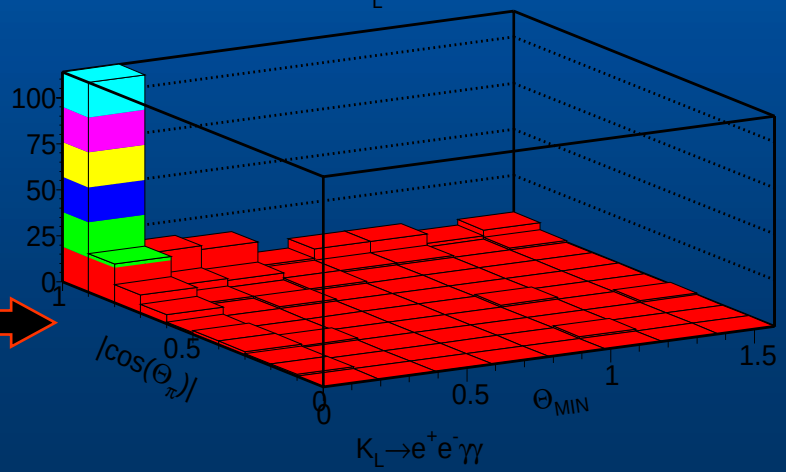
Kinematic cuts are use to eliminate background from $K_L \to e^+e^-\gamma\gamma$



$K_L \to \pi^0 e^+ e^-$



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

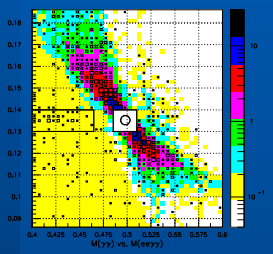


Background from $K_L \to e^+e^-\gamma\gamma$

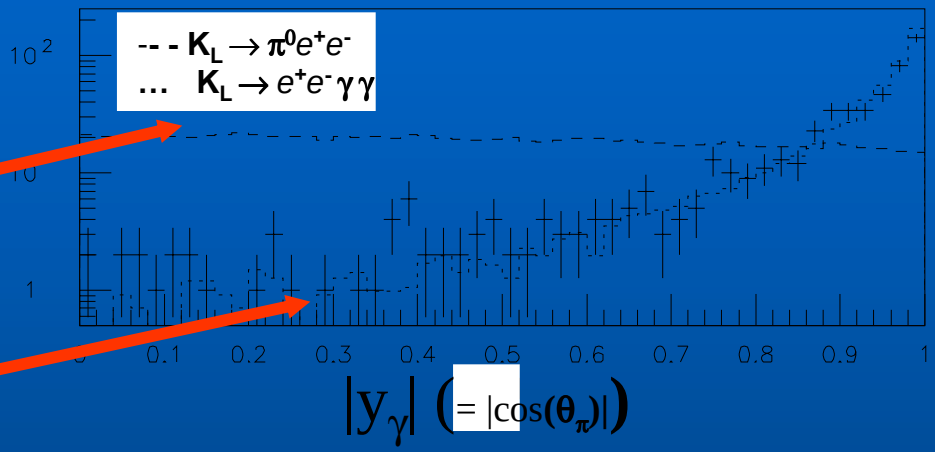
Check of background: data against MC:

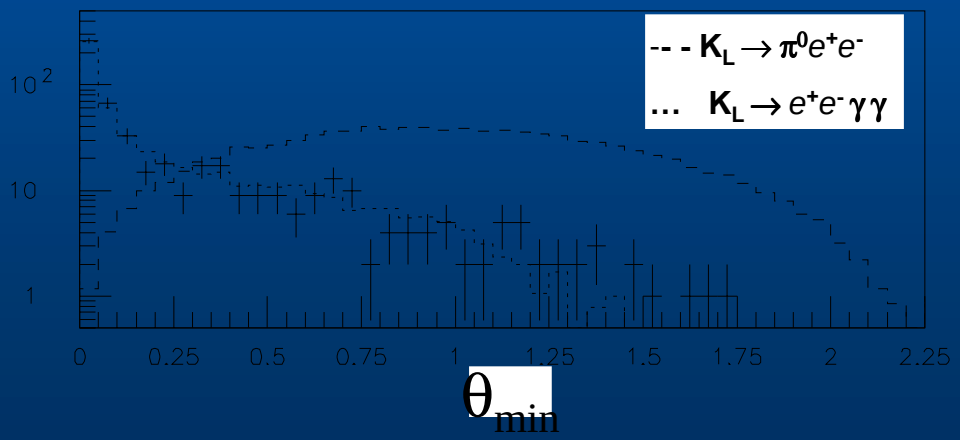
$K_L \to \pi^0 e^+ e^-$

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



Studied $K_L \to e^+e^-\gamma\gamma$ data by selecting events in a diagonal swath and outside the signal box in $M_{\gamma\gamma}$ vs $M_{ee\gamma\gamma}$ plot.

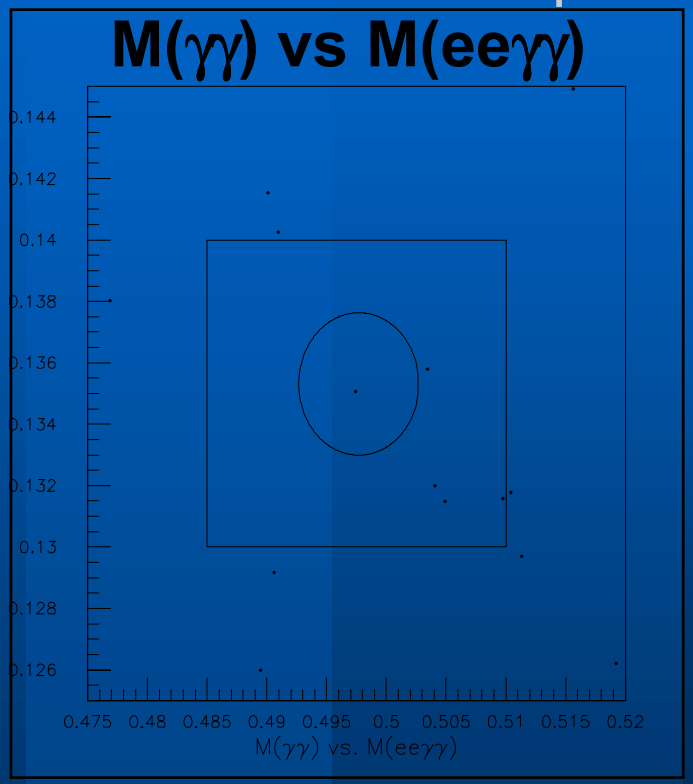




New Limit for $K_L \rightarrow \pi^0 e^+ e^-$

Previous Result (E799II, 1997):
$Br(K_L \rightarrow \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$

1999 Data Sample



NEW:

1999 *preliminary:*

After all cuts 1 event is observed in signal box;
expected from background = 0.99 ± 0.35 events

$Br(K_L \rightarrow \pi^0 e^+ e^-) < 3.5 \times 10^{-10}$ (1999)

Combined Limit:

$Br(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ (full data sample, preliminary)

KTeV Rare Decay results (1)

Results are for '97 data sample except where noted.

Decay Mode	Publ.	# Events	BR
Direct CP Violation			
$K_L \to \pi^0 e^+ e^-$	x 97	2	$< 5.1 \times 10^{-10}$
$K_L \to \pi^0 e^+ e^-$	97+99	3	$< 2.8 \times 10^{-10}$
$K_L \to \pi^0 \mu^+ \mu^-$	x	2	$< 3.8 \times 10^{-10}$
$K_L \to \pi^0 \nu\nu$	x	0	$< 5.9 \times 10^{-7}$
Indirect CP Violation			
$K_L \to \pi^+ \pi^+ \gamma$	x	8,669	$(2.08 \pm 0.03) \times 10^{-2}$ x $B(K_L \to \pi^+ \pi^+)$
$K_L \to \pi^+ \pi^- e^+ e^-$		1,558	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$
χPT and VMD			
$K_L \to \pi^0 \gamma\gamma$	x	884	$(1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$
$K_L \to \pi^0 e^+ e^- \gamma$	x	48	$(2.34 \pm 0.35 \pm 0.13) \times 10^{-8}$
$K_L \to \pi^0 \pi^0 e^+ e^-$	x	1	$< 5.4 \times 10^{-9}$

KTeV Rare Decay results (2)

Decay Mode	Publ.	# Events	Branching Ratio
		$K\gamma\gamma^*$ Vertex	
$K_L \to e^+e^-\gamma$		93.4k	$(10.13 \pm 0.04 \pm 0.06 \pm 0.29) \times 10^{-6}$
$K_L \to \mu^+\mu^-\gamma$	x	9,327	$(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$
$K_L \to e^+e^-\gamma\gamma$	x	1,543	$(5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$
$K_L \to \mu^+\mu^-\gamma\gamma$	x	4	$(1.04^{+0.75}_{-0.59} \pm 0.07) \times 10^{-8}$
		$K\gamma^*\gamma^*$ Vertex	
$K_L \to e^+e^-\ e^+e^-$	x 97	441	$(3.72 \pm 0.18 \pm 0.23) \times 10^{-8}$
$K_L \to e^+e^-\ e^+e^-$	97+99	1056	$(4.07 \pm 0.12 \pm 0.11 \pm 0.16) \times 10^{-8}$
$K_L \to e^+e^-\ \mu^+\mu^-$	x 97+99	132	$(2.69 \pm 0.24 \pm 0.12) \times 10^{-9}$
		Lepton Flavor Violation	
$K_L \to e^{\pm}e^{\pm}\mu^7\mu^7$	x 97+99	0	$< 4.12 \times 10^{-11}$
$K_L \to \pi^0\mu^{\pm}e$		2	$< 4.4 \times 10^{-10}$

Summary and Conclusions

- **Preliminary results for $K_L \to \pi^0 e^+e^-$ and $K_L \to e^+e^- e^+e^-$ from the full E799 data sample were presented.**
- **The first rare kaon decay results from 1999 KTeV data sample were published this past year.**
  - **$K_L \to e^+e^- \mu^+\mu^-$ branching ratio and form factor**
- **The KTeV 1999 data set will double the statistics of the 1996-97 data reducing the statistical error for $Re(\varepsilon'/\varepsilon)$ to about 10^{-4}.**
- **More results from KTeV rare decays expected soon –**
  - **$K_L \to e^+e^- e^+e^-$ form factor will all data**
  - **$K_L \to e^+e^- \gamma$ form factor with full data sample**
  - **$K_L \to \pi^0 \pi^0 \pi^0$ with $\pi^0 \to e^+e^- e^+e^-$**
  - **$K_L \to \pi^+ \pi^- e^+e^-$ update with full data set**