Search for Lepton Flavor Violating Kaon Decays from The KTeV Experiment at Fermilab

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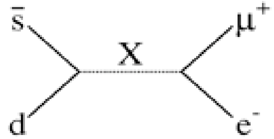
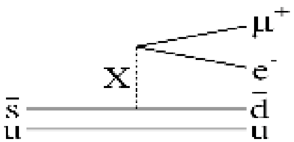
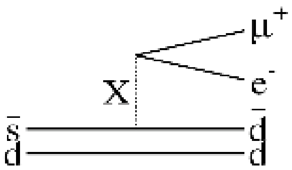
Lepton Flavor Violation in Kaon Decays

- Permitted in the Nu Standard Model, but suppressed beyond experimental sensitivity by small neutrino masses
- Negligible SM background means LFV decays are sensitive to new physics.
- Attainable sensitivity to $M_X > 100$ TeV, clean signatures.
- LFV in kaon decays is expected in most new physics scenarios:
  - SUSY
  - Extended Technicolor
  - Heavy neutrinos
  - Horizontal gauge bosons
  - Large extra dimensions
  - Leptoquarks
- For V-A interactions $K \to \mu e$ is the most sensitive kaon decay. If the LFV interaction is pure vector, 2 body modes would be suppressed and 3 body modes like $K \to \pi^0 \mu e$ are more promising.

Current Limit on LFV Kaon Decays

Very high mass scales can be probed by LFV kaon decays. A common example is through a hypothetical LFV boson X. Assuming weak coupling, lower limits on m_X can be extracted. For example....

	Branching Fraction Limit	Mass Limit
	$B(K_L \to \mu e) < 4.7 \times 10^{-12}$ PRL **81**, 5734 (1998)	150 TeV/c^2
	$B(K^+ \to \pi^+\mu^+e^-) < 1.3 \times 10^{-11}$ PRD **72**, 012005 (2005)	31 TeV/c^2
	$B(K_L \to \pi^0\mu^+e^-) < 3.4 \times 10^{-10}$ (KTeV Preliminary)	37 TeV/c^2

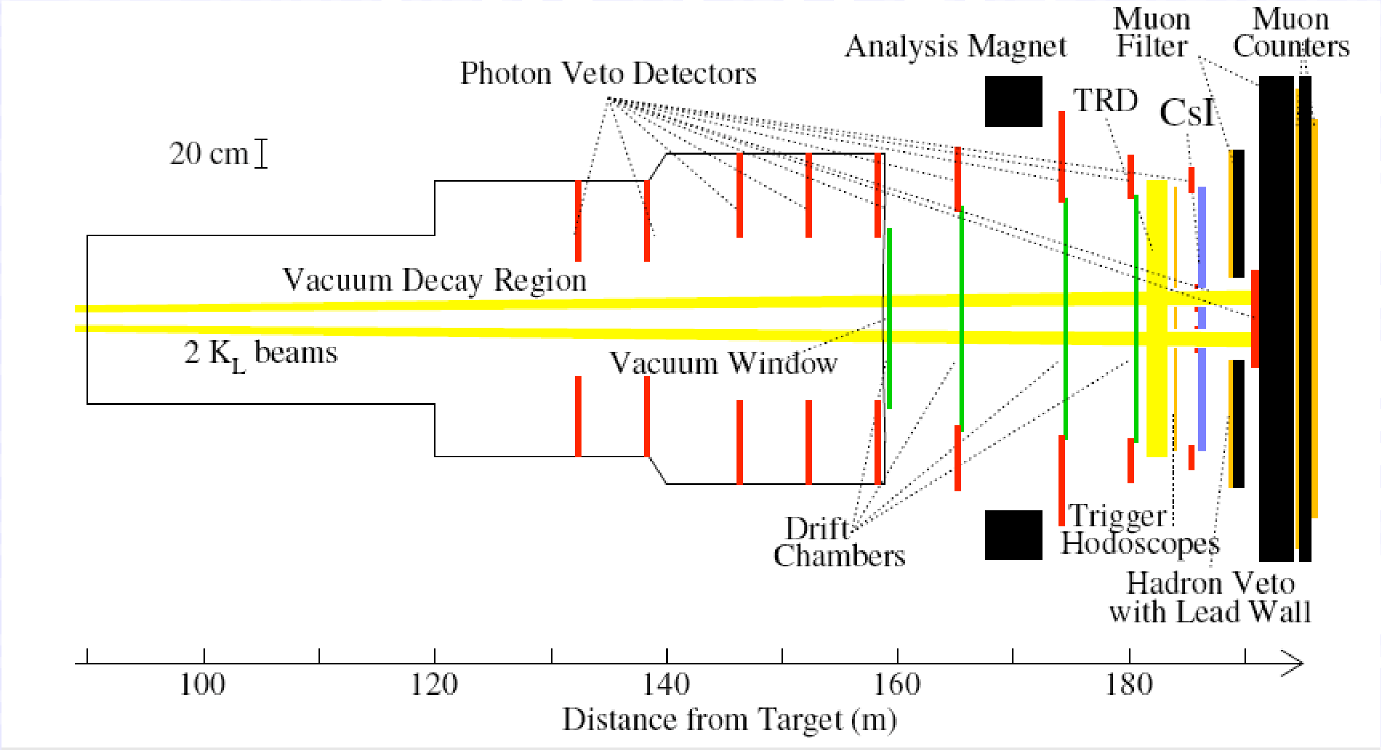
KTeV

U. Arizona
U. Campinas, Brazil
U. California, Los Angeles
U. California, San Diego
U. Chicago
U. Colorado
Elmhurst College
Fermilab
Osaka Univesity, Japan
Rice University
U. Sao Paulo, Brazil
U. Virginia
U. Wisconsin

Lepton Flavor Violation analyses led by Rice University.

Analyses presented are based on the 1997 and 1999 fixed target runs of the Fermilab Tevatron.

KTeV Detector



- CsI calorimeter
  - 3100 crystals
  - Energy resolution: $\sigma(E)/E = 2\%/\sqrt{E} + 0.45\%$
  - Position resolution: ~1 mm
- Clean beams
- Spectrometer, low mass, tracking in beam, better than 100-μm hit resolution
- TRD for e/π separation.

LFV Decays in KTeV

- KTeV has good sensitivity to a number of LFV decays
  - $K_L \rightarrow \pi^0 \mu e$ — New Results Today.
  - $K_L \rightarrow \pi^0 \pi^0 \mu e$
  - $\pi^0 \rightarrow \mu e$ (from $K_L \rightarrow 3\pi^0$)

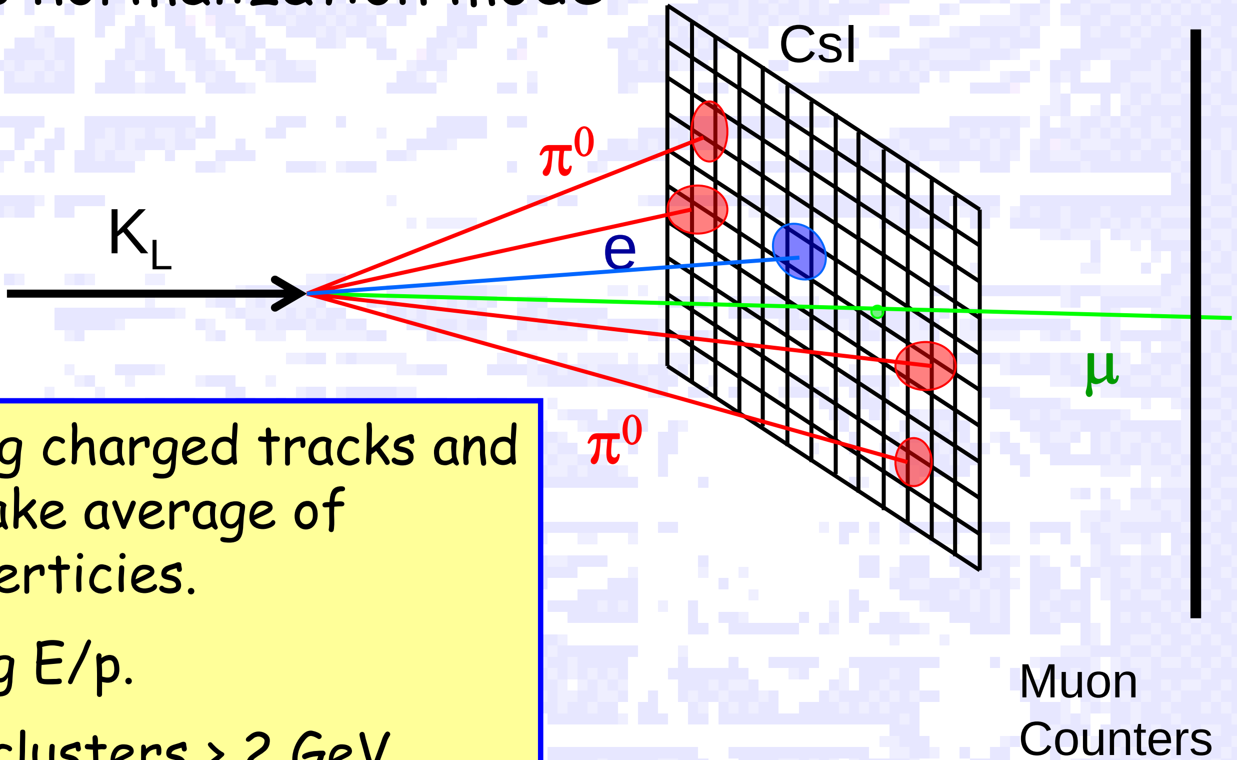
  } Preliminary Results. Boxes opened recently.

  - KTeV's large kaon flux and well understood beam and detector make this an ideal environment to search for rare decays.

$K_L \to \pi^0\pi^0\mu e$

Lower background than $K_L \to \pi^0\mu e$ due to $2\pi^0$ requirement

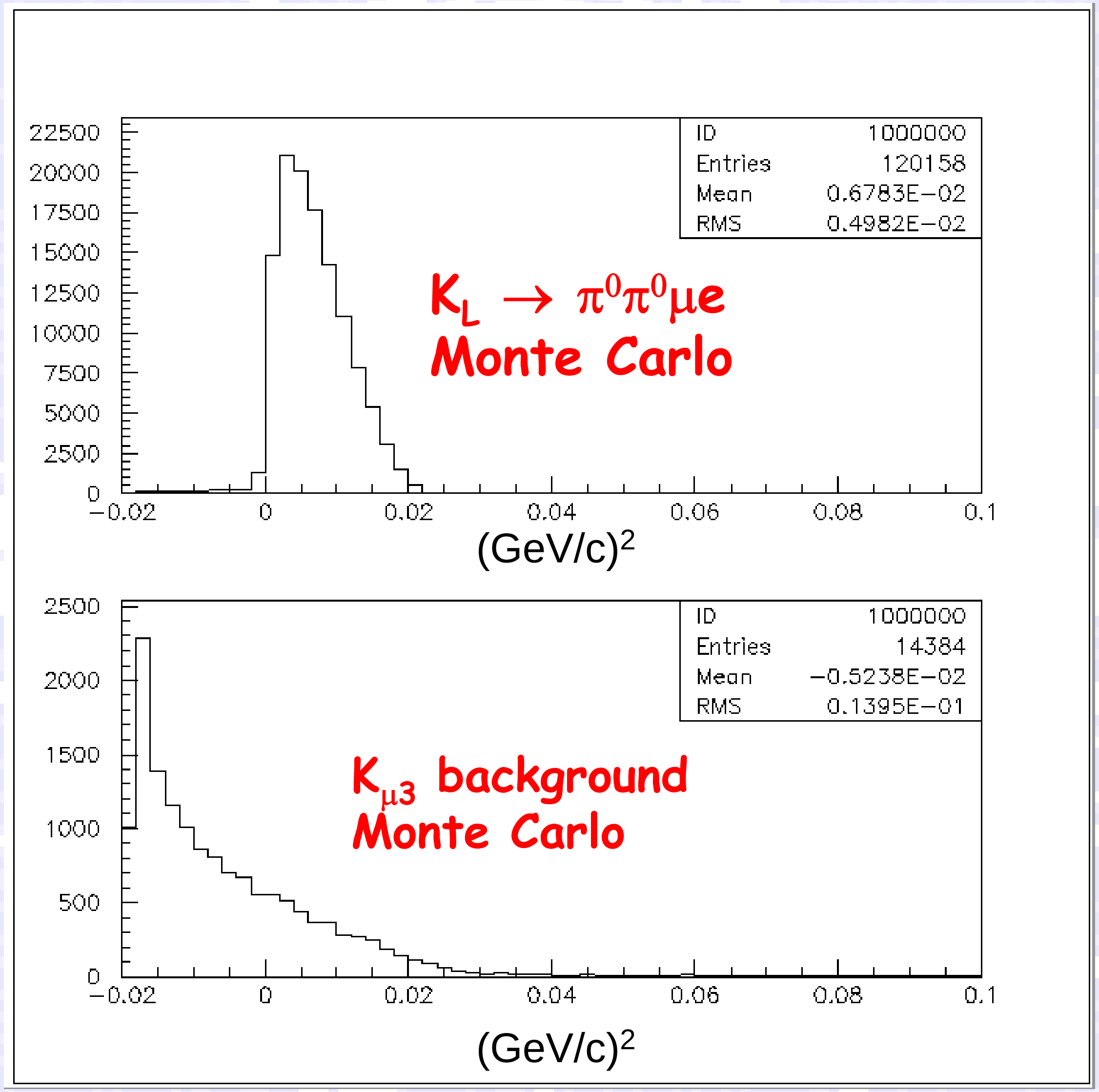
Use $K_L \to \pi^0 \pi^0 \pi^0_D$ as normalization mode



- Determine vertex using charged tracks and π^0 mass constraint. Take average of charged and neutral verticies.
- Identify electron using E/p.
- Require 5 in-time CsI clusters > 2 GeV with electromagnetic shower shape
- $E\mu$ > 8 GeV/c with < 1 GeV in CsI and hits in μ counters

Backgrounds to $K_L \to \pi^0\pi^0\mu e$

- $K_L \to \pi^{\pm}\mu^{\mp}\nu$ with 4 accidental photons
- $K_L \to \pi^{\pm}e^{\mp}\nu$ with 4 accidental photons and the π misidentified as a μ
- The square of the π^0 momentum in the K_L rest frame is a good discriminator against these backgrounds.
  - Calculate invariant mass of charged tracks and one π^0
  - Do for both π^0
  - For real signal events the quantity must be positive
  - Negative for many backgrounds



Square of the π^0 momentum in K rest Frame

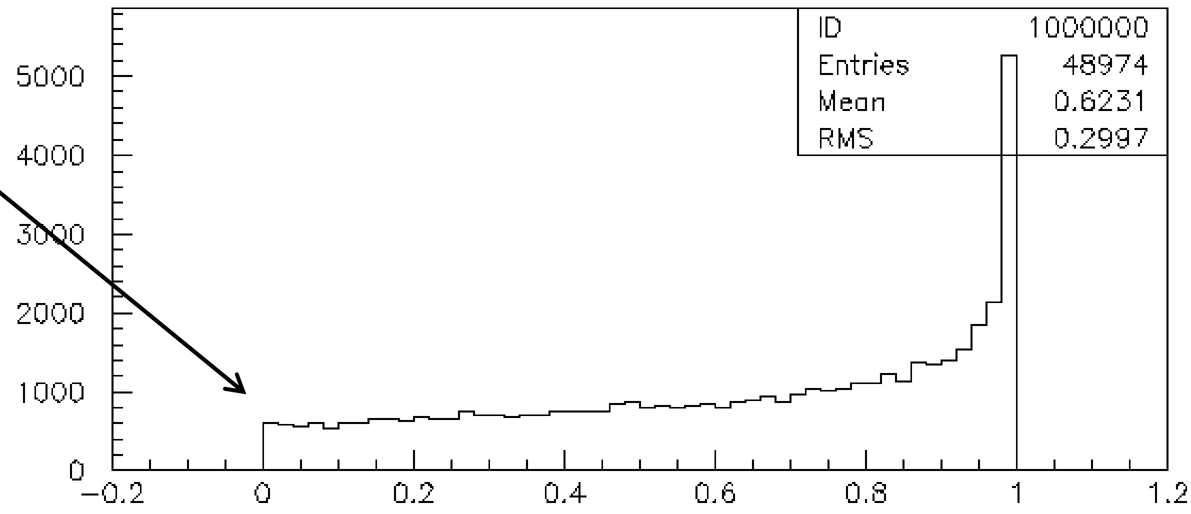
Backgrounds to $K_L \to \pi^0\pi^0\mu e$

$K_L \to \pi^0\pi^0\pi^0_D$ where an accidental muon satisfies the muon trigger and happens to be close to one of the Dalitz electrons.

This can be eliminated by making an "anti-electron" cut on the muon track using the TRDs.

Require Muon Probability > 0.015 (98% efficient for muons, eliminates 85% of electrons).

Electrons peak close to zero



TRD Muon Probability from Kμ3 data

$K_L \rightarrow \pi^0\pi^0\mu e$ Cuts

- Z vertex between 96 and 155 m. X & Y vertex inside CsI beam holes.
- Difference between charged and neutral vertices less than 2.5 m.
- Square of π^0 momentum in K rest frame between 0 and 0.025 $(GeV/c)^2$
- π^0 masses between 0.132 and 0.138 GeV/c^2

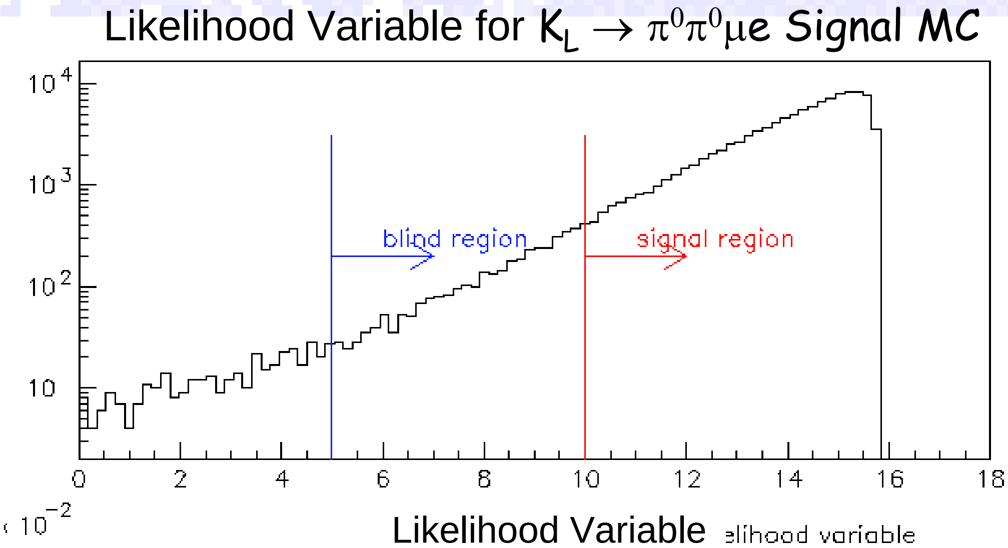
- E/p for electron between 0.95 and 1.05
- TRD signal for μ track is not consistent with electron ($prob_\mu$ > 0.015)
- Fusion χ^2 < 10 for electron and neutral clusters (eliminates overlapping clusters)
- μ momentum $>$ 8 GeV. μ energy $<$ 1 GeV in CsI.

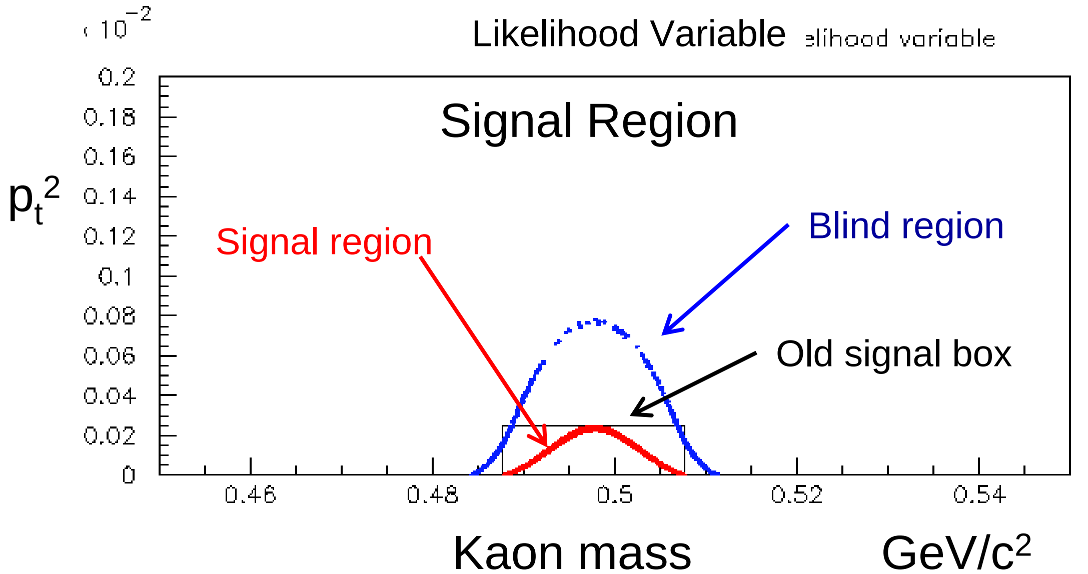
- **Exactly 5 in-time clusters above 2 GeV in CsI.**
- **< 0.3 GeV in photon veto counters.**
- **< 15 GeV in beam veto counter.**
- **< 3 extra in-time drift chamber hit pairs.**

Kinematic cuts Particle ID Cuts **Accidental cuts**

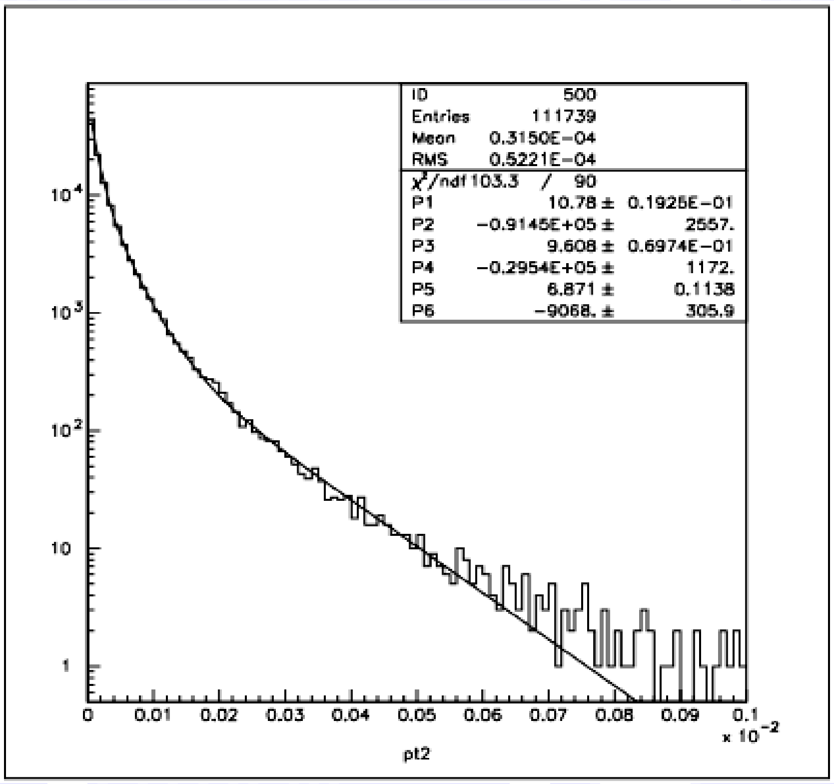
Likelihood Analysis

- Blind analysis
- Signal region defined by p_t^2 and kaon mass
- Fit analytical functions to p_t^2 and kaon mass.
- Normalize to form PDFs. Likelihood is product of the two PDFs.
- Signal acceptance ~2% after all cuts on previous page.
- Cut at 10 preserves 95% of the signal events remaining after all cuts.

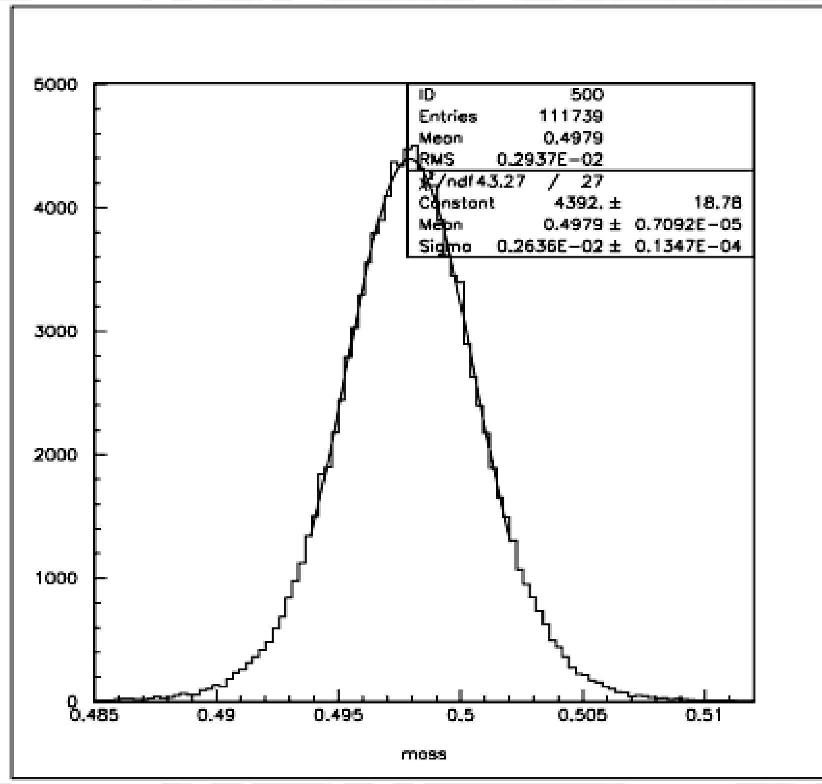




Components of the 2d PDF for $K_L \to \pi^0\pi^0\mu e$



$K_L \to \pi^0\pi^0\mu e$ p_t^2, $(\mathrm{GeV/c})^2$

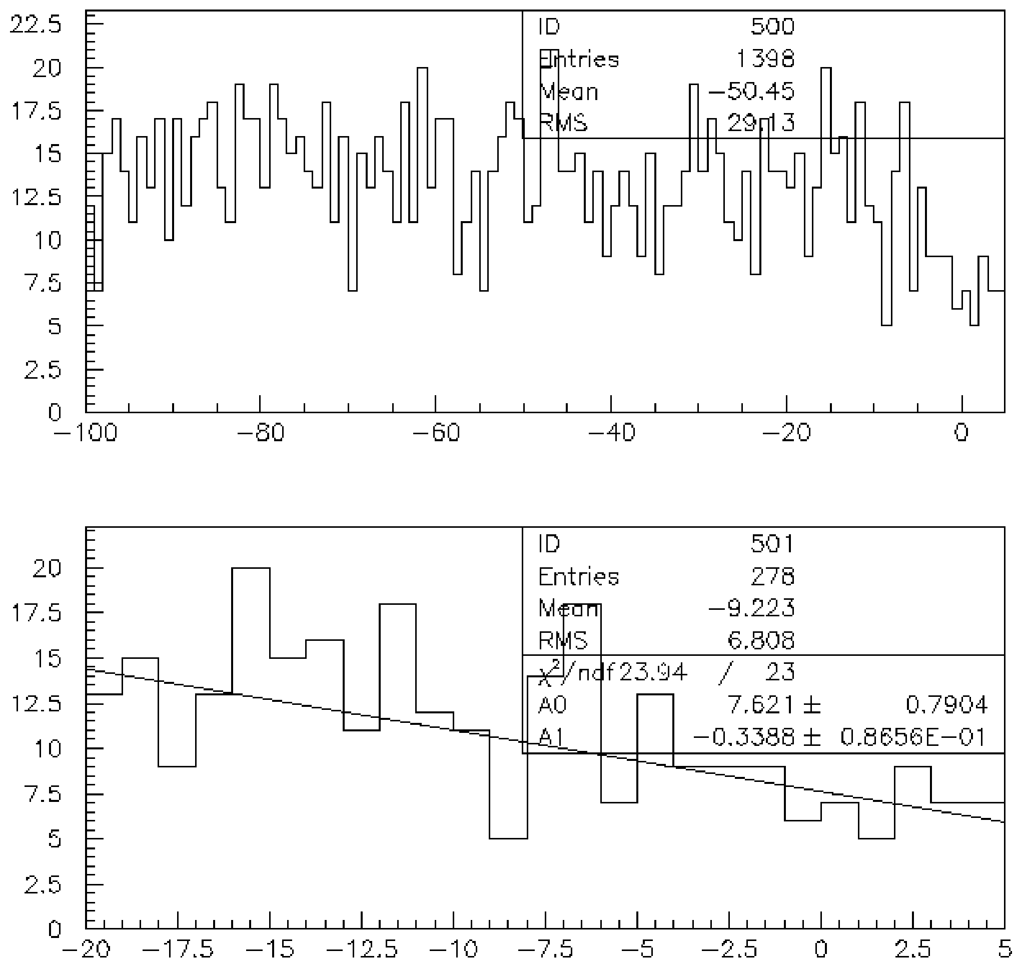


$K_L \to \pi^0\pi^0\mu e$ mass, $\mathrm{GeV/c^2}$

Background Estimate

- We don't trust the MC to estimate background to 1 part in 10^{10}. Use data.
- Fit likelihood variable outside of signal region and extrapolate into signal region.
- BUT - if all cuts are in place there are not enough events!
- Solution - fit likelihood variable for data with relaxed cuts and determine suppression factors by reapplying the cuts.

Fit to Likelihood Function with Relaxed Cuts



Likelihood Variable

Signal region is for Likelihood variable > 10

Take ± 1σ on fit parameters to determine systematic error on background estimate.

Suppression Factors

Cut set	Suppression factor
Kinematic	0.092 ± 0.016
Particle ID	0.273 ± 0.024
Accidental	0.261 ± 0.024
Kinematic + ID	0.012 ± 0.009
Kinematic * ID	0.025 ± 0.005
Kinematic + Accidental	0.025 ± 0.009
Kinematic * Accidental	0.024 ± 0.005
ID + Accidental	0.077 ± 0.015
ID * Accidental	0.071 ± 0.009

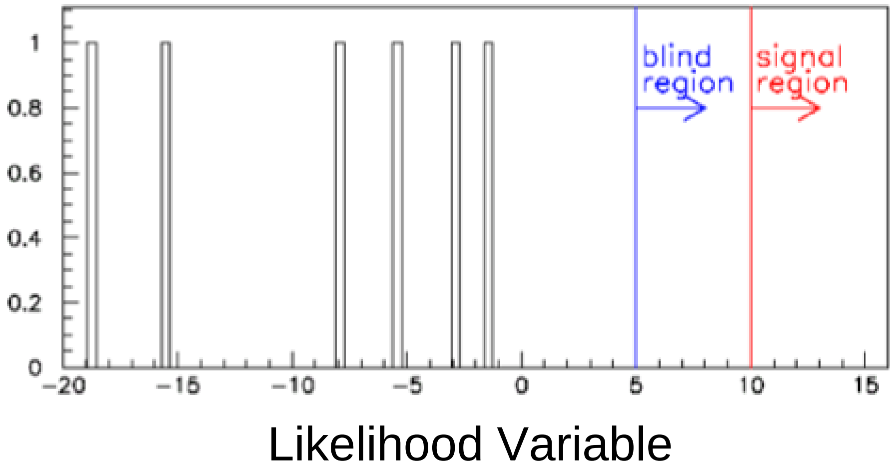
Joint criteria (+) and the product of individual cut sets (*) are equivalent within errors indicating that cut sets are relatively independent.

Result for $K_L \to \pi^0\pi^0\mu e$

Expected background = 0.44 ± 0.12 events

Box opened

No events in signal or blind region



PRELIMINARY result using Feldman-Cousins method

$BR(K_L \to \pi^0\pi^0\mu e) < 1.58 \times 10^{-10}$ (90% CL)

$\pi^0 \to \mu e$ From $K_L \to \pi^0\pi^0\pi^0$

Identical to $K_L \to \pi^0\pi^0\mu e$ analysis. Just add cut on $M_{\mu e}$

Expected background = 0.03 ± 0.02 events

Box opened. No events in signal or blind region.

PRELIMINARY result using Feldman-Cousins method

$BR(\pi^0 \to \mu e) < 3.63 \times 10^{-10}$ (90% CL)

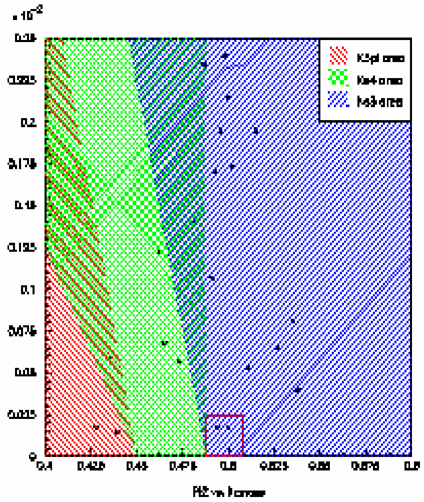
Previous results

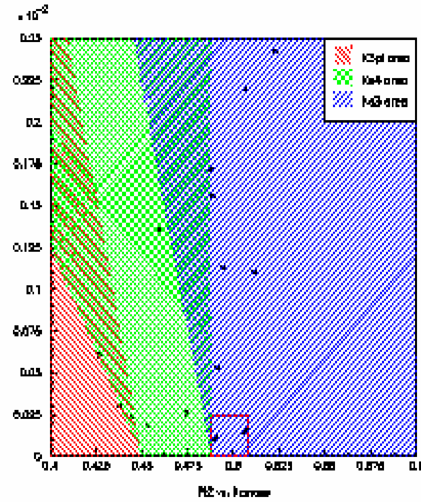
$BR(\pi^0 \to \mu e) < 1.72 \times 10^{-8}$ (90% CL) E799I (PL **B320** 407 (94))
$BR(\pi^0 \to \mu^+ e^-) < 3.8 \times 10^{-10}$ (90% CL) (PRL **85** 2450 (00))
$BR(\pi^0 \to \mu^- e^+) < 3.4 \times 10^{-9}$ (90% CL) (PRL **85** 2877 (00))

KL → $\pi^0\mu e$ History

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

…circa 2003





- 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.

….but no discovery claimed, upper limits quoted in conferences.

Backgrounds to $K_L \rightarrow \pi^0 \mu e$

- $K_L \rightarrow \pi^+\pi^-\pi^0$ with two Particle-ID errors.

- $K_L \rightarrow \pi^\pm e^\pm \pi^0 \nu_e$ with a soft neutrino and one Particle-ID error. Need to know form factor, recent measurements have improved the modeling substantially.

- $K_L \rightarrow \pi^\pm e^\pm \nu_e$ and two accidental photons. Aggressively veto on extra track fragments and energy deposits in veto systems outside of acceptance. Particularly important in the 1999 data set which ran with higher beam intensity.

Moving forward with $K_L \to \pi^0 \mu e$:

- Box excess doesn't match signal PDF.....

Close the Box!

• Bug found in simulation of the Ke4 $\pi \to \mu$ decay/punch-thru probability. Fixed, and improved Ke4 form-factors used. This results in net increase of expected Ke4 background.

•Better use of fast timing in beam-hole veto to reduce accidental losses (100 MHz beam).

•Replace box with signal pdf Likelihood analysis.

$K_L \rightarrow \pi^0 \mu e$ Selection

- Good (X^2<20) charged Z vertex between 96 and 155 m. X & Y vertex inside CsI beam holes.
- Assuming Ke4 decay, require the neutrino momentum to be negative.
- Square of π^0 momentum in K rest frame between 0 and 0.025 $(GeV/c)^2$
- π^0 masses between 0.132 and 0.138 GeV/c^2 (+/- 1.4σ).

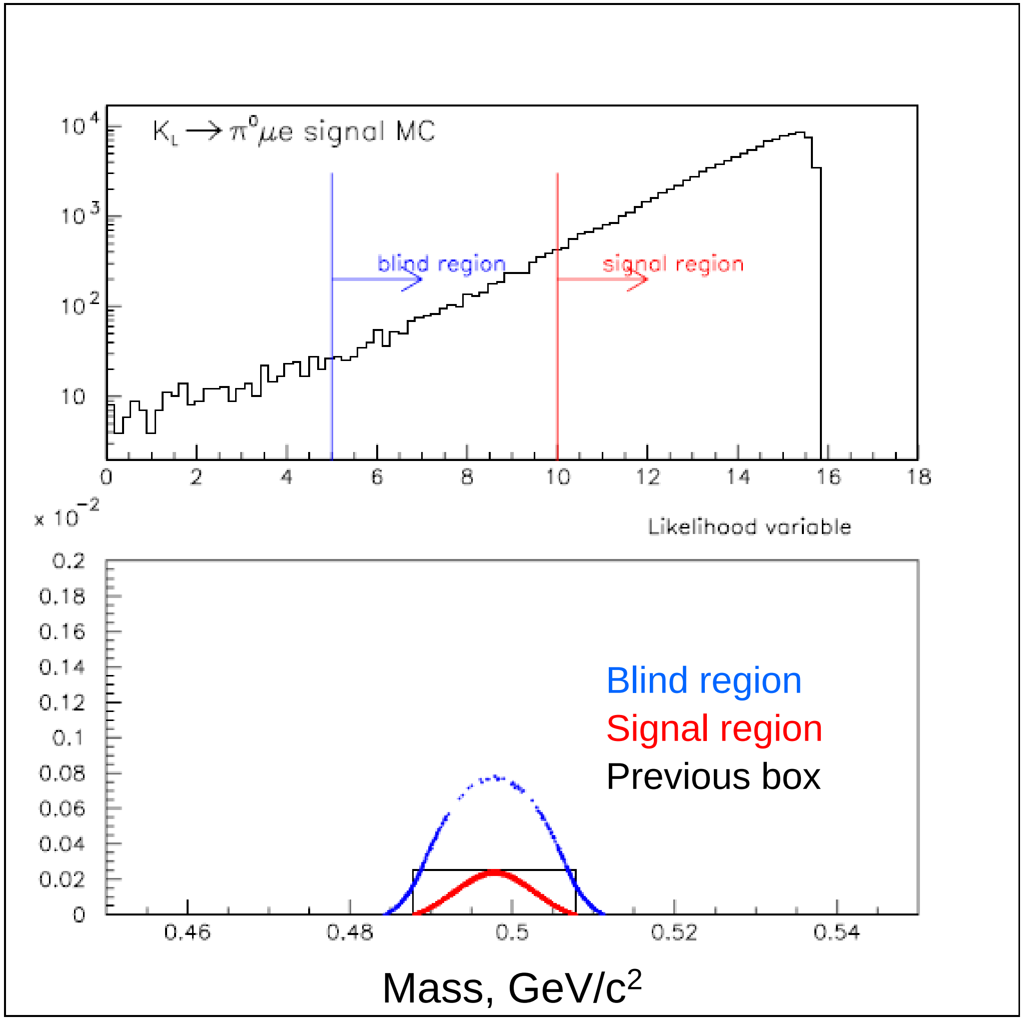
- E/p for electron between 0.95 and 1.05
- TRD signal for the electron candidate has an electron probability > 0.98)
- Good cluster shape (Fusion χ^2 < 10) for electron and photon clusters.
- μ momentum > 8 GeV. μ energy < 1 GeV in CsI, very good hit match to projected muon counters required

- **Exactly 3 in-time clusters above 2 GeV in CsI.**
- **< 0.3 GeV in photon veto counters.**
- **< 15 GeV in beam veto counter.**
- **No extra in-time drift chamber hit pairs in upstream spectrometer planes. < 3 extra in-time drift chamber hit pairs allowed downstream.**

Kinematic cuts | Particle ID Cuts | **Accidental cuts**

Likelihood Analysis

- Re-blinded analysis
- Signal region defined by p_t^2 and kaon mass
- Fit analytical functions to p_t^2 and kaon mass.
- Normalize to form PDFs. Likelihood is product of the two PDFs.
- Signal acceptance is 4% after all cuts on previous page.
- Cut at 10 preserves 95% of the signal events remaining after all cuts.

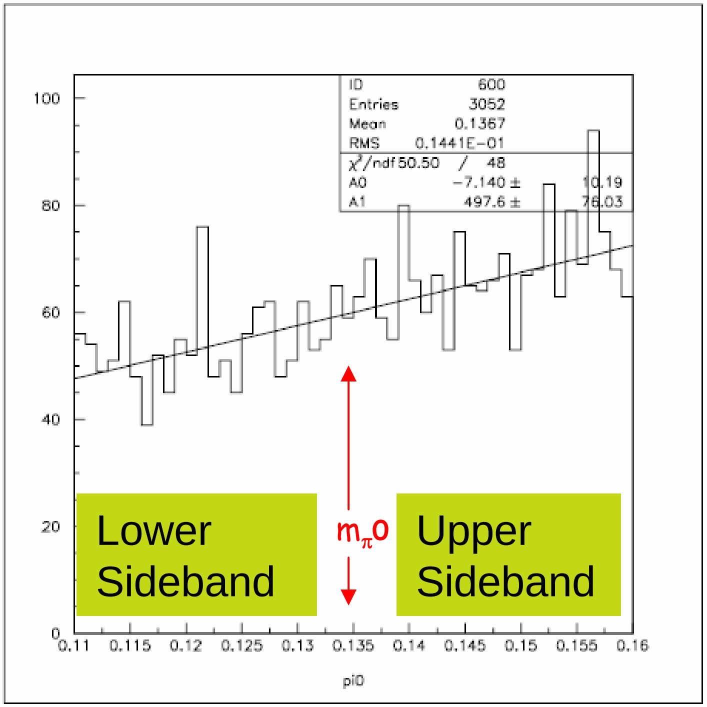


Backgrounds to $K_L \to \pi^0 \mu e$

$K_L \to \pi^+\pi^-\pi^0$ background is projected to be negligible in the signal region.

$K_L \to \pi^\pm e^\pm \pi^0 \nu_e$ background is projected to be (0.1±0.05) small in the signal region.

$K_L \to \pi^\pm e^\pm \pi^0 \nu_e + 2\gamma_{acc}$ is the dominant background and is estimated from the data in two ways:



$M_{\gamma\gamma}$ GeV/c², all cuts, -20< PDF <5.

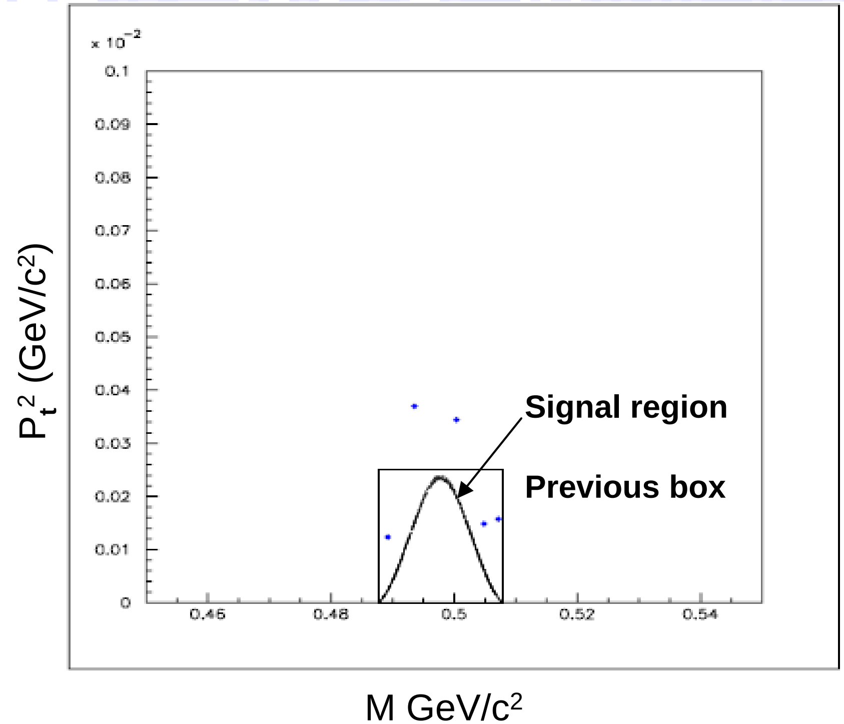
Method	99 signal	99 blind	97 signal	97 blind
pdf extrap.	0.55 ±0.54	0.98 ± 0.39	0.43 ± 0.43	0.57 ± 0.29
$M_{\gamma\gamma}$ sidebands*	0.28 ± 0.16	1.83 ± 0.41	0.28 ± 0.16	0.73 ± 0.26

* Exclude $m_{\gamma\gamma}$ signal region, look in PDF blind and signal regions and scale.

Opening the KL $\rightarrow \pi^0 \mu e$ Box

The total estimated background in the blind region is 4.21±0.53 events, 5 events are observed.

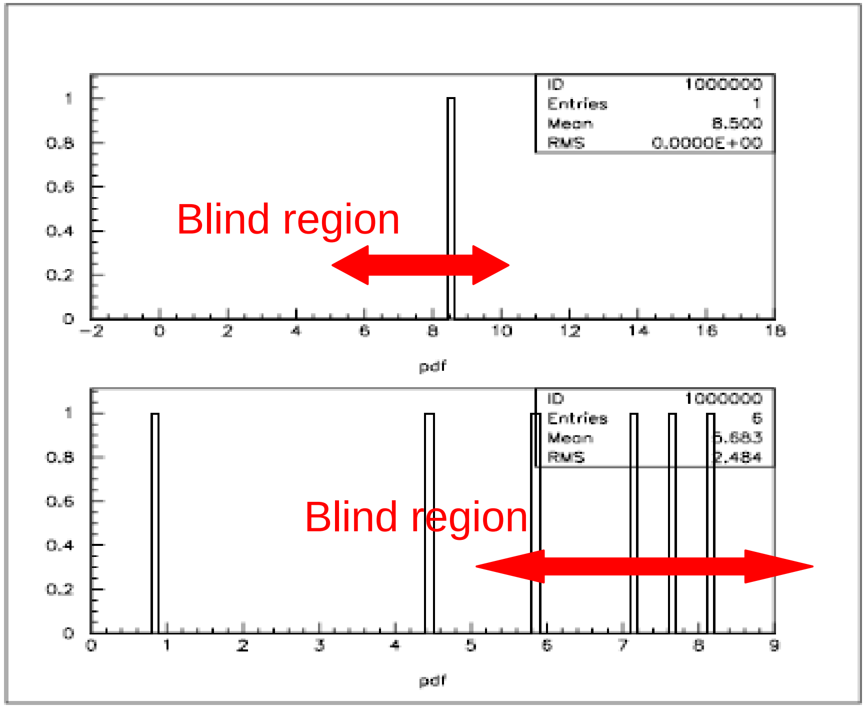
The total estimated background in the signal region is 0.66±0.23 events, No events are observed in the signal region.



p_t^2 vs K_{mass} showing the old and new signal regions. The points are the 99+97 data with pdf > 5 and passing all other cuts.

Rate dependence of $K_L \rightarrow \pi^0 \mu e$ background

In order to broadly maximize the senisitivity for the 1999 rare-decay run, the instantaneous beam intensity was doubled from ~100 MHz (1997) to ~200 MHz . The background is dominantly rate-dependent, consistent with $K_L \rightarrow \pi^{\pm} e^{\pm} \pi^0 \nu_e + 2\gamma_{acc}$



1997 Data

1999 Data

PDF after all cuts. Signal > 10.

Result for $K_L \to \pi^0 \mu e$

Expected background = 0.66 ± 0.23 events

Box opened. No events in signal region.

PRELIMINARY result using Feldman-Cousins method

$BR(K_L \to \pi^0 \mu e) < 7.56 \times 10^{-11}$ (90% CL)

Corresponding to $M_{X^0} > 54$ TeV/c^2.

Previous results: $B(K_L \to \pi^0 \mu e) < 3.4 \times 10^{-10}$ (KTeV Preliminary)

$B(K_L \to \pi^0 \mu e) < 6.2 \times 10^{-9}$ (E799, PL **B320** 407 (94))

Summary

KTeV has new preliminary results based on the full data.

- $BR(K_L \to \pi^0\pi^0\mu e) < 1.58 \times 10^{-10}$ (90% CL)
  - New mode, no events in signal box.
  - Background estimate of 0.44 ± 0.12 events
- $BR(\pi^0 \to \mu e) < 3.63 \times 10^{-10}$ (90% CL)
  - No events in signal box
  - Background estimate of 0.03 ± 0.02 events
- $BR(K_L \to \pi^0\mu e) < 7.56 \times 10^{-11}$ (90% CL)
  - No events in signal box, x80 improvement on PDG limit.
  - Background estimate of 0.66 ± 0.23 events
  - At beam intensity limit for KTeV configuration.