Recent Results from KTeV

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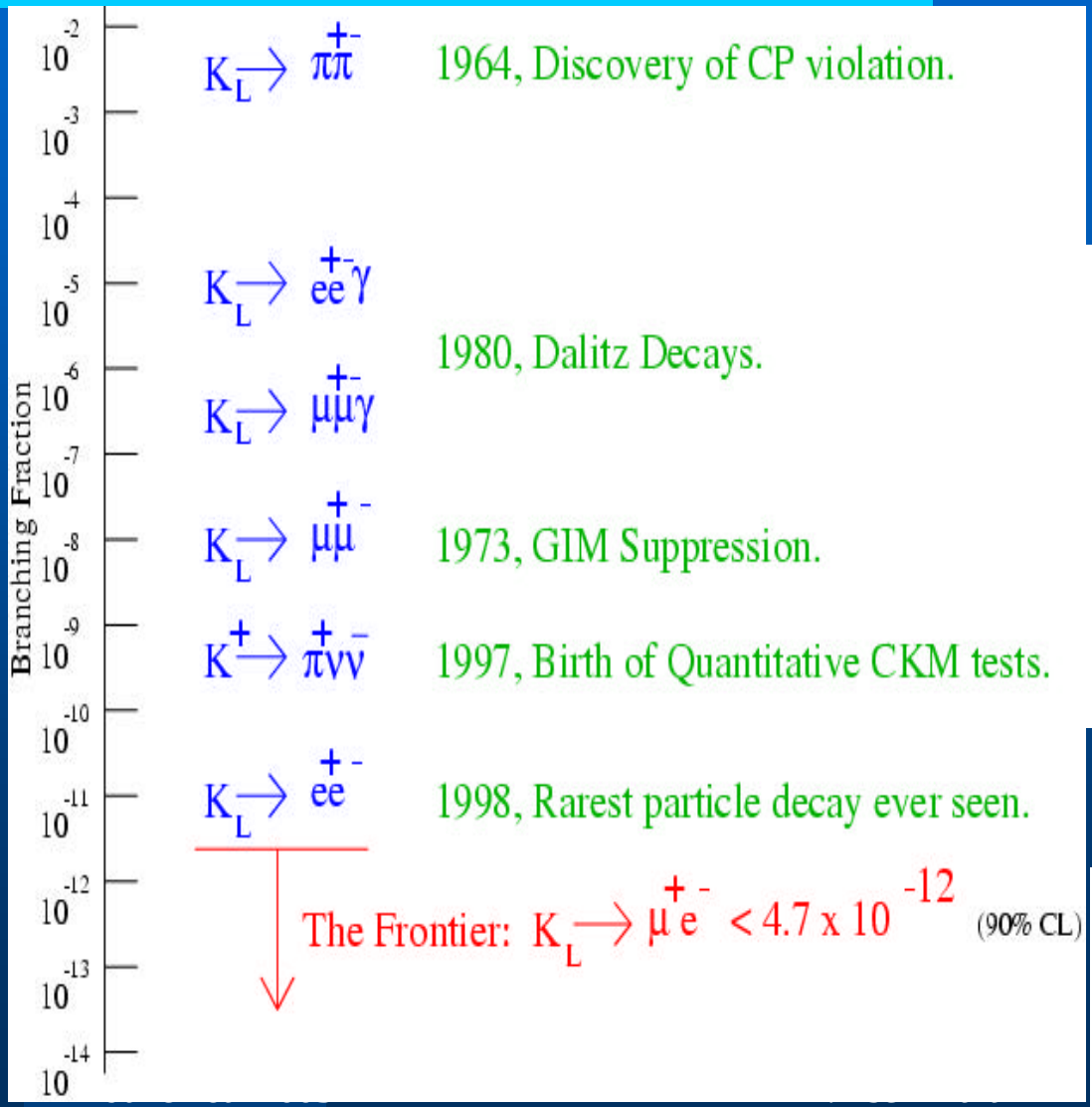
The Context of KTeV in HEP:

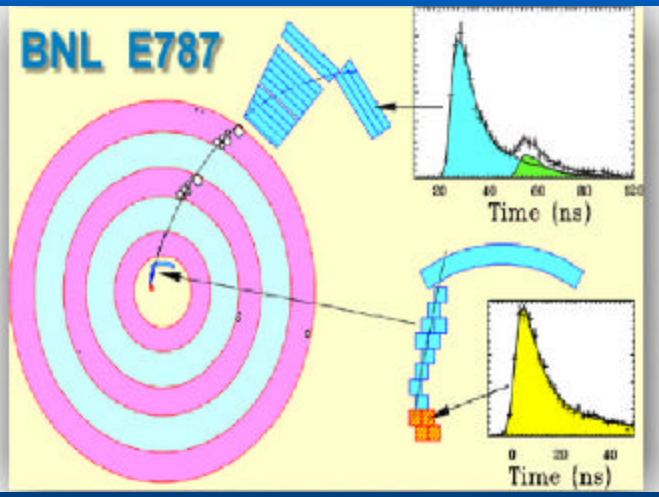
- **The Energy Frontier:** **Where the frontier lies is reckoned from measurement of virtual effects. This inference requires good theory. (ex: W/Z + top ⇨ Higgs)**

- **The Precision Frontier: (ex: g_m-2)**
  From KTeV: Direct CPV, CPT tests.

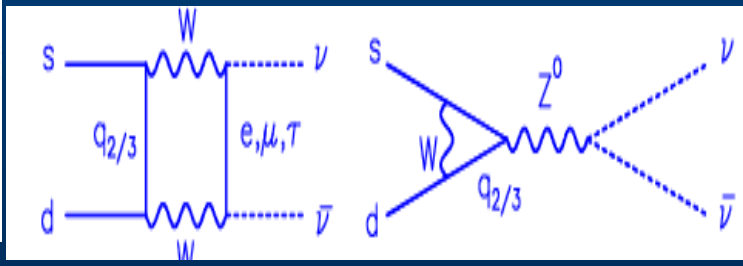
- **The Rarity Frontier: (ex: K ⇨ $p n \bar{n}$)**
  From KTeV: K_L ⇨ $p^0 l \bar{l}$; $p^0 me$; g*g; g*g*

Evolution of the Rarity Frontier…





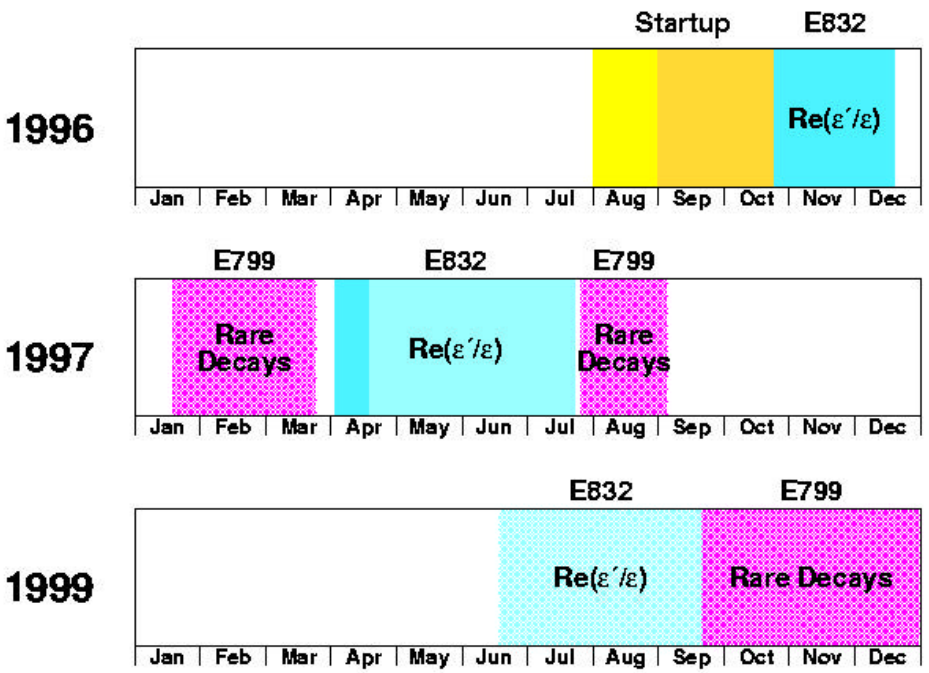
$B(K^+ \to p^+nn) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$



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) (Decay Amplitude Matter-Antimatter Asymmetry)

E799: Advance the K_L Rarity Frontier by ~ x50.

KTeV Menu Today:

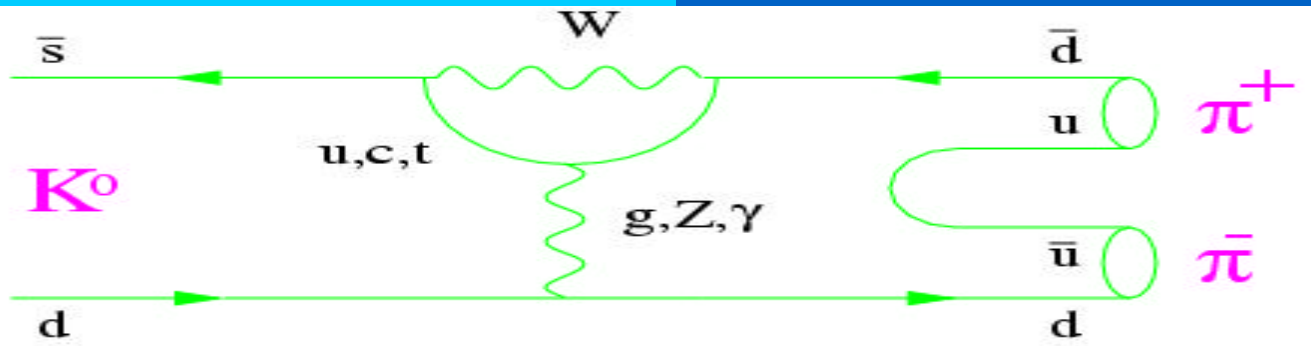
- **Prospects of Precision Measurements:**
  Re(e'/e); Direct CP Violation.

Based on 600 Billion K_L decays:

- **New Results on Medium Rare Physics:**
  $K_L \Rightarrow p^+p^0e^-n$; $K_L \Rightarrow e^+e^-g$; $K_L \Rightarrow e^+e^-e^+e^-$.

- **New Results on Ultra Rare Physics:**
  $K_L \Rightarrow p^0e^+e^-$; p^0me.

Measurement of Re(ε'/ε)



$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon'$$

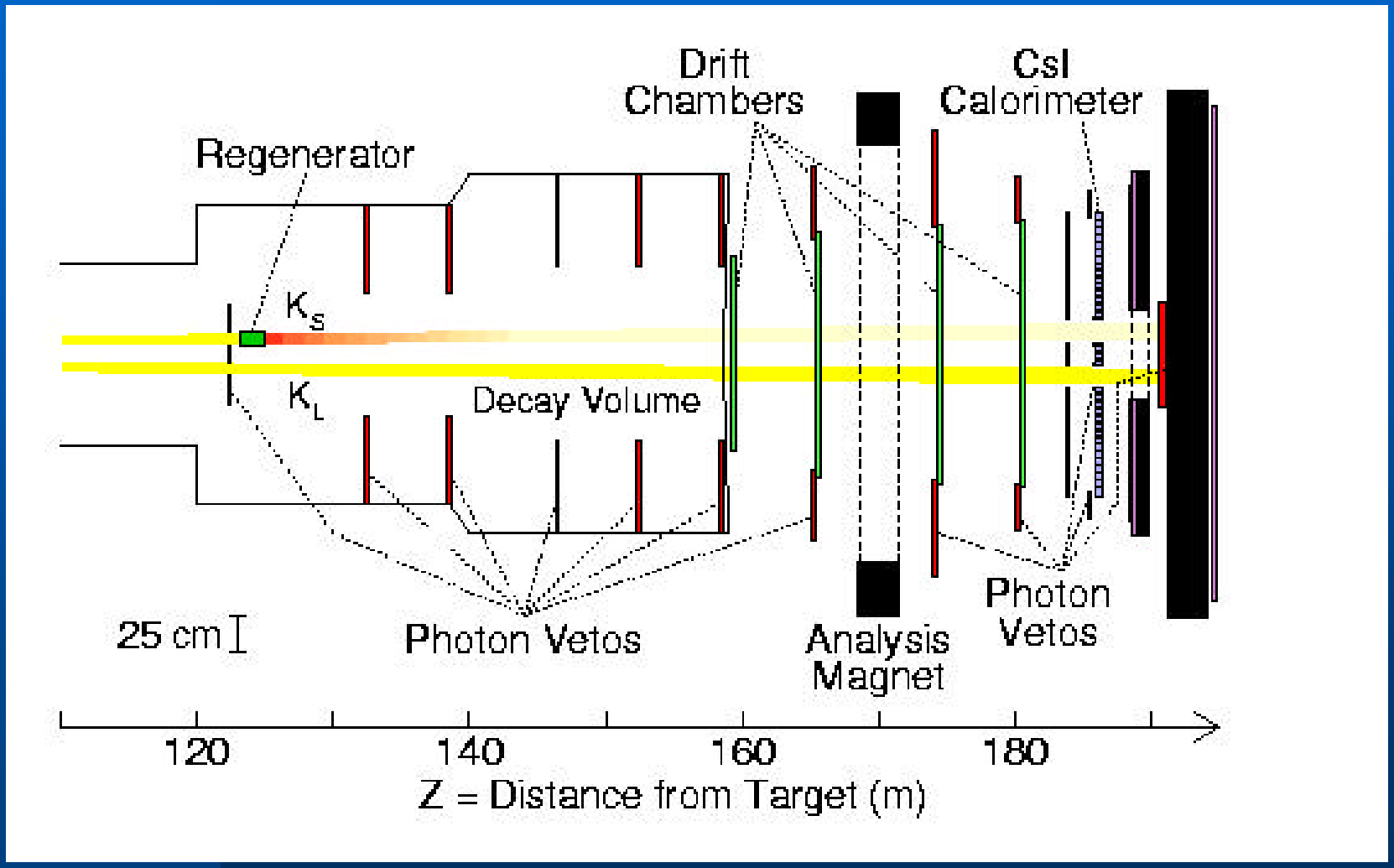
$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\ \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

IF the 4 modes are taken

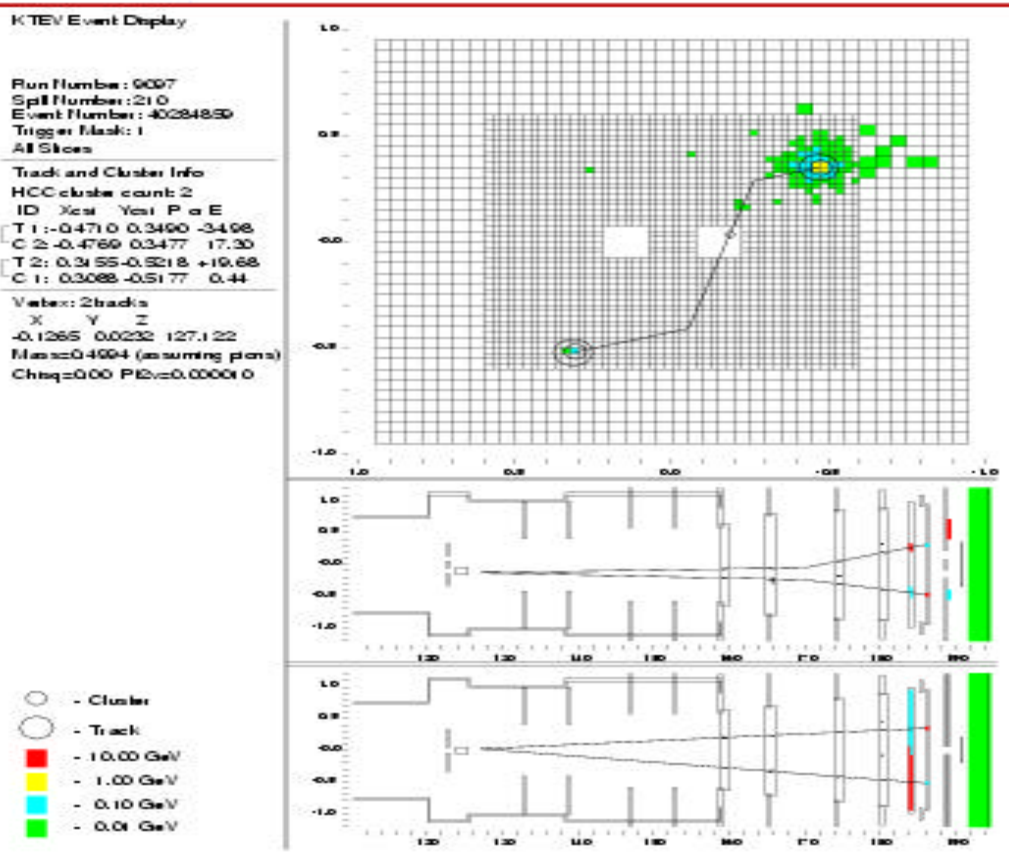
- simultaneously
- in the same decay region

$$R = \frac{N(K_L \to \pi^0\pi^0)\ N(K_S \to \pi^+\pi^-)}{N(K_S \to \pi^0\pi^0)\ N(K_L \to \pi^+\pi^-)}$$

The KTeV Detector (E832)

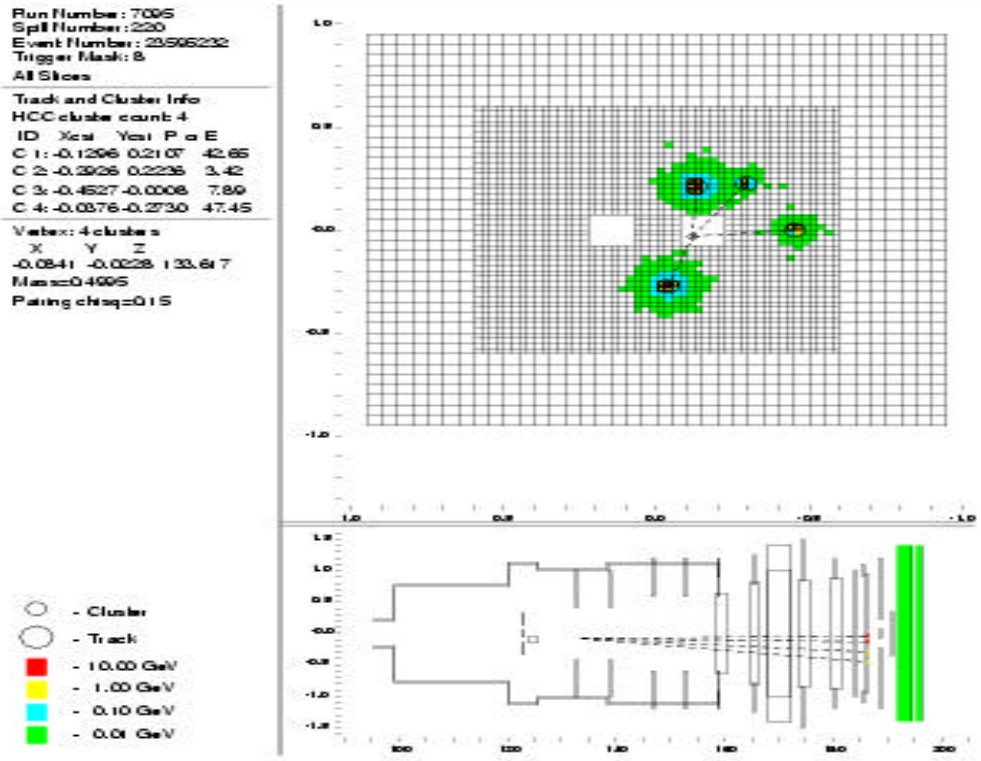


Sample $K \to \pi^+\pi^-$ Event



- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using x-vertex position
- Clearance cuts define fiducial volume.

Sample $K \to \pi^0\pi^0$ Event



- CsI calorimeter to reconstruct photons energies and positions
- z_v determined as average of

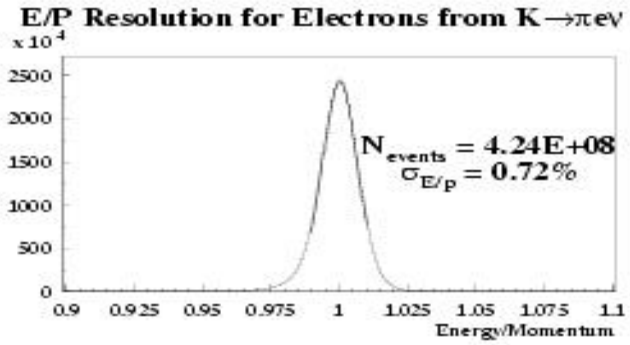
$$z_{\pi^0} = \sqrt{E_1 E_2} R_{12} / m_{\pi^0}$$

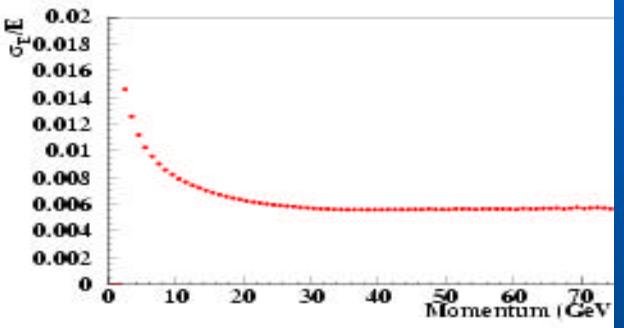
- Regenerator/Vacuum beam identification using x-center of enegy
- Fiducial volume defind by veto detectors & z_v

The KTeV Detector Performance

NEUTRAL:

- CsI energy res: 0.7% at 15 GeV (1.3% at 3 GeV)
- CsI position res: $\sim$ 1 mm





CHARGED:

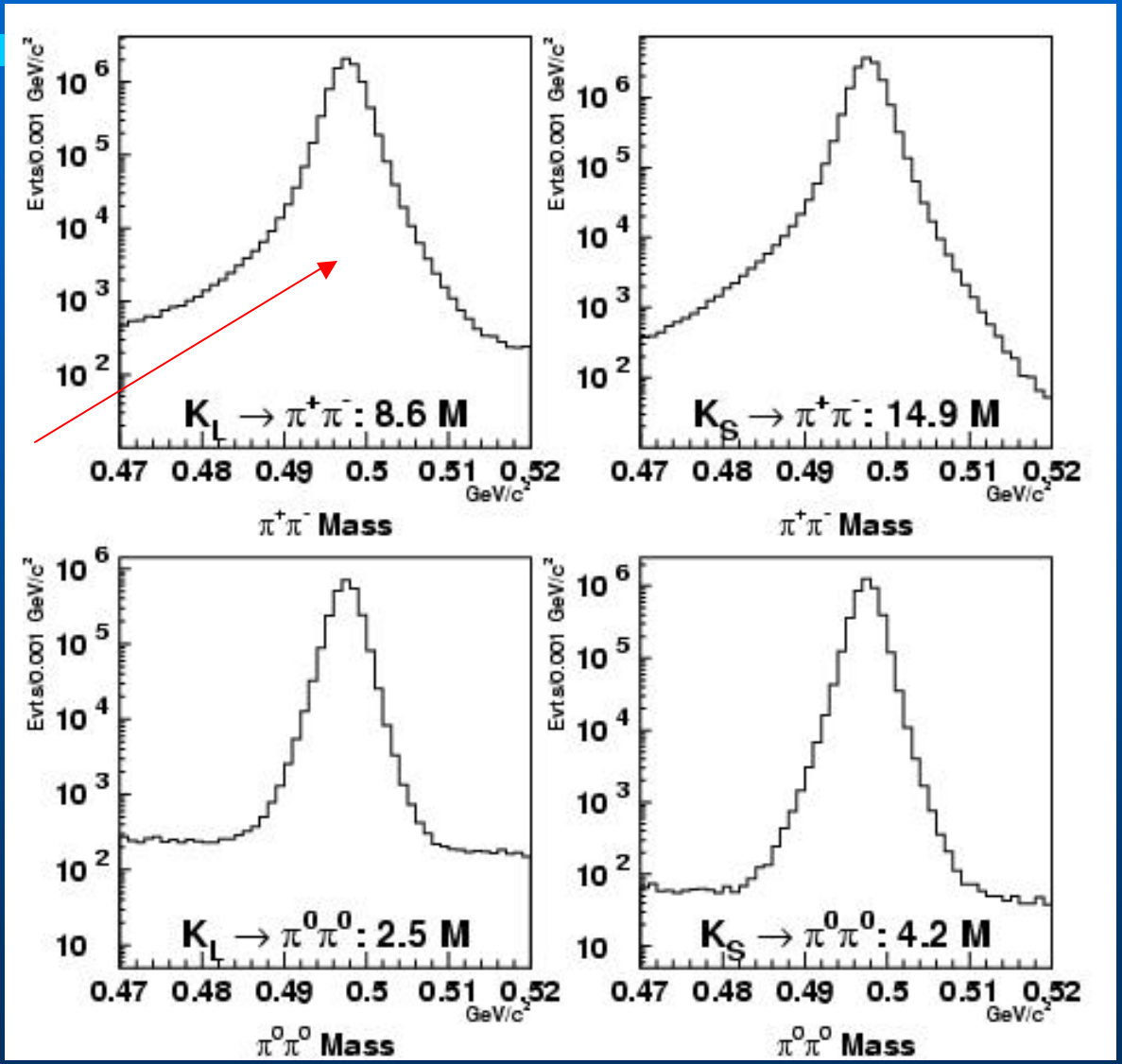
- Drift Chamber resolution: 100 μm.
- Momentum resolution:

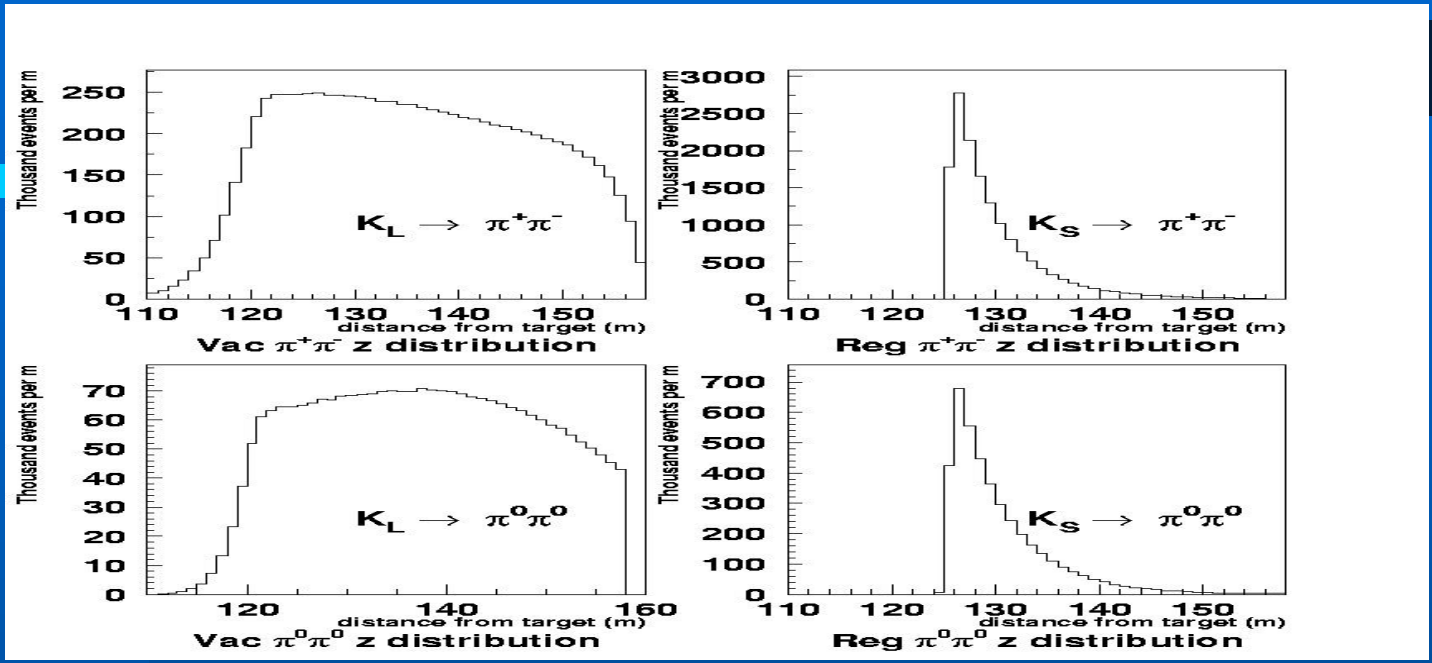
$$\frac{\sigma_p}{p} = 0.17\% \oplus 0.0071\% \cdot p \text{ [GeV]}$$

$$\sigma(M_{\pi^+\pi^-}) \sim \sigma(M_{\pi^0\pi^0}) \sim 1.5 \text{ MeV}$$

Raw $K^0 \Rightarrow \pi\pi$ Statistics(1997): $\sigma(\varepsilon'/\varepsilon) = 1.7 \times 10^{-4}$

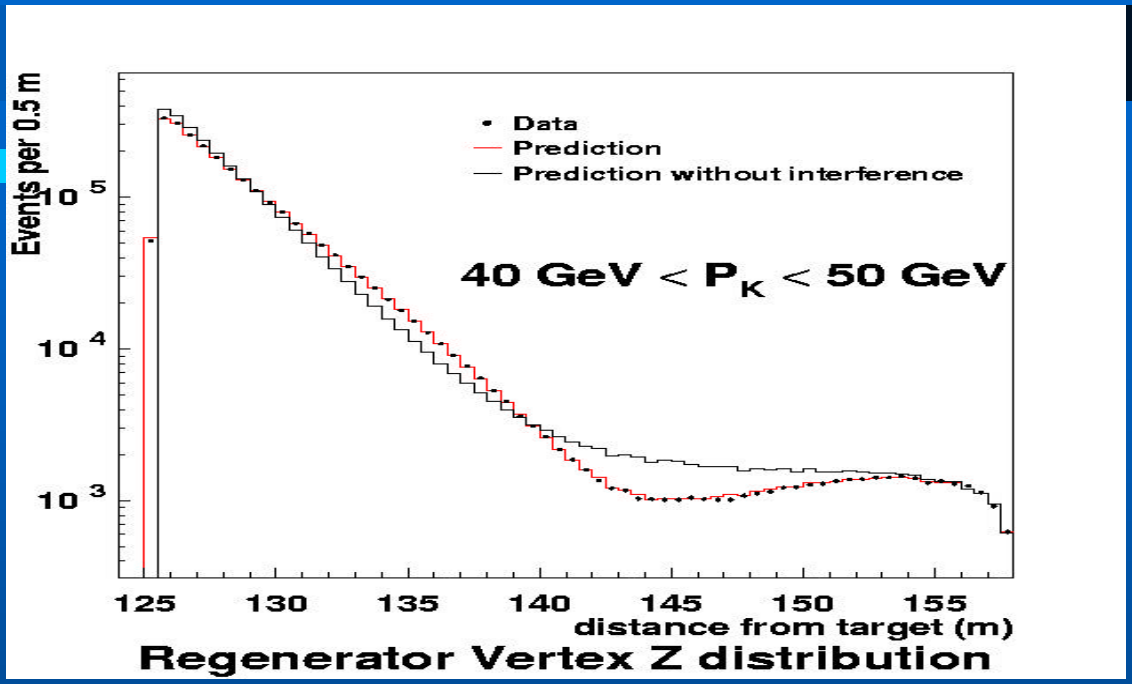
CPV first found with 47 $K_L \rightarrow \pi^+\pi^-$ events!





- **K_L and K_S decays have different decay distributions.**
- **Use Monte Carlo to understand acceptance correction: ~80 x 10^{-4}** (ε'/ε units; ~5% in R)
  - **~70 x 10^{-4} from geometry**
  - **~10 x 10^{-4} from resolutions and inefficiencies**

Δm, τ_S, f_{+-} Measurements :



Published:

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

$\Delta m = (52.61 \pm 0.15) \times 10^{8}\ hs^{-1}$

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

$F_{+-} = [(44.12 \pm 0.72\ (stat) \pm 1.15\ (syst)]^{o}$

$\Delta f = [\pm 0.39 \pm 0.22\ (stat) \pm 0.48\ (syst)]^{o}$

$Im(\varepsilon'/\varepsilon) = [-22.9 \pm 13\ (stat) \pm 28\ (syst)] \times 10^{-4}$

KTeV Result for Re(ε′/ε)

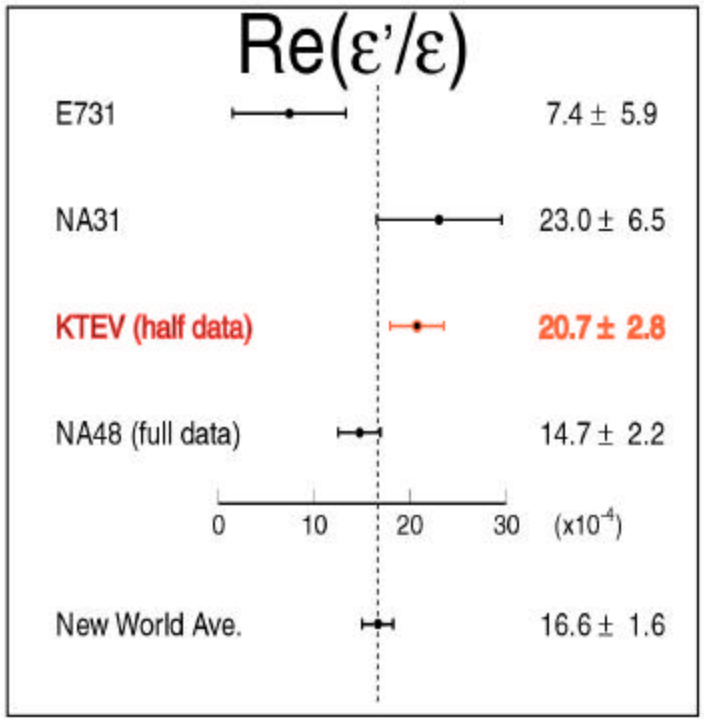
$$\mathrm{Re}(\varepsilon'/\varepsilon) \quad 1/6\left[\frac{\Gamma(K_L\to\pi^+\pi^-)/\Gamma(K_S\to\pi^+\pi^-)}{\Gamma(K_L\to\pi^0\pi^0)/\Gamma(K_S\to\pi^0\pi^0)}-1\right]$$

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

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

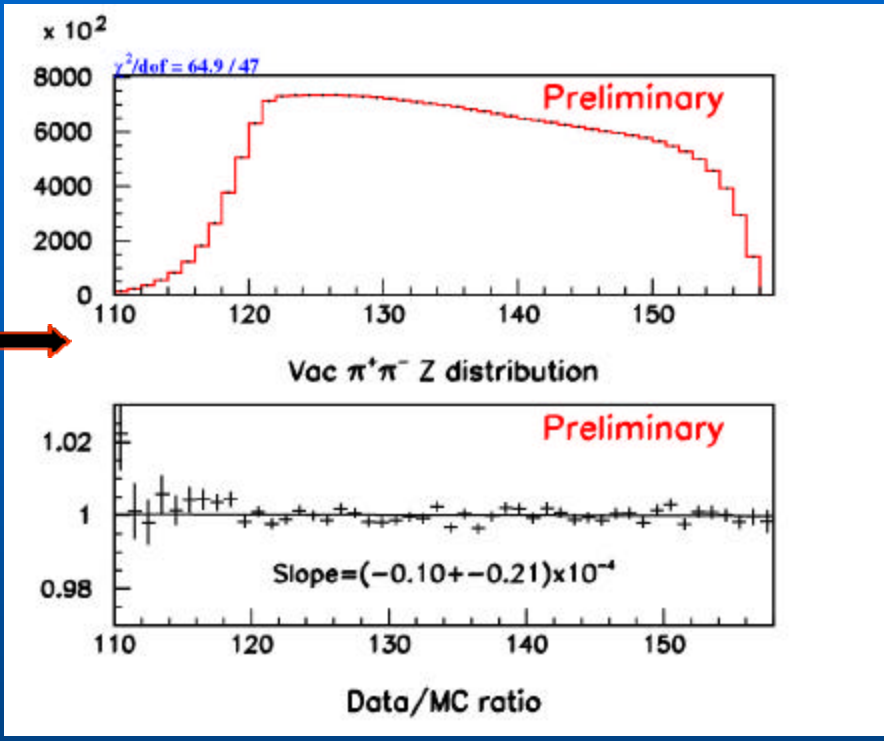
Published: *Measurements of direct CP violation, CPT symmetry, and other parameters in the neutral kaon system,* PRD 67, 012005 (2003).

Update on $\mathrm{Re}(\varepsilon'/\varepsilon)$: 1999 data sample is currently being analyzed (½ of the full data sample).



Analysis of Full E832 Data Sample

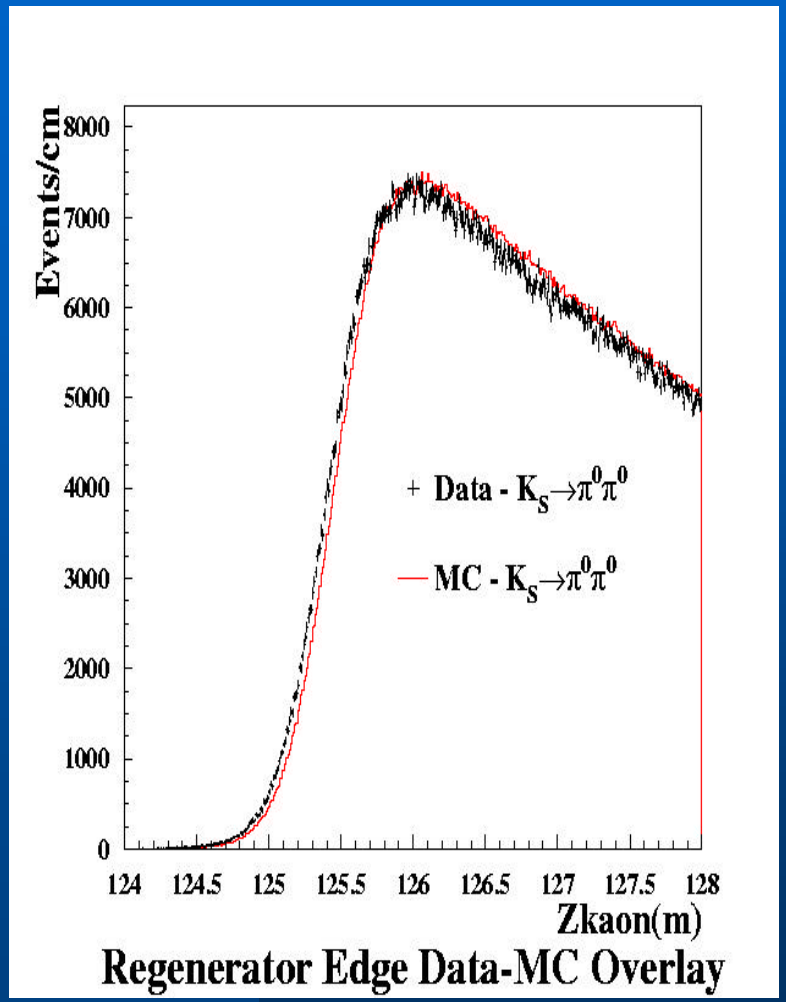
Data / Monte Carlo Comparison:
$K_L \to \pi^+\pi^-$ from the full E832 data sample including the 1999 data.

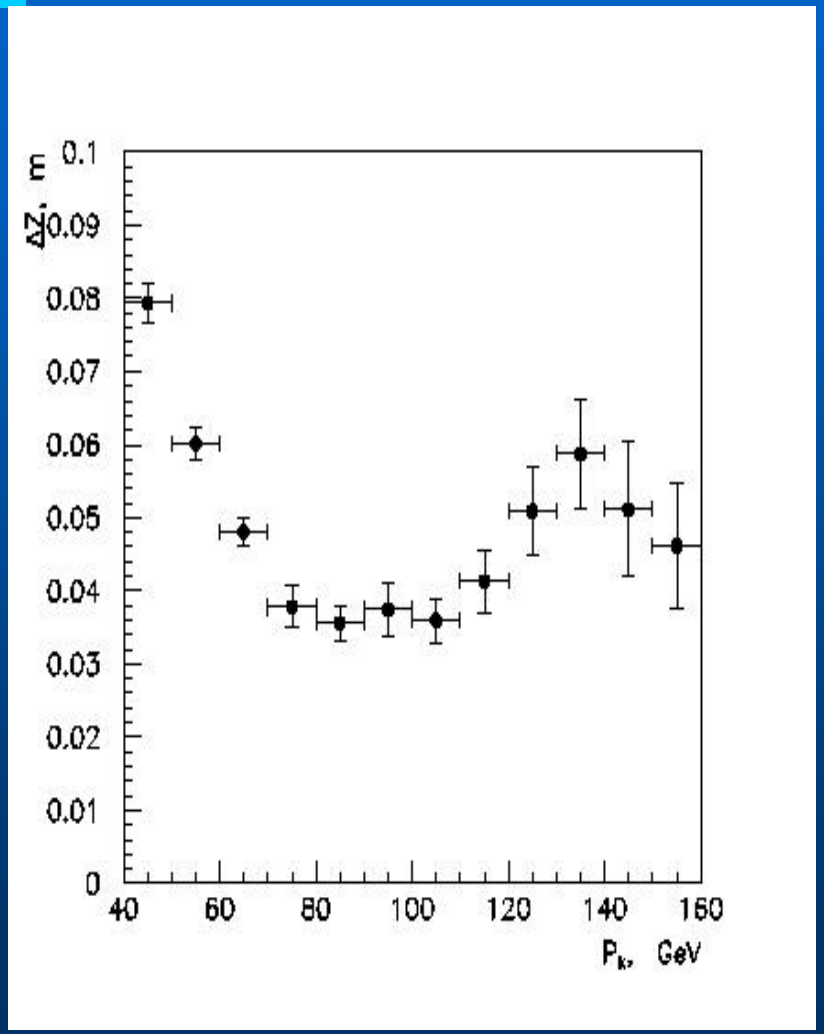


Improvements in systematics are needed to take advantage of the increase in statistics. (Numbers in the table are approximate.)

	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

Understanding the Neutral Mode Energy Scale is the Lead Systematic





Large Control Data Sets Used to Control Systematics…

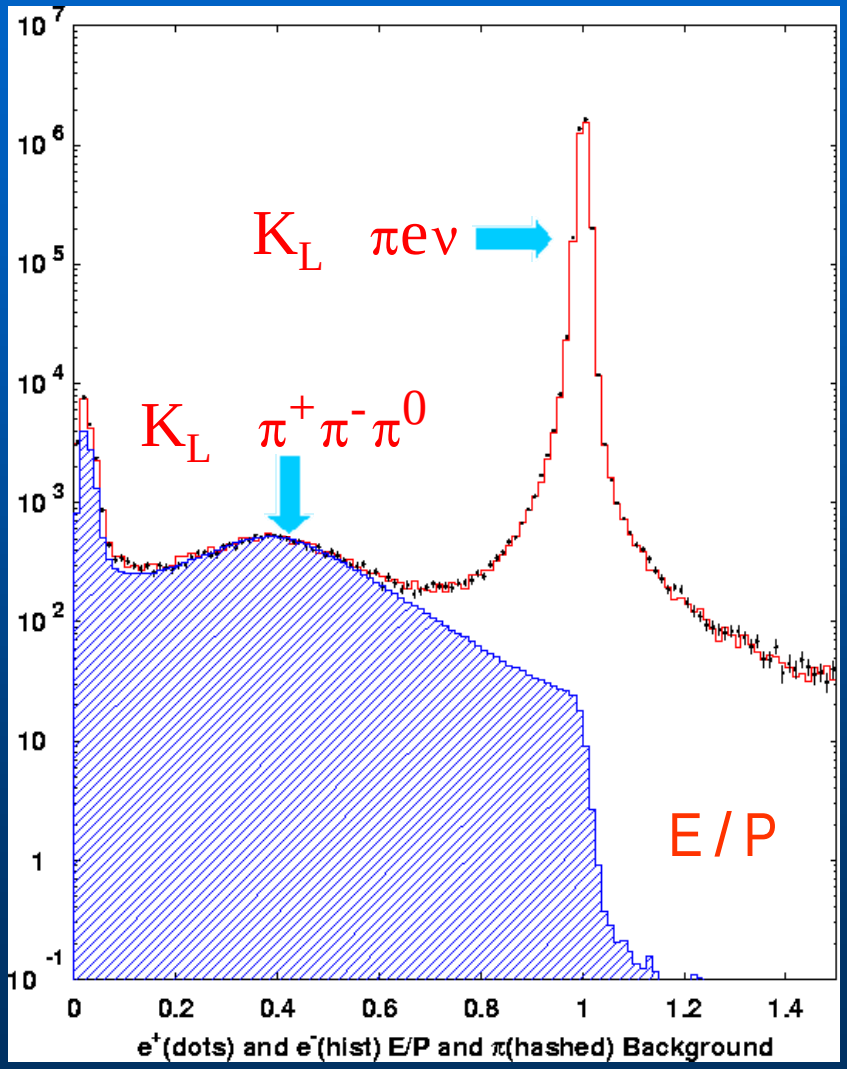
Getting From here to there: Calibrate with electrons, goal is photon response.

Issues:

Different angular distributions.

Different depth distributions.

Skewed electron momentum.



KTeV Future Prospects for the Precision Frontier:

Improvements in neutral mode Reconstruction will enable systematics on Re(ε'/ε) and Im(ε'/ε) [CPT test] to approach the existing statistical accuracy.

Measurement of Re(ε'/ε) will remain the most precise of probe of Decay-Amplitude CP-Violation for some time. Significantly better theory is required to connect the this measurement to quark level dynamics.

Lattice Community: The world is waiting!

Towards a New Precision Measurement of $K_L \to \pi^+\pi^0 e^- \nu_e$

Underlying physics

The invariant amplitude for K^0_{e4} can be written as

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \sin\theta_C \bar{u}_\nu \gamma_\mu (1-\gamma_5) v_e \langle \pi\pi | V^\mu + A^\mu | K \rangle,$$

with the vector and axial hadronic currents

$$\langle \pi\pi | V_\mu | K \rangle = \frac{1}{M^3} H \epsilon_{\mu\lambda\alpha\beta} K_\lambda (p_1+p_2)^\alpha (p_1-p_2)^\beta$$

$$\langle \pi\pi | A_\mu | K \rangle = \frac{1}{M} \left[F(p_1+p_2)_\mu + G(p_1-p_2)_\mu + R(K-p_1-p_2)_\mu \right].$$

Given the available energy in the final state one can write

$$F = f_S e^{i\delta_S} + f_P e^{i\delta_P} \cos\theta_\pi, \quad G = g e^{i\delta_P}, \quad H = h e^{i\delta_P}$$

Isospin symmetry, and $\Delta I = 1/2$ rule, dictate that the neutral K^0_{e4} is dominated by P waves for the $\pi\pi$ state. In contrast, S waves are predominant in the charged K^+_{e4} mode.

$$d^5\Gamma = \frac{G_F^2 \sin^2\theta_C}{(4\pi)^6 M_K^3} \beta I(s_\pi, s_l, \theta_\pi, \theta_e, \Phi) ds_\pi ds_l d\cos\theta_e d\cos\theta_\pi d\Phi$$

where I holds all the dependence on the form factors

$$\begin{aligned} I &= I_1 + I_2\cos 2\theta_e + I_3 \sin^2\theta_e \cos 2\Phi + I_4 \sin 2\theta_e \cos\Phi + I_5 \sin\theta_e \cos\Phi \\ &+ I_6 \cos\theta_e + I_7 \sin\theta_e \sin\Phi + I_8 \sin 2\theta_e \sin\Phi + I_9 \sin^2\theta_e \sin 2\Phi, \end{aligned}$$

An approximate expression of the total decay amplitude is

$$\Gamma = 1970F^2 + 400G^2 + 3H^2 + \ldots$$

Therefore, we expect:

- Clear determination of F and G;
- Small sensitivity to H;
- f_P should dominate over f_S;

First observation of 16 events at Brookhaven[a].

E731(FNAL) collected 729 ± 15 events, reporting a branching ratio [b,c]:

$$\frac{\Gamma(K_L \to \pi^0 \pi^\pm e^\mp \nu(\bar{\nu}))}{\Gamma(K_L \to \text{all})} = [5.16 \pm 0.20(\text{stat}) \pm 0.22(\text{syst})] \times 10^{-5}$$

and measuring the neutral K^0_{e4} form factors

$$\begin{aligned} f_s/g &= 0.010 \pm 0.016 \pm 0.017 \\ f_p/g &= -0.079 \pm 0.049 \pm 0.022 \\ h/g &= -0.07 \pm 0.31 \pm 0.31 \end{aligned}$$

The measurement doesn't demonstrate the dominance of P waves in the K^0_{e4} decay.

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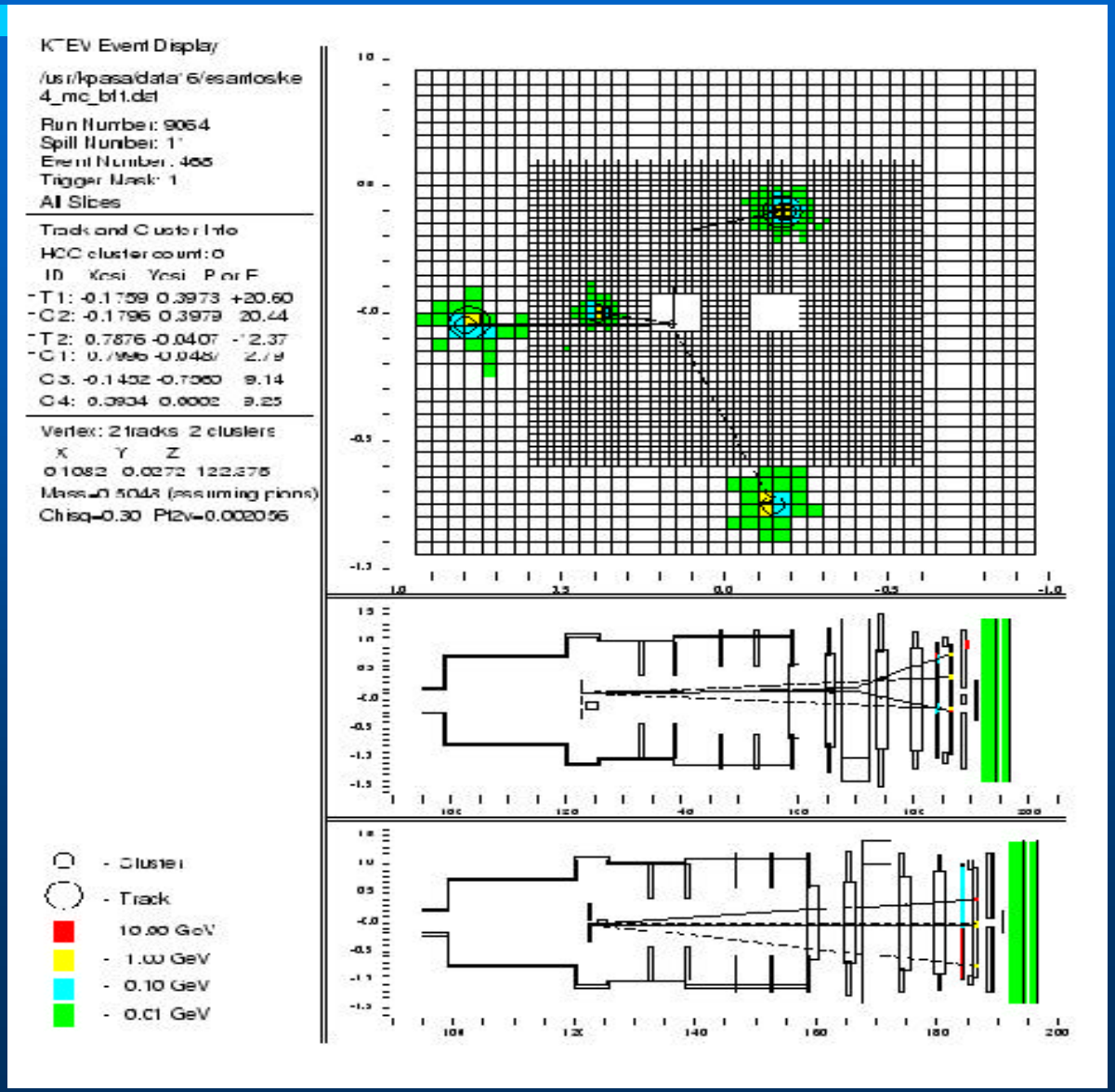
[a] A.S. Carroll et al., Phys. Lett. 98B, 407 (1980)

[b] C. Makoff et al., Phys. Rev. 70,1591 (1993)

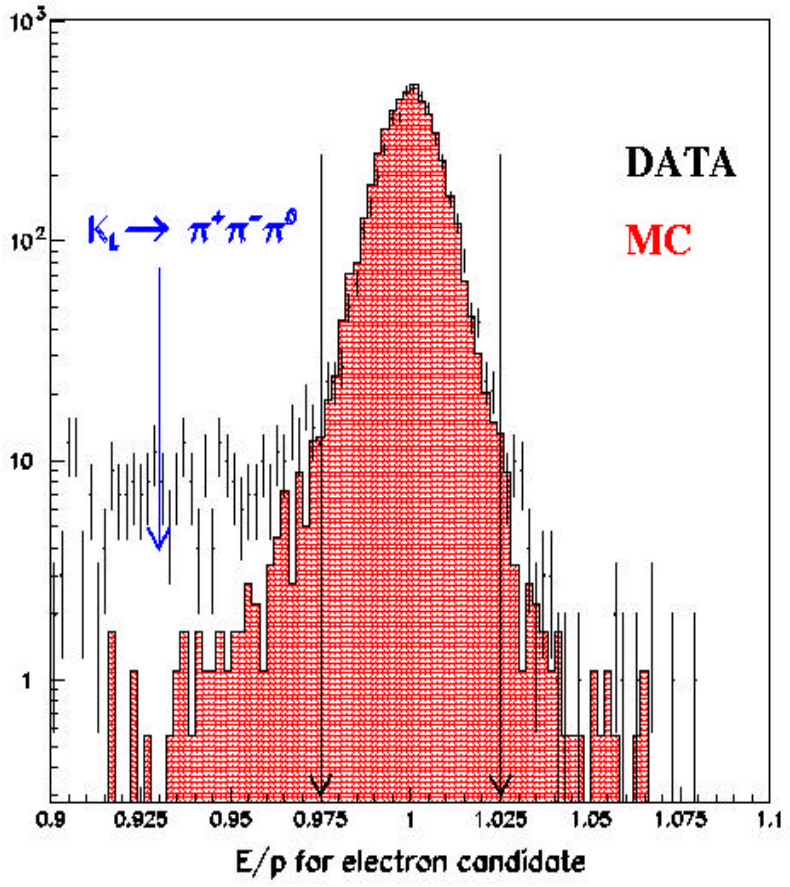
[c] C. Makoff, PhD thesis, University of Chicago, 1993

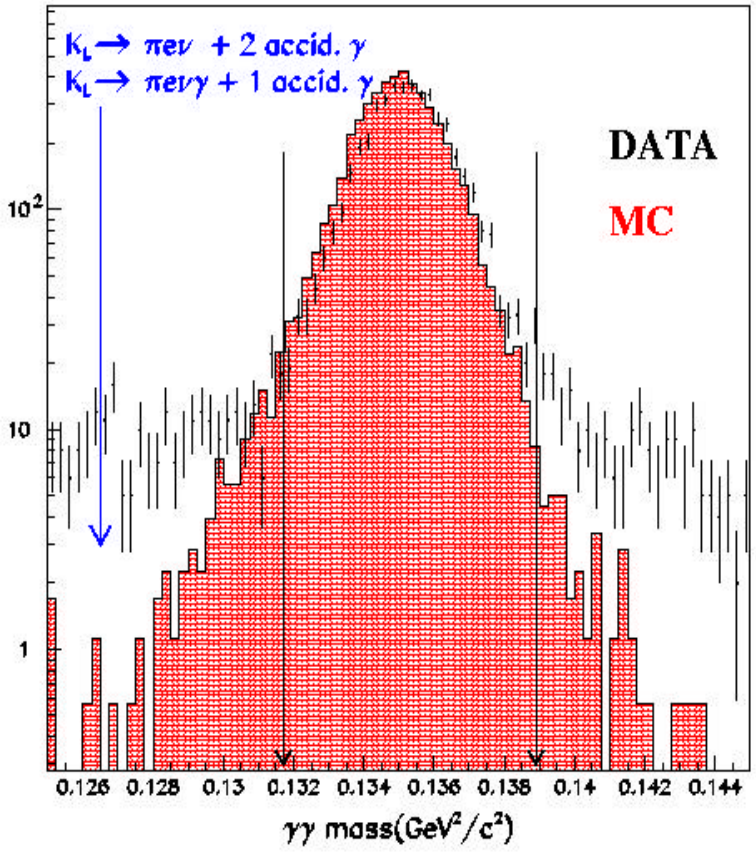
Ke4 Decay in the KTeV Detector.



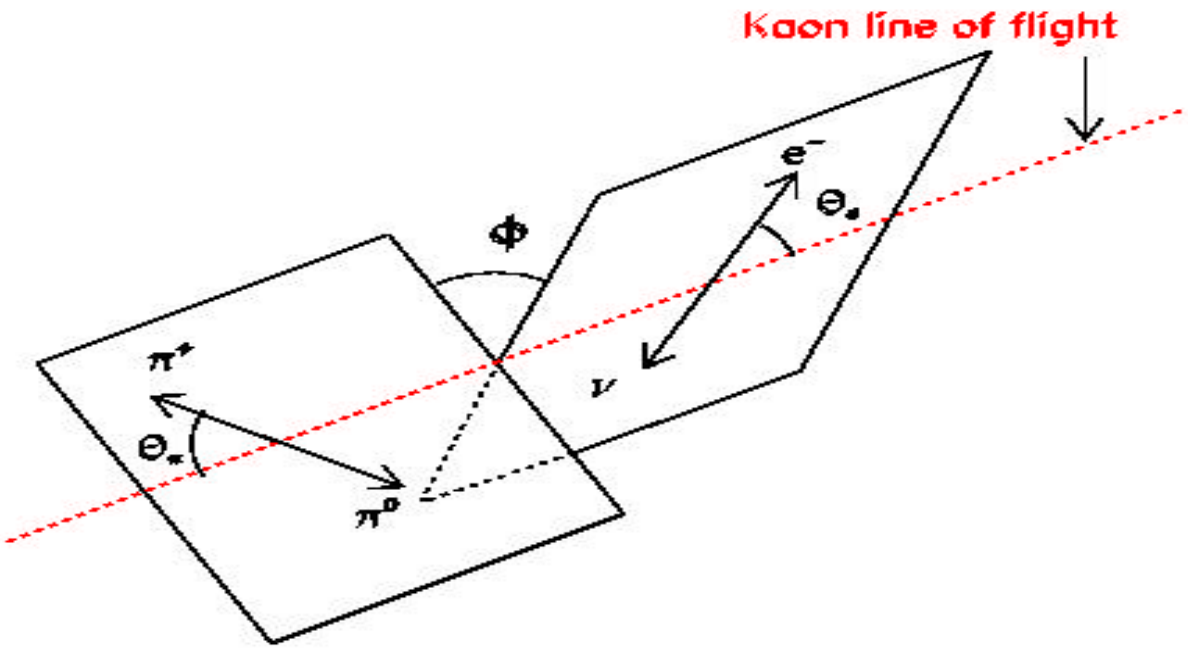
June 26th 2003

E/p & m($\gamma\gamma$) Ke4 Signal: (4400 evts)



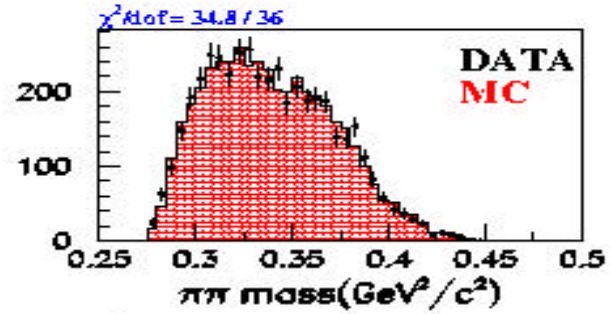


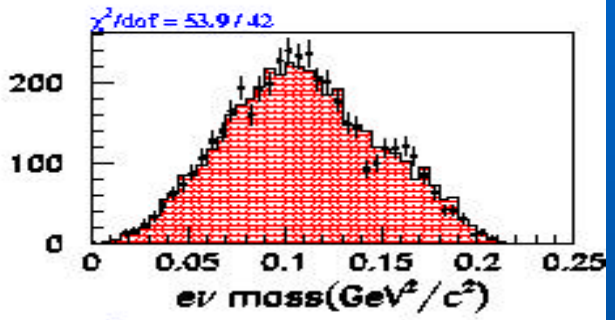
Definition of Ke4 Kinematics

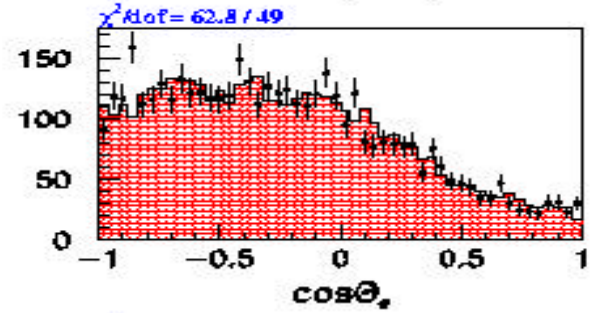


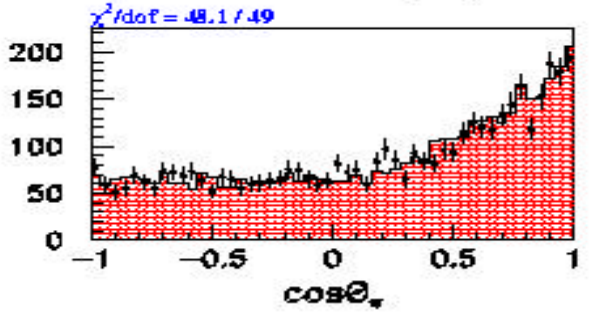
Background Subtracting Ke4 Distributions:

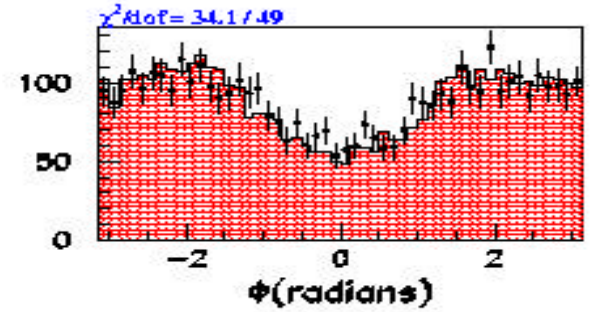
E731 Form Factors used:











Prospects for KTeV Neutral Ke4 Measurements:

- **A clean signal of 4400 events has been found from the 1997 data set. Comparable statistics exist in the 1999 data set.**

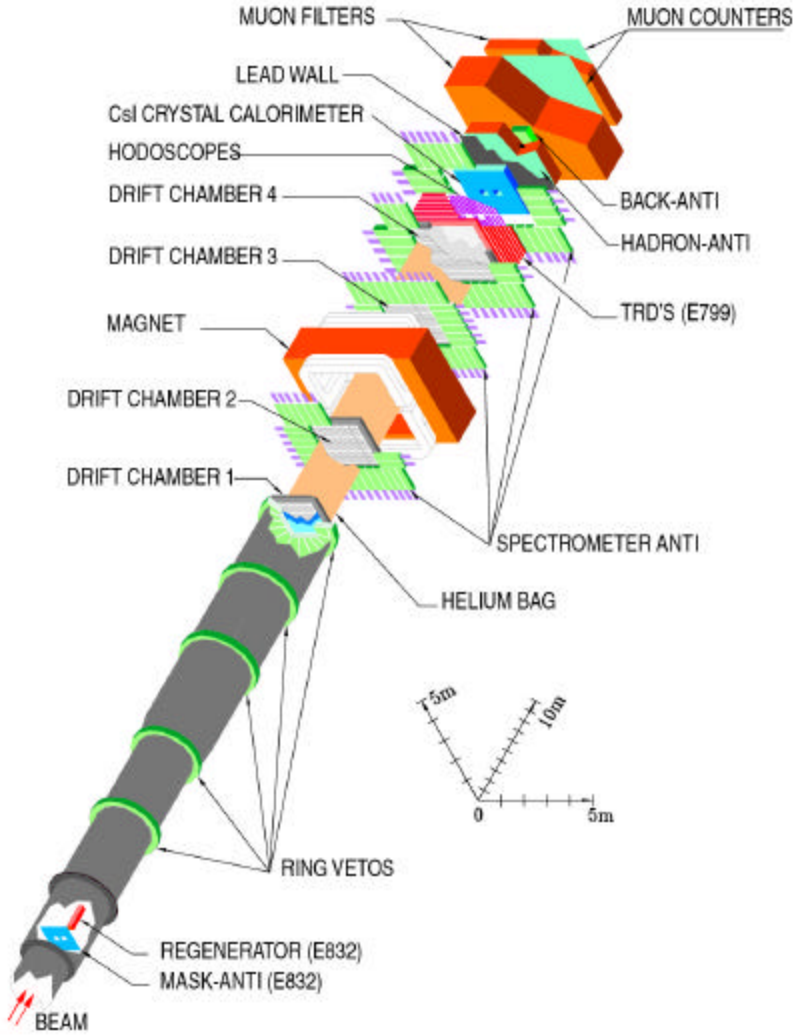
- **The statistical sensitivity for both the p-wave and s-wave $\pi\pi$ components of x3-4 over the E731 data set is in the offing. Results soon.**

Clear opportunity to observe the p-wave component of the decay.

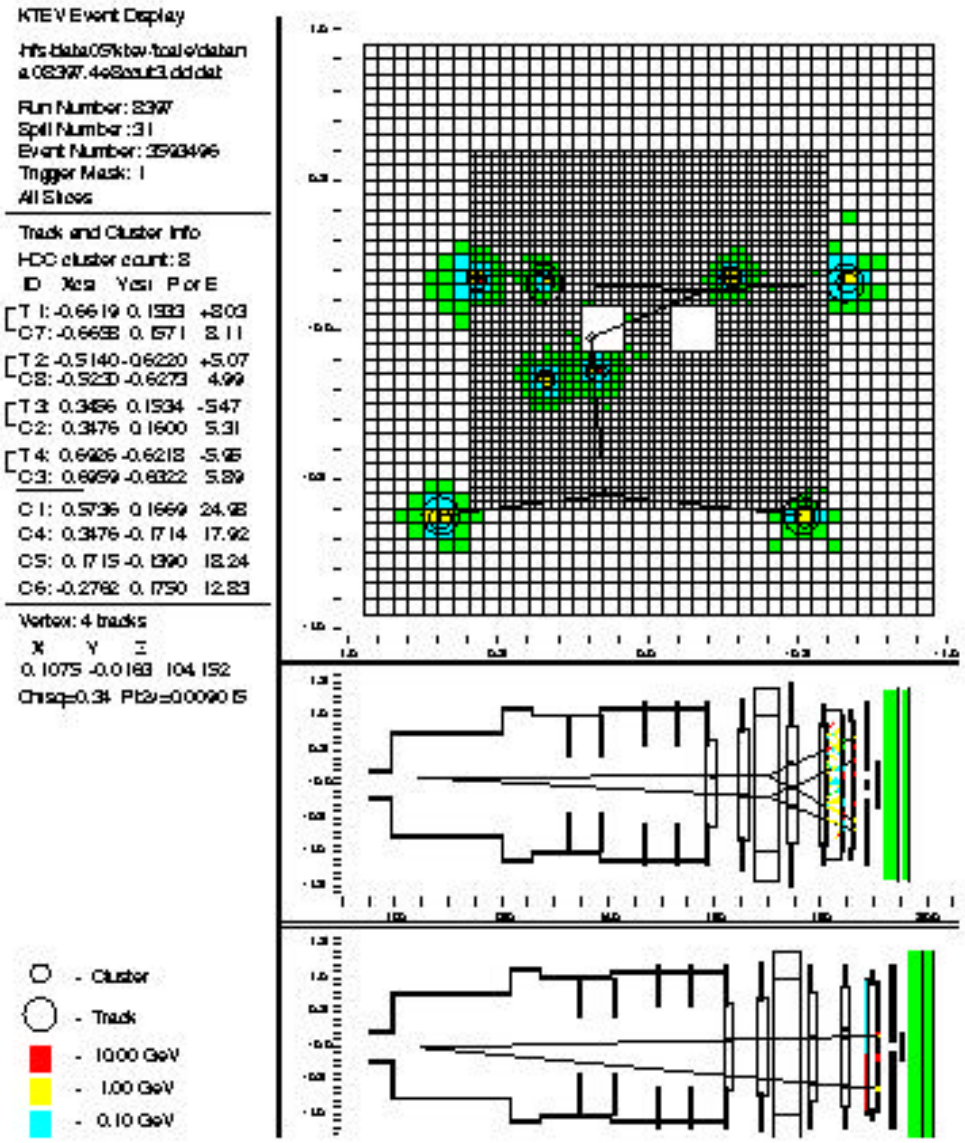
The KTeV Detector (E799, Rare Decays)

- **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



Samios et al Bubble Chamber Measurement 40 yrs l

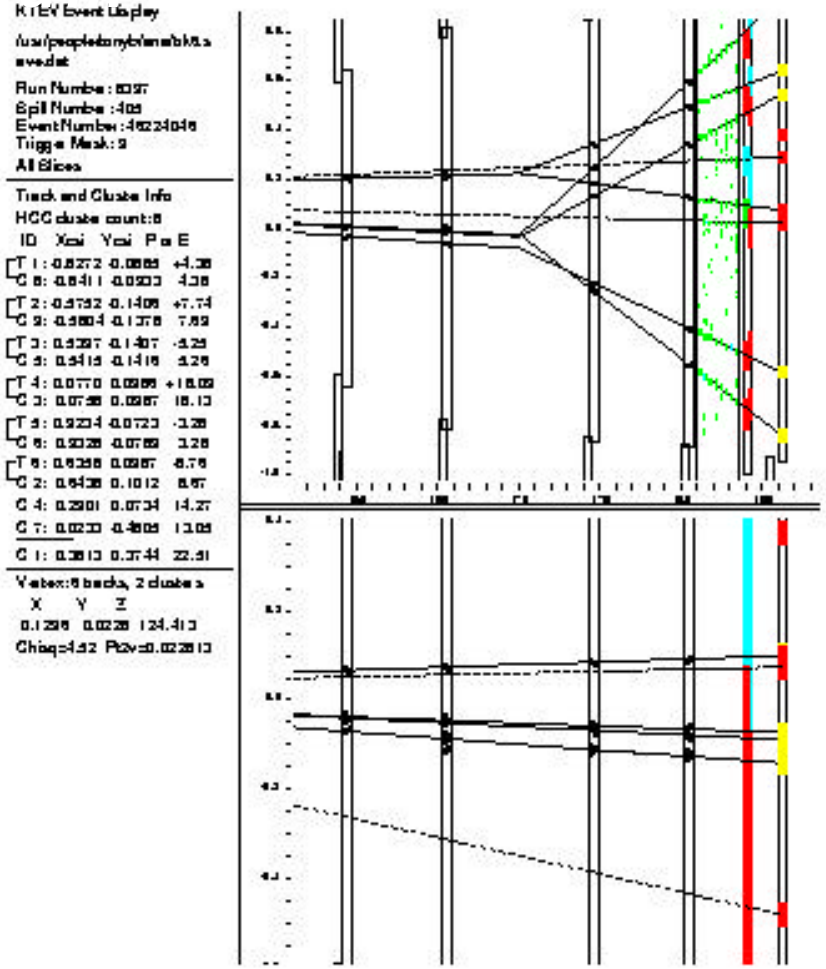


KTeV Detector

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

Views shown are CsI calorimeter beam's eye view, and charged spectrometer plan and elevation views.

A Large TRD System Performs well in the Field



KTeV Detector

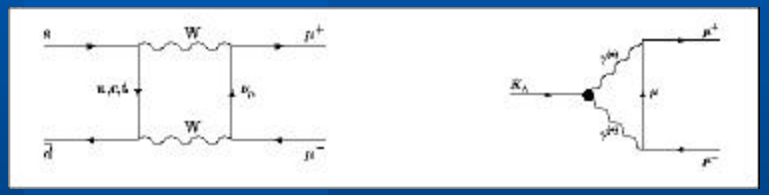
Event display, showing activity in the TRD system for a $K_L \rightarrow \pi^0\pi^0\pi^0$ event with three π^0 Dalitz decays.

The TRD's can achieve 90% electron-identification efficiency with a less than 1% pion misidentification. This is important in reducing background from common K_{e3} decays combined with accidentals.

K_L ® e^+e^-g branching ratio and form factor

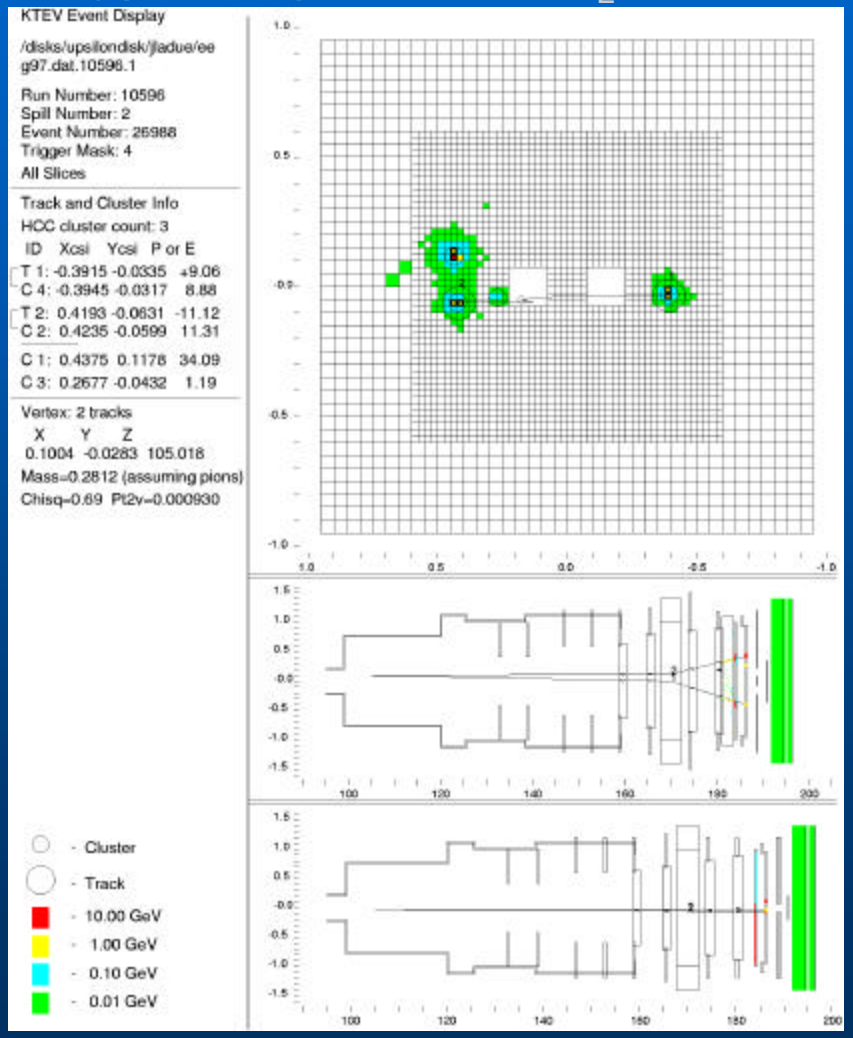
$K_L\gamma\gamma^*$ form factor

- 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 can be used to determine the form factor. The form factor is a function of the parameter α_{K^*}.

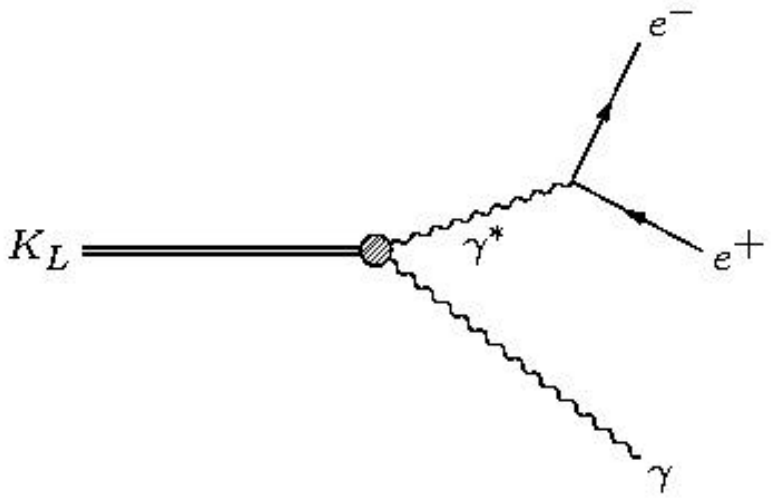
A typical signal event: $K_L \rightarrow e^+e^-\gamma$



One of the $K_L \Rightarrow \gamma^*\gamma$ Descendents:

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

The decay $K_L \to e^+e^-\gamma$ proceeds via $K_L \to \gamma^*\gamma$, where the virtual photon converts internally into an e^+e^- pair:

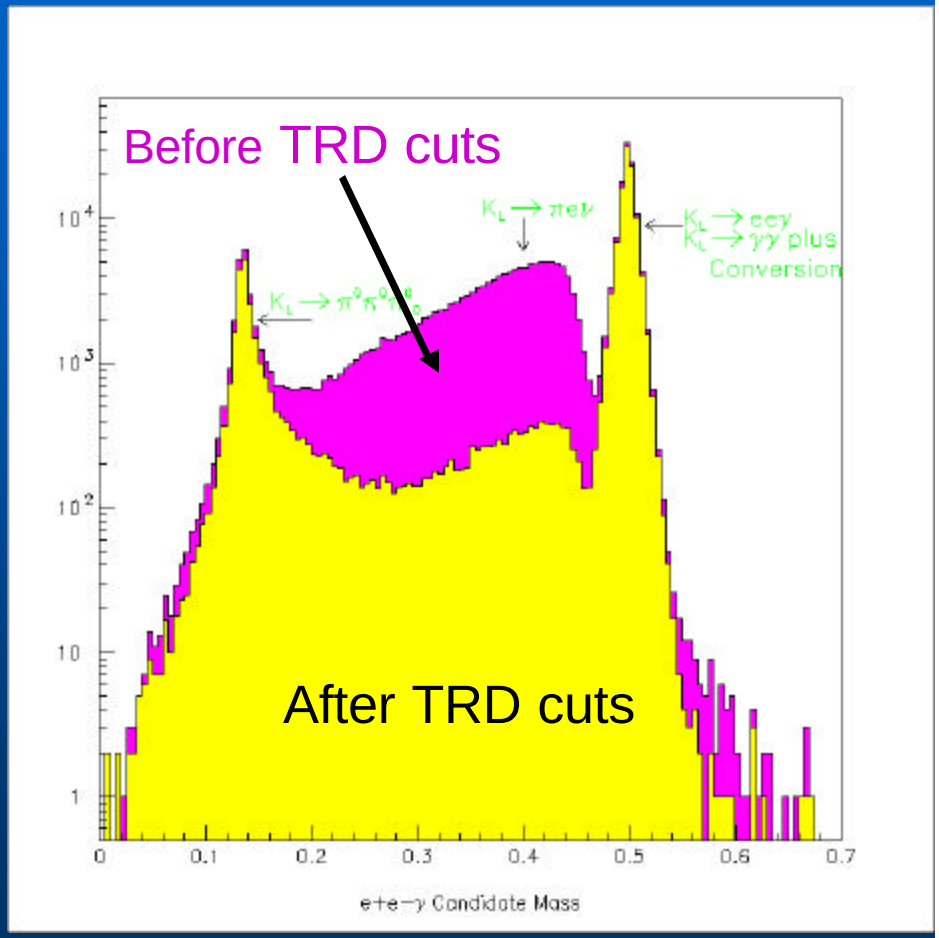


The functional dependence of the $K_L\gamma\gamma^*$ coupling on the q^2 of the virtual photon is called the $K_L\gamma\gamma$ form factor. It can be determined from the observed M_{ee} spectrum.

K_L ® e^+e^-g 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 $K_L \rightarrow \pi^0\pi^0\pi^0_D$. ($\gamma\gamma$ $\gamma\gamma$ $e^+e^-\gamma$)



Analysis of Systematics:

Statistical Uncertainty	0.36%
Internal Systematic Uncertainty	
Absolute Photon Inefficiency	0.43%
Drift Chamber Inefficiencies	0.37%
Vary Cuts	0.33%
Energy Slope	0.23%
Energy Resolution	0.14%
Background	0.08%
Upstream Material	0.07%
Track Position Resolution	0.04%
Form Factor Uncertainty	0.03%
$\mathcal{O}(\alpha^3)$ Radiative Corrections	0.03%
Total Internal Systematic	0.72%
External Systematic Uncertainty	2.85%

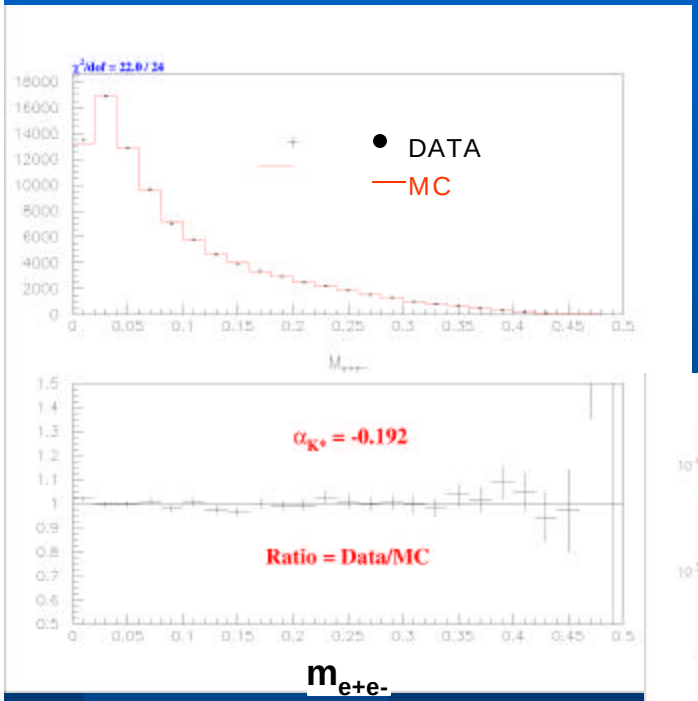
$K_L \rightarrow e^+e^-\gamma$ Branching Ratio

Contributions to overall uncertainty

External systematic is mostly from uncertainty in the $\pi^0 \rightarrow e + e^-\gamma$ branching fraction. Can KTeV improve this?

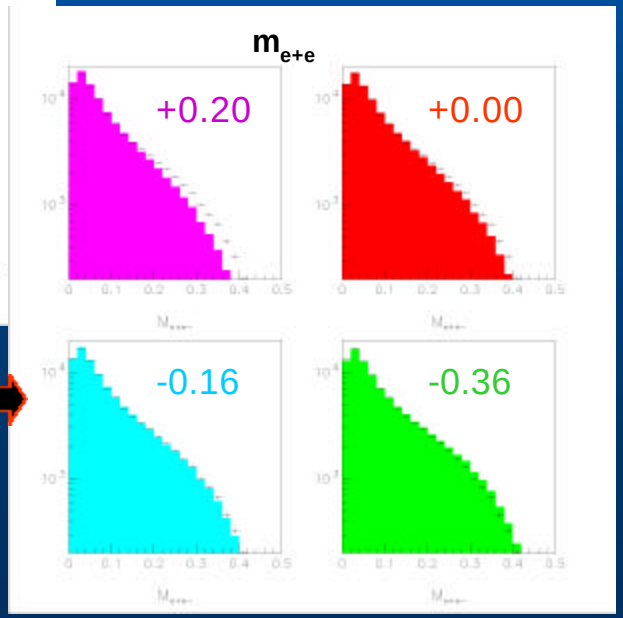
$K_L \to e^+e^-\gamma$ Results (1997, preliminary)

BR($K_L \to e^+e^-\gamma$) = (10.19 ± 0.04(stat) ± 0.07(sys) ± 0.29(norm)) X 10^{-6}

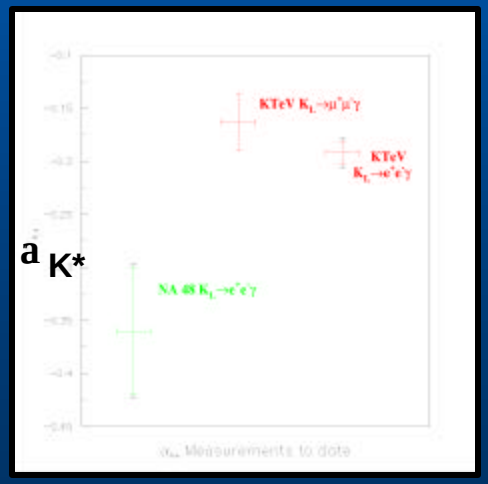


The mass of the e+e- system is sensitive to the BMS form factor parameter a_{K^*}.

a_{K^*} = -0.192 ± 0.011(stat) ± 0.009(sys)



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



Comparison to previous measurements

June 26th 2003

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

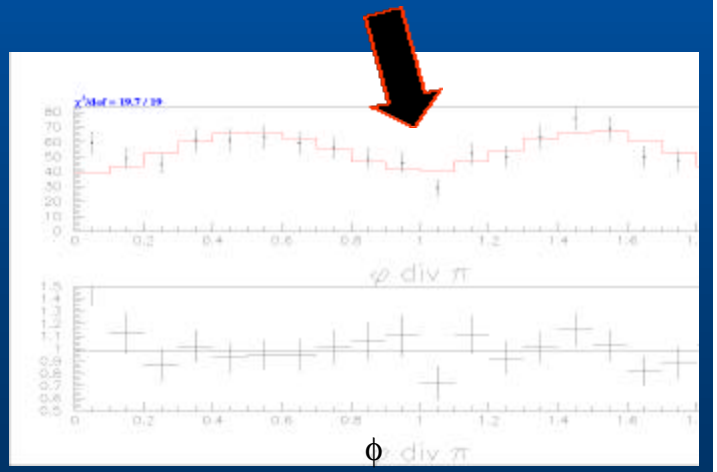
Analysis of the Kaon Double-Dalitz Decay

- **Predicted rate: Br($K_L \to e^+e^- e^+e^-$) @ 3.5×10^{-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:

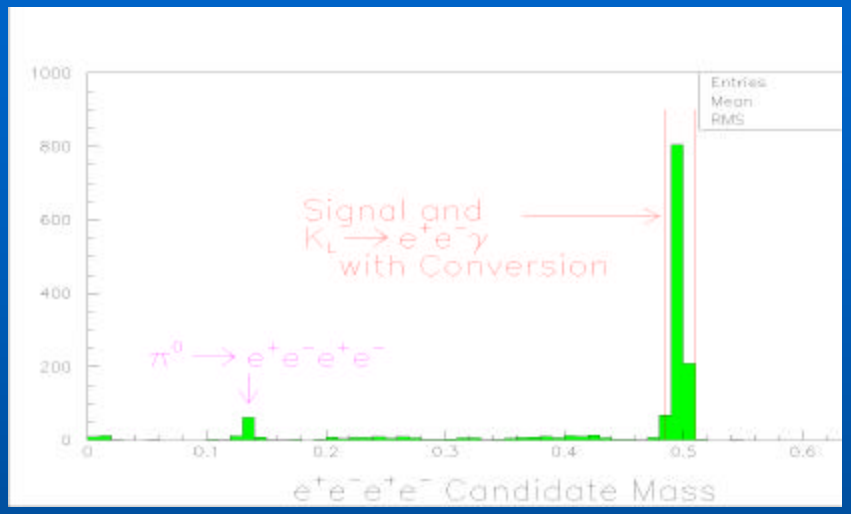
  $BR(K_L \to e^+e^- e^+e^-) = (3.72 \pm 0.18(stat) \pm 0.23(sys)) \times 10^{-8}$

  (1997 data sample)



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

KTeV has analyzed the combined 1997 and1999 $K_L \to e^+e^-e^+e^-$ data sample and has made a preliminary measurement of the branching ratio. Combined Form Factor analysis is forthcoming.

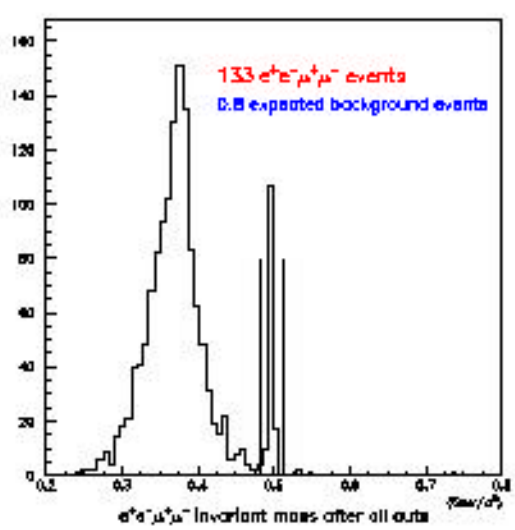


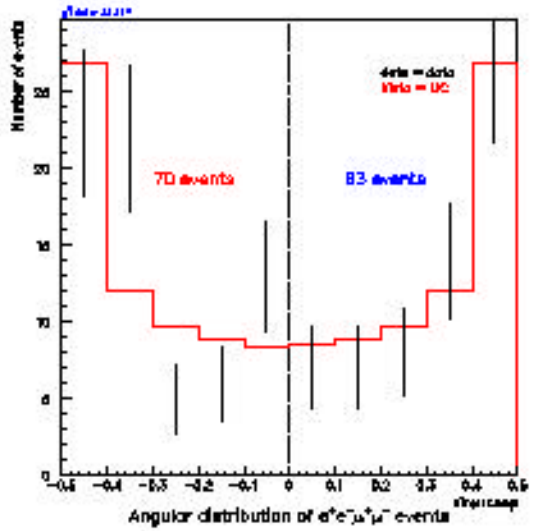
$BR(K_L \to e^+e^-e^+e^-) = (4.16 \pm 0.13(stat) \pm 0.13(sys) \pm 0.17(norm)) \times 10^{-8}$

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

The Ultimate $K_L \Leftrightarrow$ g*g* Laboratory:

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





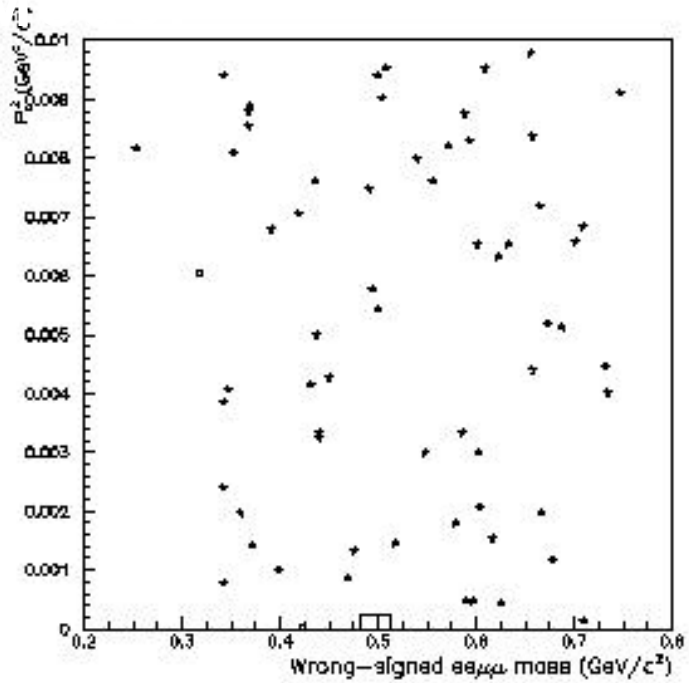
A total of 133 candidate events remain after all cuts, with a background estimated at 0.82 events.

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.

Looking for Lepton Flavor Violation in This Mode



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

As a byproduct of the measurement of $K_L \to e^+e^-\mu^+\mu^-$, we have search for the lepton-flavor-violating decay $K_L \to e^+e^+\mu^-\mu^-$ 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

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

at the 90% confidence level.

Search for $K_L \to p^0 e^+ e^-$

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

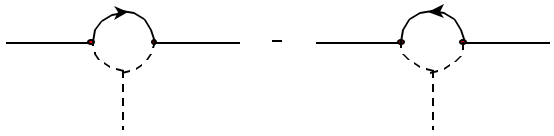
$p^0 g^* \to p^0 e^+ e^-$ **Indirect CP Violation**

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

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

$p^0 g^*$, $p^0 Z^*$, $p^0 W^{+*} W^{-*} \to p^0 e^+ e^-$ **Direct CP Violation**

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



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

$\mu \; \acute{A}(V_{td}V_{ts}^*) \quad \mu \; A^2 \lambda^5 \eta$

The Standard Model prediction for the Branching Ratio is (3-30 x 10^{-12}).

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

$p^0 g^* g^* \to p^0 e^+ e^-$ **CP conserving Helicity suppressed**

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

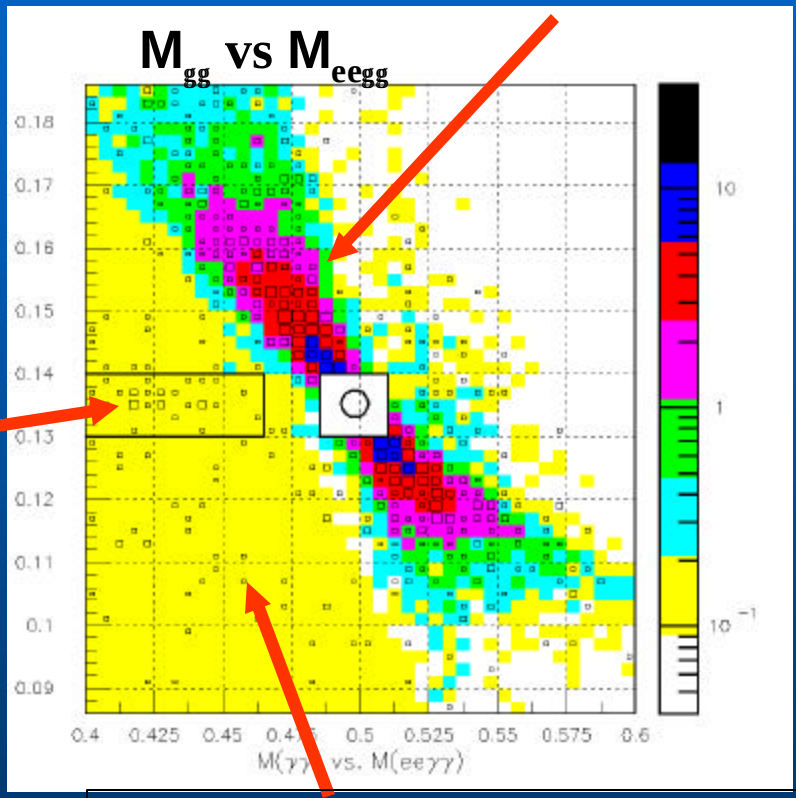
- Other backgrounds come from a kaon decay modes such as $K_L \rightarrow \pi^0\pi^0\pi^0_D$.
- The most significant and dangerous background comes from $K_L \rightarrow ee\gamma\gamma$ decays.

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

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

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

$K_L \rightarrow ee\gamma\gamma$

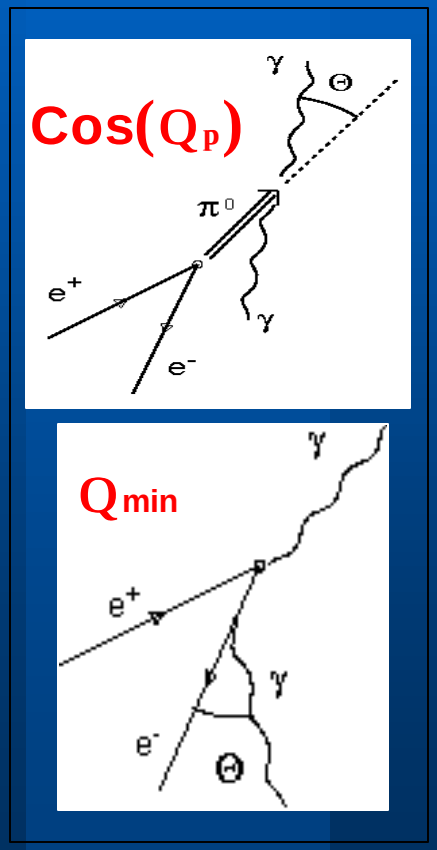


$K_L \rightarrow \pi^0\pi^0\pi^0, \quad \pi^{\pm} e \ \gamma\nu + \gamma_{ACC}$

- $\rightarrow e^+\gamma X$
- $\rightarrow e^- X$
- $\rightarrow \gamma X$

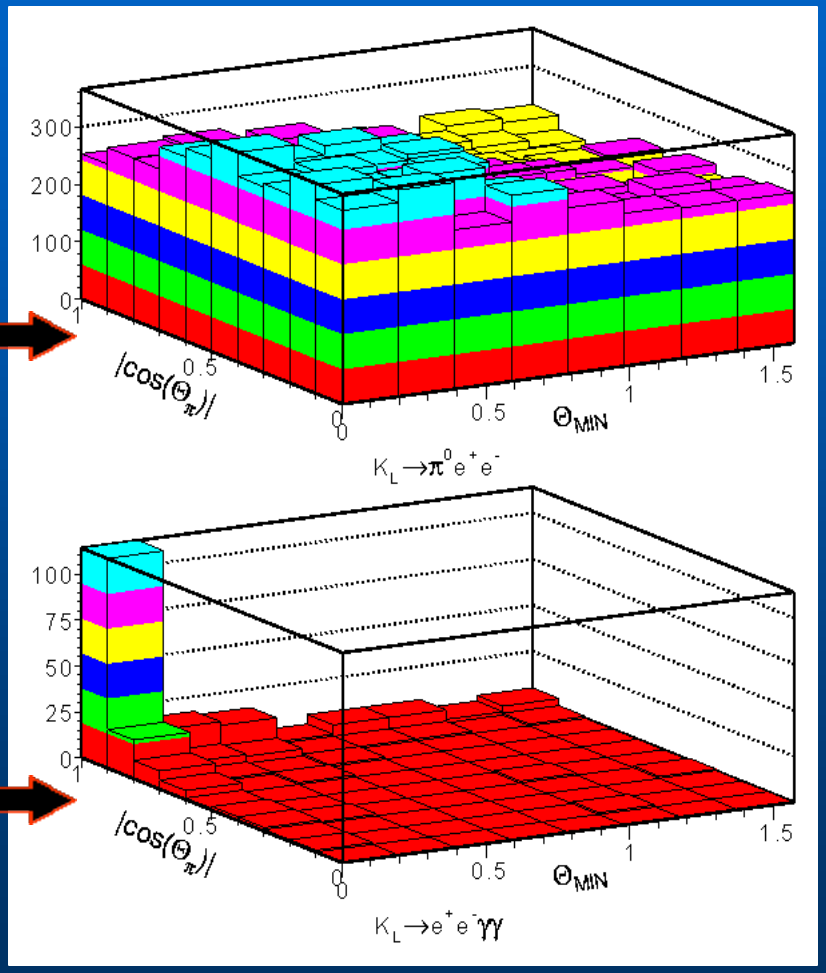
$K_L \to \pi^0 e^+ e^-$ vs. $K_L \to e^+ e^- \gamma\gamma$

Kinematic cuts are use to eliminate background from K_L ® e^+e^-gg



K_L ® $p^0e^+e^-$

K_L ® e^+e^- g g

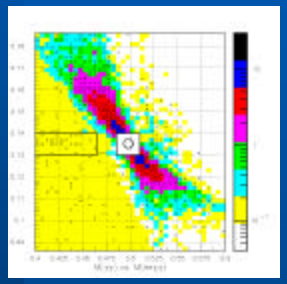


Background from $K_L \to e^+e^- g\, g$

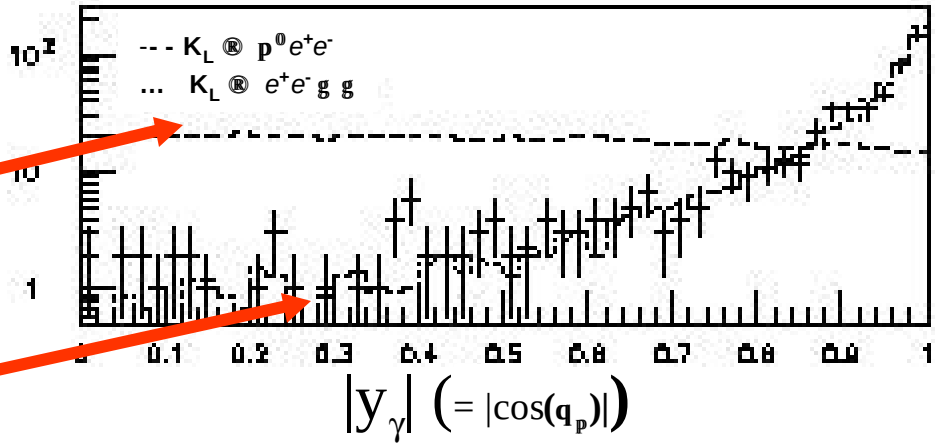
Check of background: data against MC:

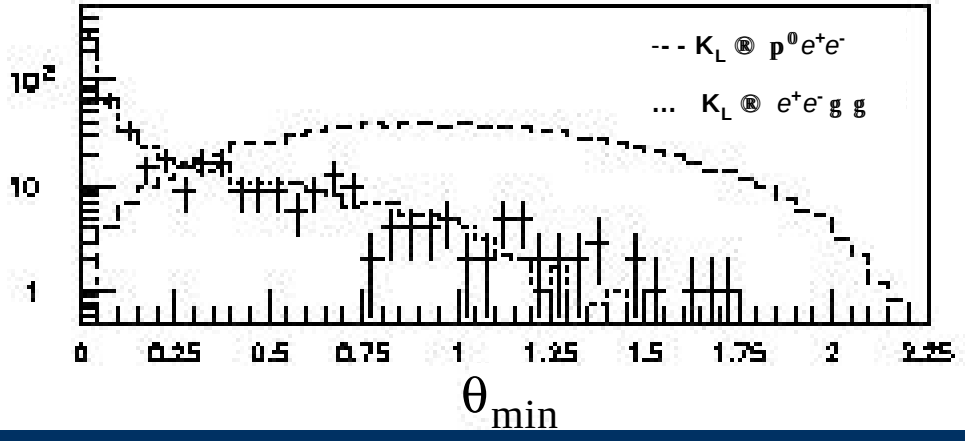
$K_L \to p^0 e^+ e^-$

$K_L \to e^+e^- g\, g$



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

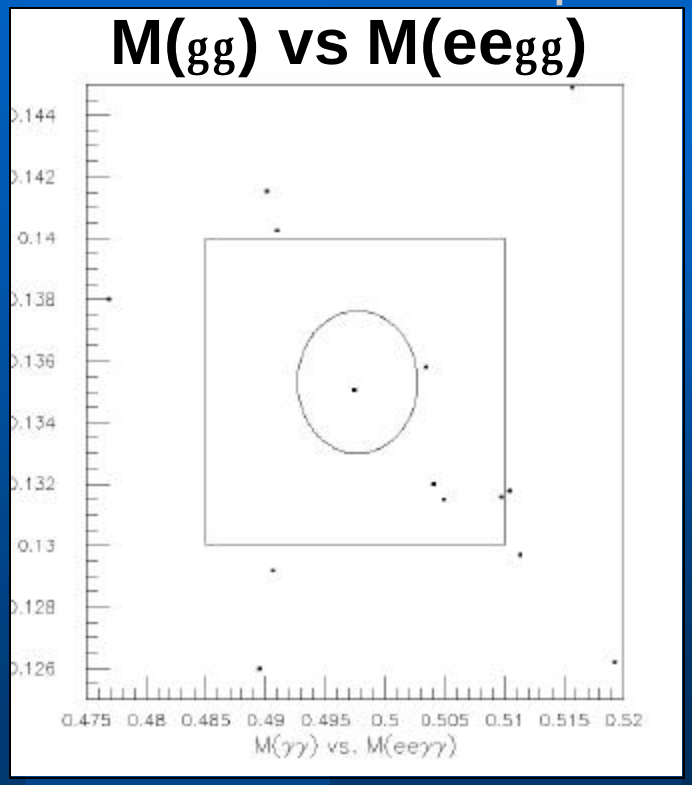




New Limit for $K_L \to p^0 e^+ e^-$

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

1999 Data Sample



NEW:

1999 *preliminary:*

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

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

Combined Limit:

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

What about the NA48 K_S Measurement?

- **The NA48 Experiment at CERN has recently measured $Br(K_S \to p^0 e^+ e^-) = (6 \pm 3) \times 10^{-9}$.**

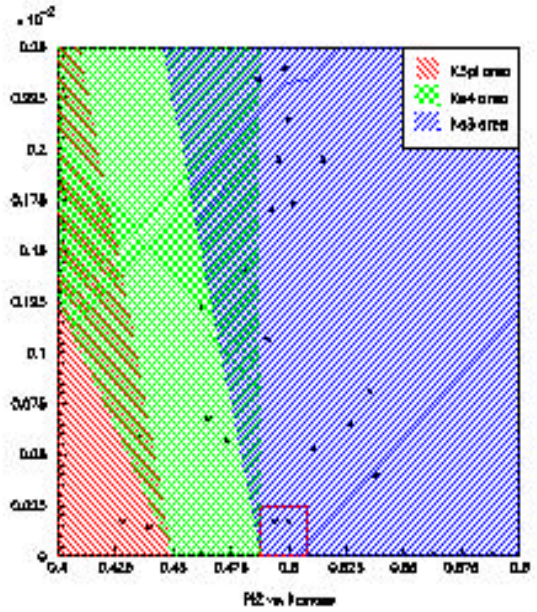
- **This enables an estimate of the Indirect & Direct CP Violating components:**

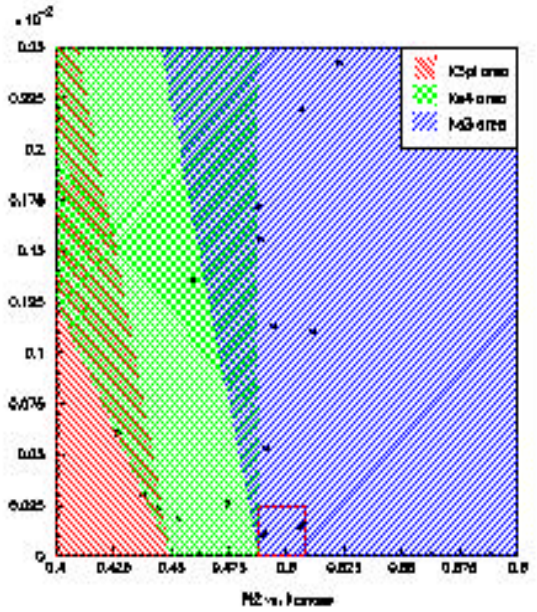
$Br(K_L \to p^0 e^+ e^-)$ [CP-Violating]:

(18 [indirect] + 10 [int.] + 5[direct])$\times 10^{-12}$

~10% of the current KTeV Sensitivity! The ee$\gamma\gamma$ background is at the Brick Wall.

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.

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

- 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:

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

- A search for $\pi^0 \to \mu^\pm e^\mp$ using $K_L \to \pi^0 \pi^0 \pi^0$ is also underway. Results have not yet been determined.

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	$< 5.4 \times 10^{-9}$

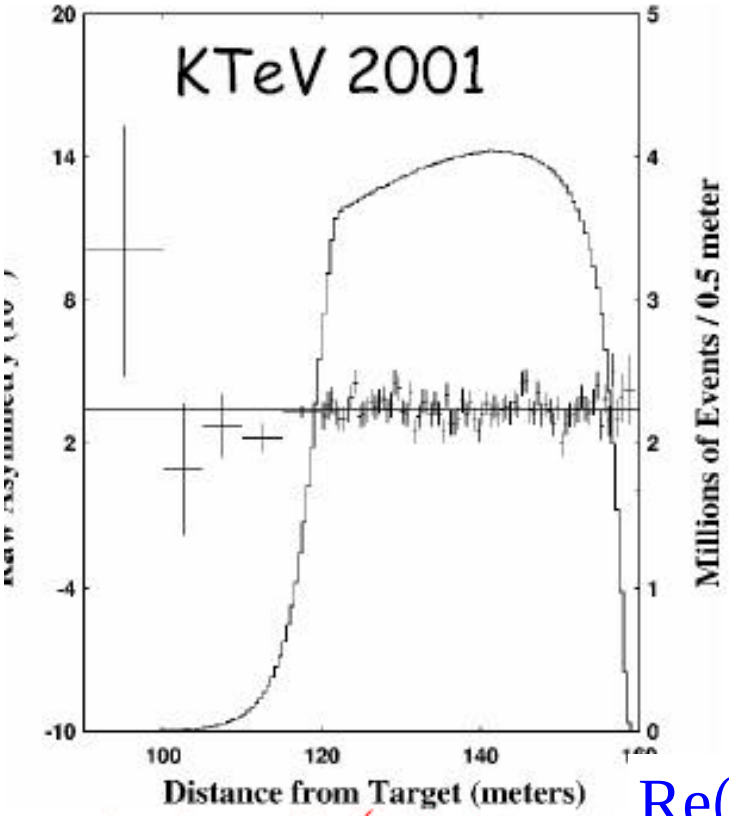
KTeV Rare Decay results (2)

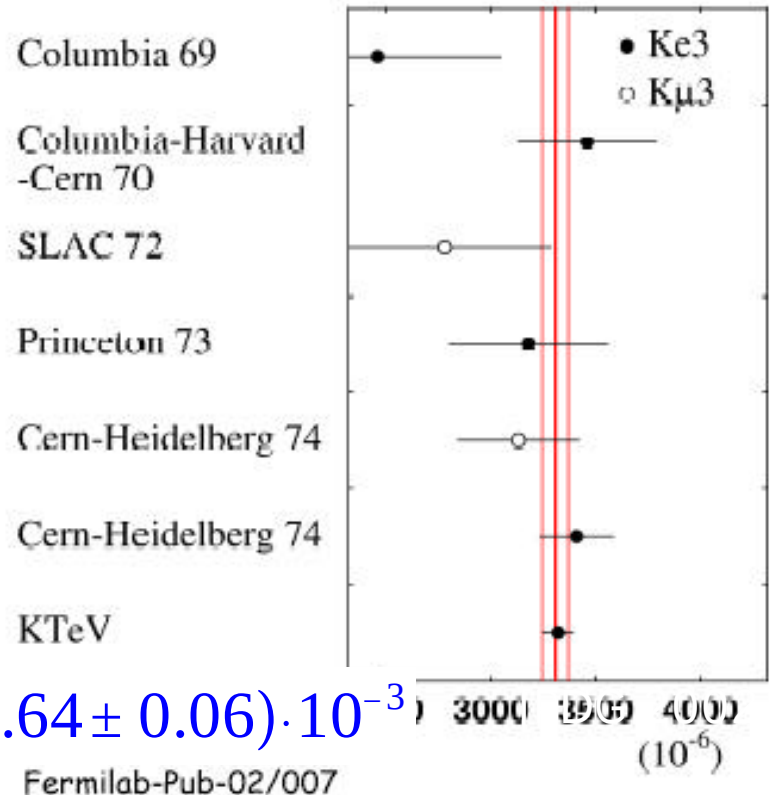
Decay Mode	Publ.	# Events	Branching Ratio
		K_{gg^*} Vertex	
$K_L \to e^+e^-\gamma$		93.4k	$(10.13 \pm 0.04 \pm 0.06 \pm 0.29) \times 10^{-6}$
$K_L \to \mu^+\mu^-\gamma$	x	9,327	$(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$
$K_L \to e^+e^-\gamma\gamma$	x	1,543	$(5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$
$K_L \to \mu^+\mu^-\gamma\gamma$	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	
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$	x 97+99	0	$< 4.12 \times 10^{-11}$
$K_L \to \pi^0 \mu^\pm e^\mp$		5	$< 3.31 \times 10^{-10}$

Summary and Conclusions

- **Preliminary results for $K_L \to p^0 e^+ e^-$ 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(ε'/ε) to about 10^{-4}.**
- **More results from KTeV rare decays expected soon –**
  - **$K_L \to e^+ e^- e^+ e^-$ form factor with 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**
  - **Ke4 branching fraction and form factors.**

300M $K_L \to \pi e \nu$ Decays!





$$\mathrm{Re}(\varepsilon_K) = (1.64 \pm 0.06) \cdot 10^{-3}$$

$$\mathrm{Re}(\varepsilon_m) = \delta_L (3.322 \pm 0.074) \cdot 10$$

$$\mathrm{Re}(\varepsilon_K) = (1.661 \pm 0.037) \cdot 10^{-3}$$

[KTeV 2001]