Rare K_L Decays
Recent Results from KTeV

Marj Corcoran

Rice University
for the KTeV collaboration

KTeV Collaboration (1999-2000)

Arizona, UCLA, UCSD, Campinas, Chicago,
Colorado, Elmhurst, Fermilab, Osaka, Rice,
Sao Paolo, Virginia, Wisconsin

Alghero, September 2003

KTeV Physics

- CP Violation
  - $K_{L,S} \to \pi\pi, \epsilon'$
  - Charge asymmetry δ in K_{e3}
  - CP violation in $K_L \to \pi\pi ee$
- Best limits on modes with possible direct CP-violating contributions
  - $K_L \to \pi^0 ee$
  - $K_L \to \pi^0 \mu\mu$
  - $K_L \to \pi^0 \nu\nu$
- EM processes $K \to \gamma^*\gamma$ and $K_L \to \gamma^*\gamma^*$
  - $K_L \to \mu\mu\gamma$
  - $K_L \to ee\gamma$
  - $K_L \to eeee$
  - $K_L \to ee\mu\mu$
- Lepton Flavor Violating Modes
  - $K_L \to \pi^0 \mu e$
  - $\pi^0 \to \mu e$
  - $K_L \to \mu^\pm \mu^\pm e^\mp e^\mp$

EM Decays of the K_L

$K_L \to \gamma^* \gamma$ and $K_L \to \gamma^* \gamma^*$

If these processes could be understood well, one might be able to extract the CKM parameter ρ from $K_L \to \mu^+ \mu^-$

$K_L \to \gamma^* \gamma$ can be probed with

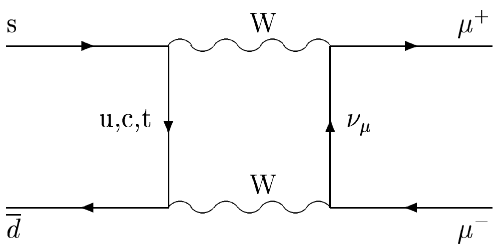
- $K_L \to \mu\mu\gamma$
- $K_L \to ee\gamma$

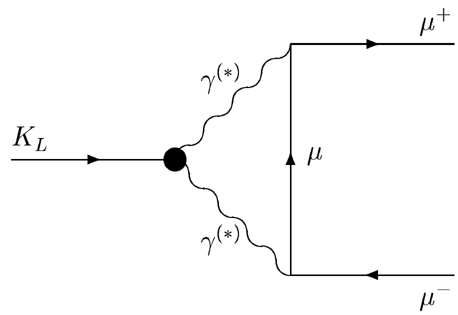
$K_L \to \gamma^* \gamma^*$ can be probed with

- $K_L \to eeee$
- $K_L \to \mu\mu ee$

$K_L \to \mu^+\mu^-$

Short Distance | Long Distance





$$BR(K_L \to \mu^+\mu^-) = |\mathrm{Re}A|^2 + |\mathrm{Im}A|^2$$

Absorptive: Calculated exactly from $K_L \to \gamma\gamma$

$$|\mathrm{Im}A|^2 = (7.07 \pm 0.18) \times 10^{-9}, \text{ Unitarity Bound}$$

$$|\mathrm{Re}A_{exp}|^2 < 3.7 \times 10^{-10} \ (90\% \ C.L.)$$

Dispersive: SD and LD components

$$\mathrm{Re}A = \mathrm{Re}A_{SD} + \mathrm{Re}A_{LD}$$

$$|\mathrm{Re}A_{SD}|^2 = 0.9 \times 10^{-9}(1.2 - \overline{\rho})^2 \left(\frac{m_t}{170 \text{ GeV}}\right)^{3.1} \left(\frac{|V_{cb}|}{0.040}\right)^4$$

$$\overline{\rho} = \rho\left(1 - \tfrac{\lambda^2}{2}\right),$$

If one can determine ReA_{LD}, one can extract a limit for the CKM matrix element ρ.

A_{LD} can be written in terms of a form factor $f(q_1^2, q_2^2)$ and $BR(K_L \to \gamma\gamma)$.

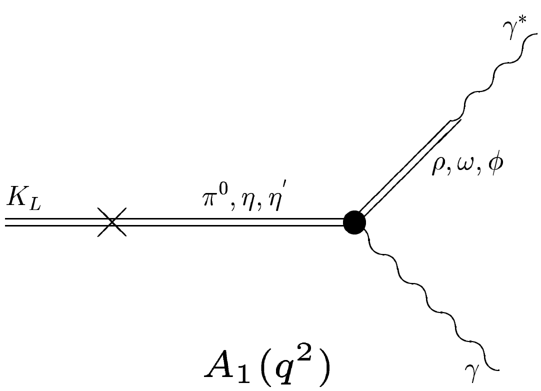
Understanding long distance physics=understanding $f(q_1^2, q_2^2)$

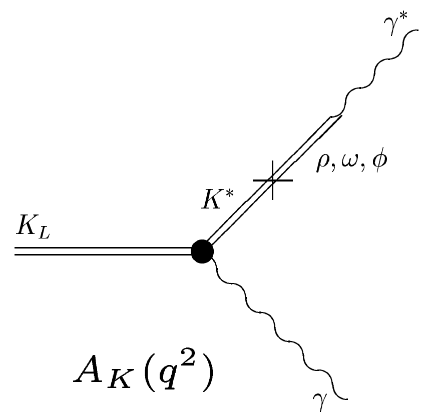
$\boxed{K_L \to l^+ l^- \gamma}$

$K_L \to \gamma^* \gamma \to l^+ l^- \gamma$

Bergström, Massó, Singer

2 long distance contributions





$$f(q^2) \propto A_1(q^2) + \alpha_{K^*} A_K(q^2)$$

Connect to $f(q_1^2, q_2^2)$ by evaluating ReA_{LD} for the case of one γ^* originating from a vector meson ($PV\gamma$ vertex), and the case of two γ^*'s coupled to vector mesons (PVV vertex), leading to

$$(-5.1 - 11.0\alpha_{K^*}) \times 10^{-5} < \mathrm{Re}A_{LD} < (-2.9 - 10.2\alpha_{K^*}) \times 10^{-5}$$

Applies to $K_L \to \mu\mu\gamma$ and $K_L \to ee\gamma$

$K_L \to l^+l^-\gamma$ and $l^+l^-l^+l^-$

D'Ambrosio, Isidori, Portolés

$K_L \to \gamma^*\gamma^*$ form factor:

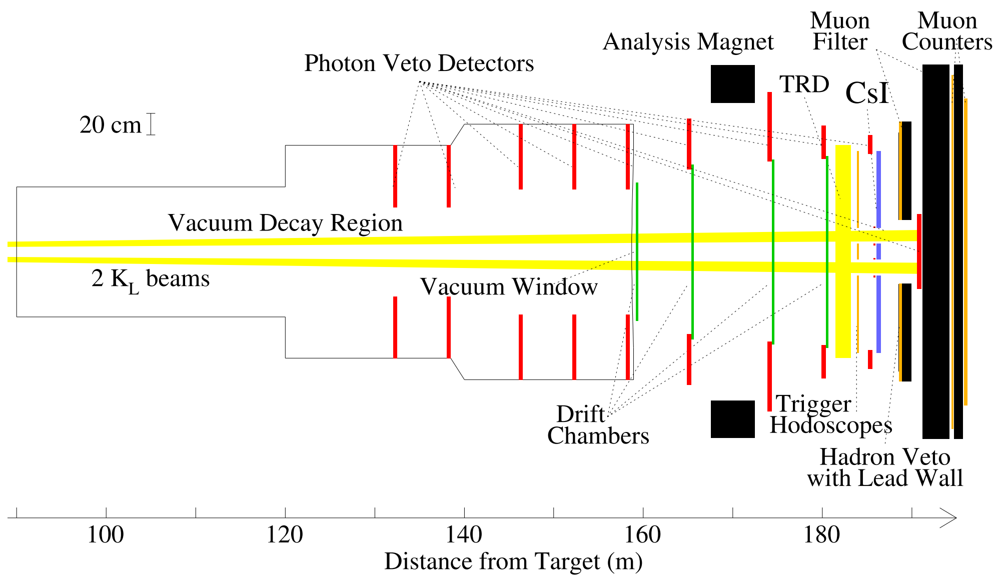
$$f(q_1^2, q_2^2) = 1 + \alpha\left(\frac{q_1^2}{q_1^2 - m_\rho^2} + \frac{q_2^2}{q_2^2 - m_\rho^2}\right) + \beta\frac{q_1^2 q_2^2}{\left(q_1^2 - m_\rho^2\right)\left(q_2^2 - m_\rho^2\right)}$$

- General parameterization compatible with a Chiral Perturbation Theory expansion
- Includes characteristic long distance pole behavior
- No specific diagrams of long distance processes are assumed
- Reduces to $K_L \to \gamma^*\gamma$ form factor by setting $q_2^2 = 0$

Dispersive long distance contribution is given in terms of $BR(K_L \to \gamma\gamma)$, α, and β

α_{DIP} is directly accessible through $K_L \to l^+l^-\gamma$.
β_{DIP} is directly accessible through $K_L \to \mu\mu ee$ and $K_L \to eeee$ (but hard)

KTeV Detector

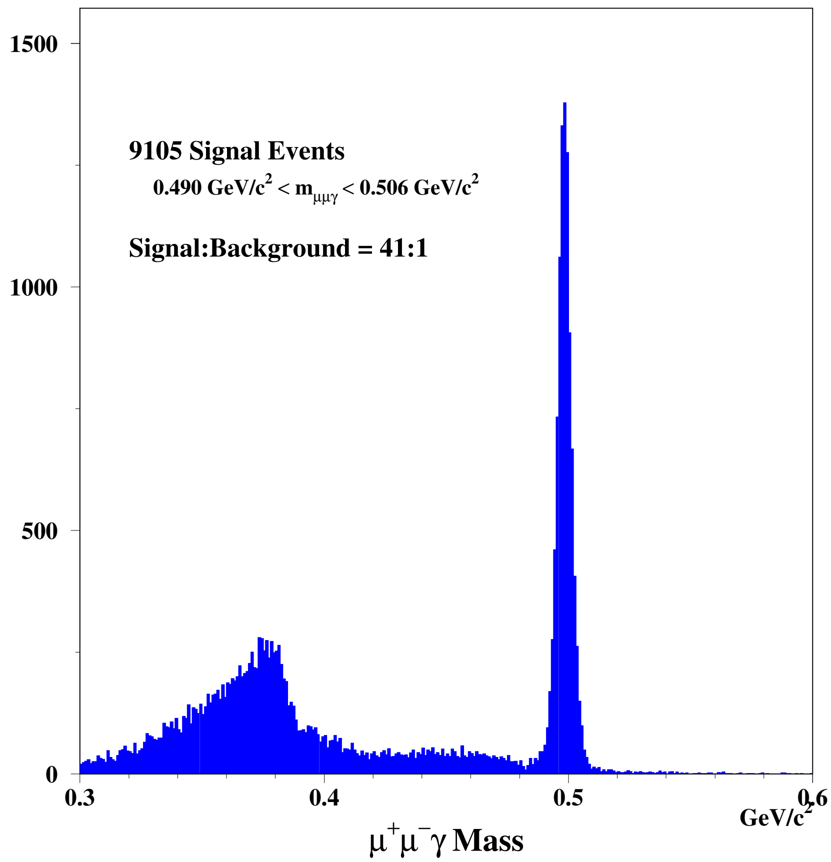


The KTeV detector has outstanding

- Electromagnetic calorimetry
- Charged particle tracking
- $\pi/e/\mu$ separation
- Vetoes on activity outside the fiducial region

KTeV took data in 1996/97 and 1999/2000. The total Kaon fluxes were 2.4×10^{11} in 97 and 3.6×10^{11} in 99

$$\boxed{K_L \to \mu^+\mu^-\gamma}$$



High statistics and low background allow for precision measurements of the BR and form factors.

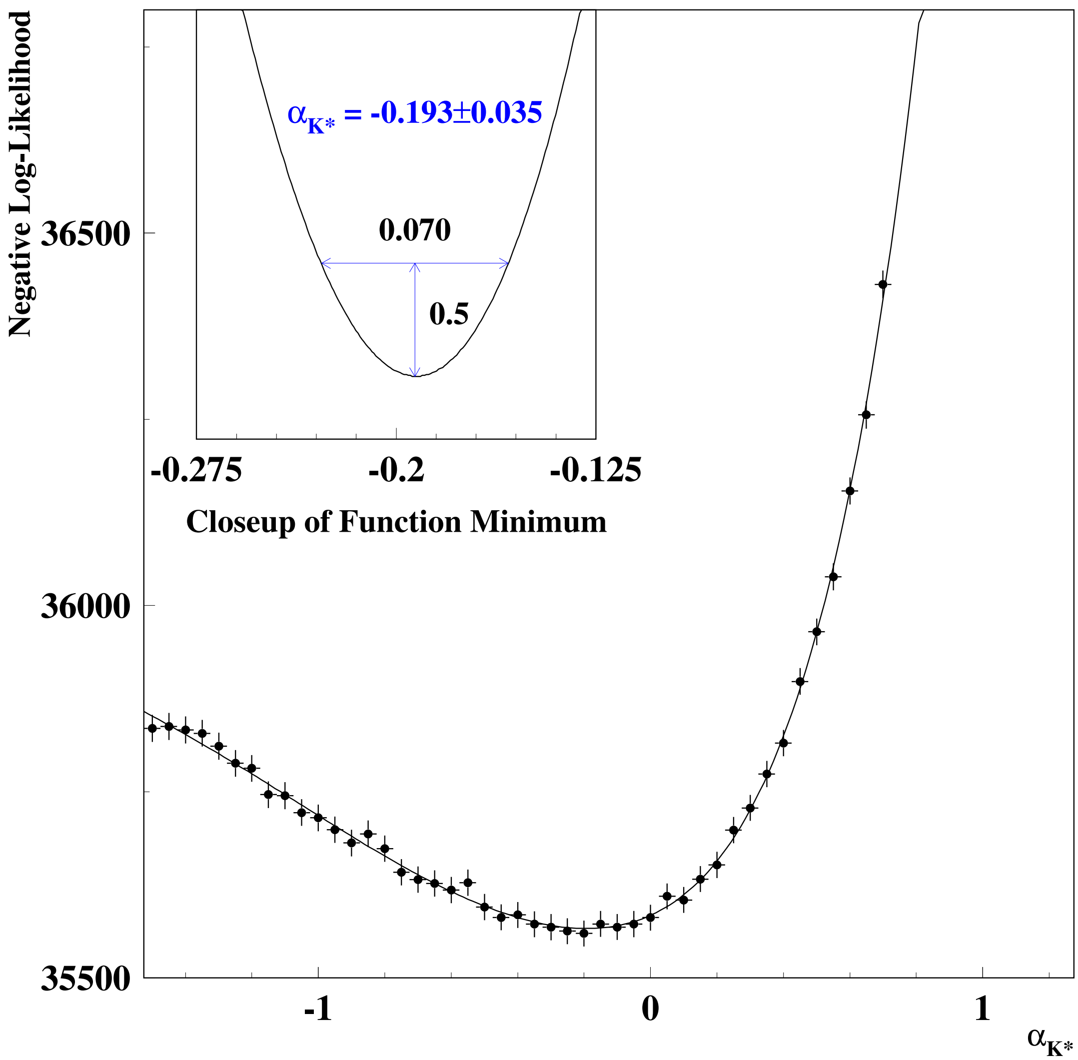
$$\boxed{BR(K_L \to \mu^+\mu^-\gamma) = (3.62 \pm 0.04_{stat} \pm 0.08_{sys}) \times 10^{-7}}$$

Thesis work of Breese Quinn

Measurement of α_{K^*}

α_{K^*} is determined by calculating the NLL of the data being consistent with MC distributions generated at various values of α_{K^*}.

10000 MC 'Data' sets are generated with the measured α_{K^*}. The NLL method is used to measure α_{K^*} for each of these sets, and the width of that distribution is a check on the error.



Measurement of α_{K^*}

Branching Ratio

Integrating the differential decay rate with the BMS form factor yields the expression

$$BR(K_L \to \mu^+\mu^-\gamma)/BR(K_L \to \gamma\gamma) = (14.33\alpha_{K^*}^2 - 51.91\alpha_{K^*} + 55.52) \times 10^{-5}$$

With our measurement of $BR(K_L \to \mu^+\mu^-\gamma)$ and the PDG value for $BR(K_L \to \gamma\gamma)$,

$$\alpha_{K^*}^{BR} = -0.117^{+0.038}_{-0.037}.$$

Dimuon Mass Shape

The systematic error on the shape anaylsis result is dominated by the cut on track momentum. Including systematic error,

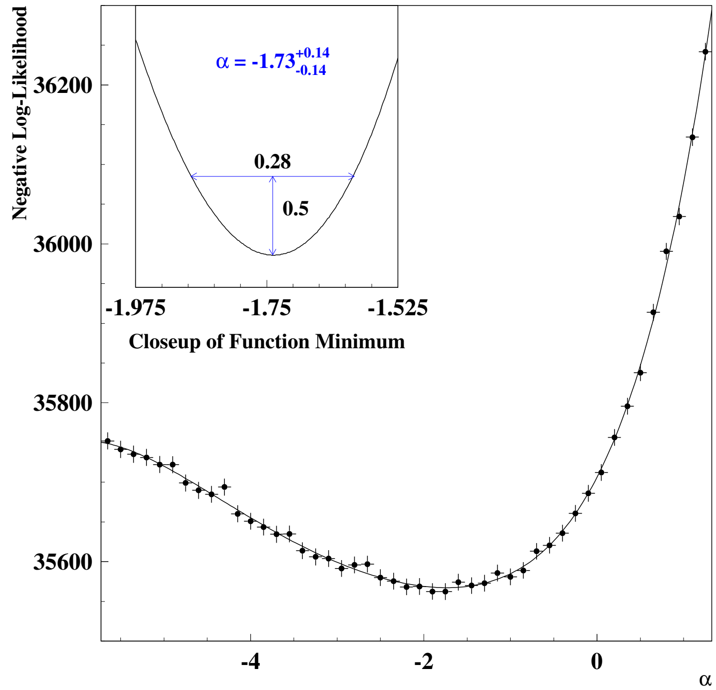
$$\alpha_{K^*}^{Shape} = -0.193^{+0.035}_{-0.049}.$$

Combined

Combining these two measurements we find

$$\boxed{\alpha_{K^*} = -0.160^{+0.026}_{-0.028}}$$

Measurement of α_{DIP}



Dimuon Mass Shape

Including the systematic error,

$\alpha^{Shape} = -1.73^{+0.14}_{-0.18}$.

Branching Ratio

Integrating the differential decay rate with the DIP form factor

$$f(x) = 1 + \alpha \left(\frac{x}{x - 2.40} \right),$$

and using our measurement of $BR(K_L \to \mu^+ \mu^- \gamma)$ and the PDG value for $BR(K_L \to \gamma\gamma)$, α is calculated to be

$$\alpha^{BR} = -1.38 \pm 0.12.$$

Combined

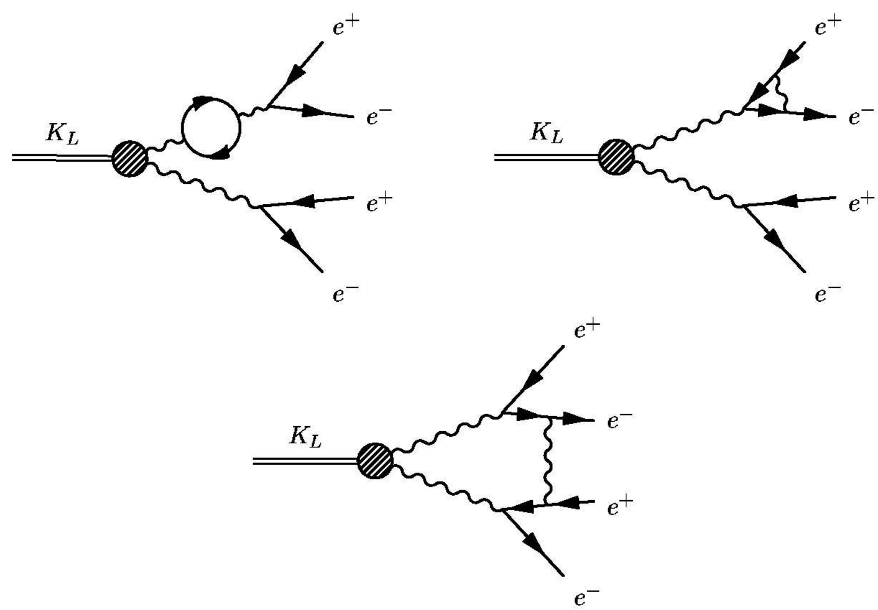
Combining these two measurements we find

$$\boxed{\alpha_{DIP} = -1.54 \pm 0.10}$$

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

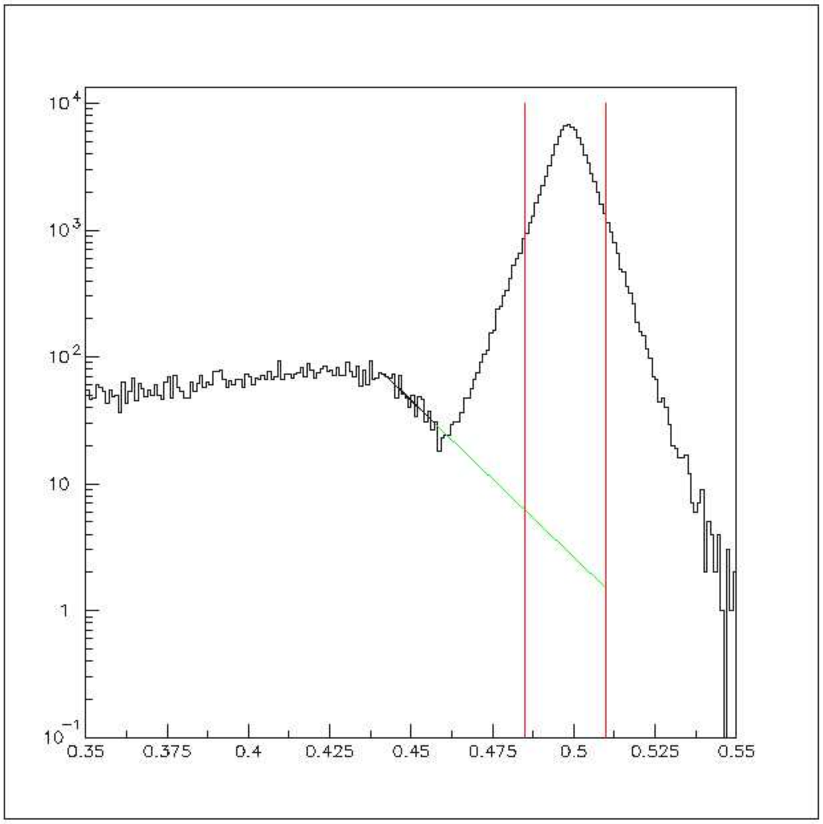
- This decay also proceeds through $K_L \to \gamma^*\gamma$ and should provide an independent means of measuring the form factors α_{K^*} and α_{DIP}.

- Radiative corrections are important for the electron modes. The Colorado group has implemented full radiative corrections to $\mathcal{O}(\alpha^3)$, included are diagrams shown below.



$$\boxed{K_L \to e^+e^-\gamma}$$

The statistics are high, background is low in this mode, as can be seen in the M_{ee} plot:



$M_{ee\gamma}$

$BR(K_L \to e^+e^-\gamma)=$

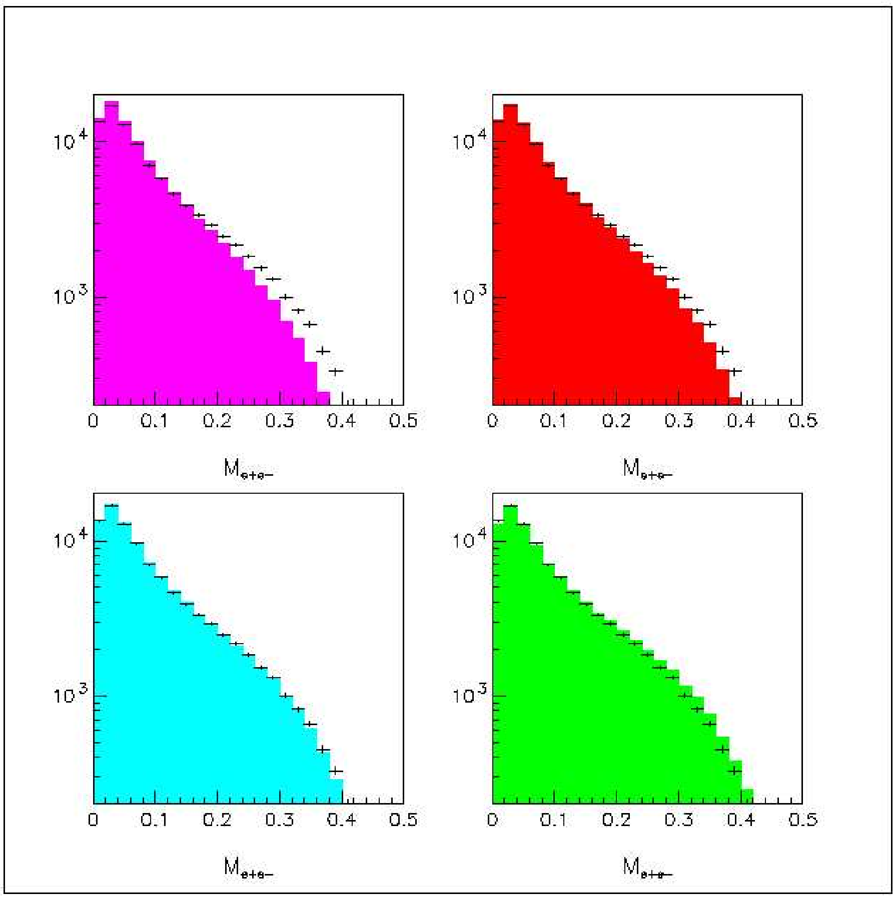
$[10.192 \pm 0.036_{stat} \pm 0.073_{sys} \pm 0.285_{ext\ \ sys}] \times 10^{-6}$

based on 92269 events

Thesis work of Jason LaDue

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

Both α_{K^*} and α_{DIP} can be measured in this mode. The sensitivity of M_{ee} to α_{K^*} is shown below. In each plot the points are the data and the colored histograms are Monte Carlo using different values of α_{K^*} as input (+.02, 0.,-0.16 and -.36).

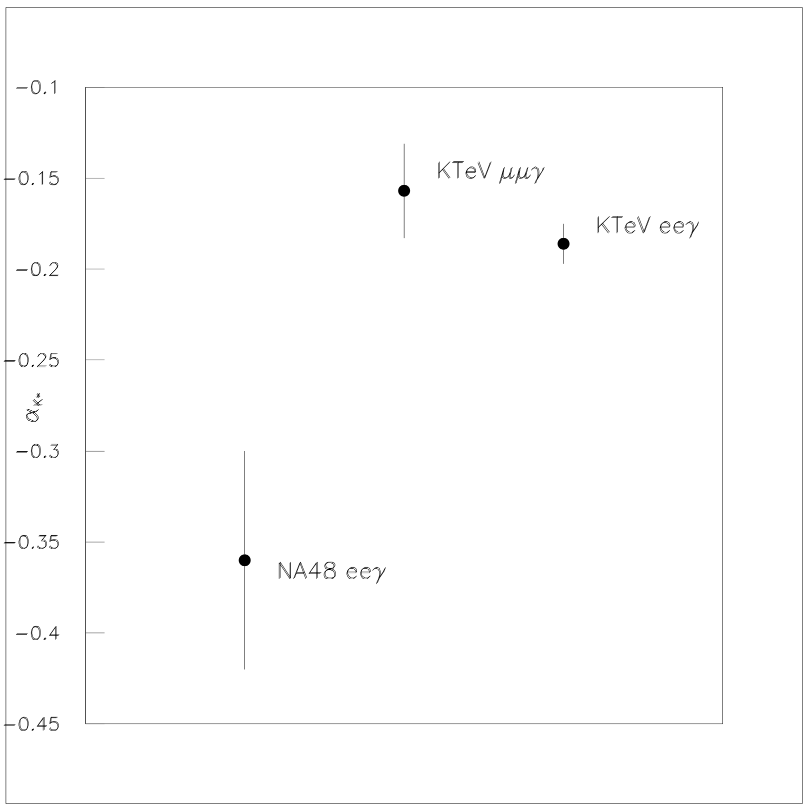


$K_L \to e^+e^-\gamma$ Form Factors

From $K_L \to ee\gamma$ we extract the form factors

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

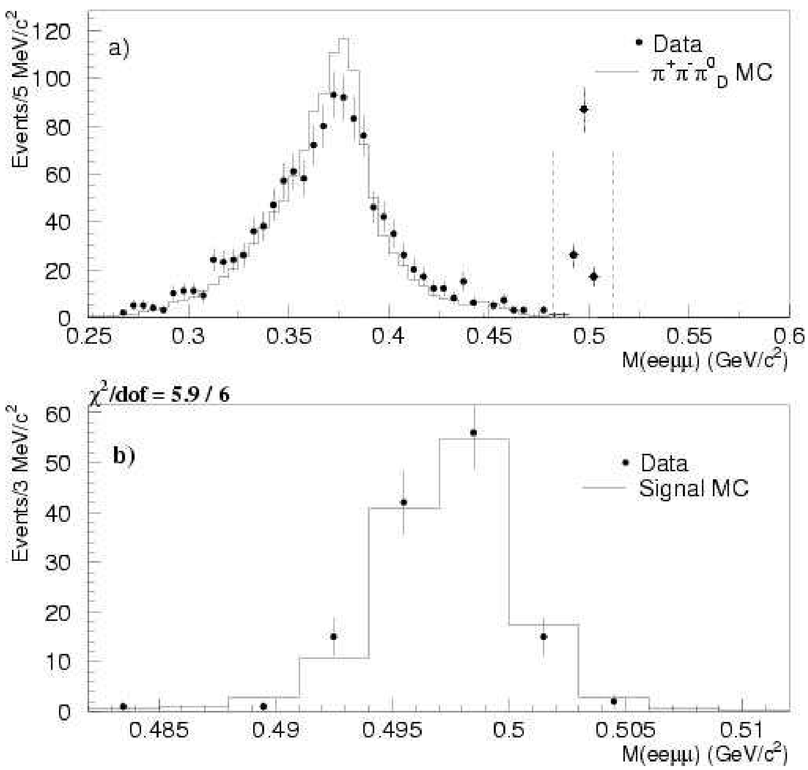
$\alpha_{DIP} = -1.63 \pm 0.038_{stat} \pm 0.028_{sys}$



Recent results for α_{K^*}, from NA48 and KTeV.

$$\boxed{K_L \rightarrow e^+e^-\mu^+\mu^-}$$

In the full KTeV data set we have 132 $K_L \rightarrow ee\mu\mu$ events.



$M_{ee\mu\mu}$ showing both signal and background (above) and expanded view of the signal region (below).

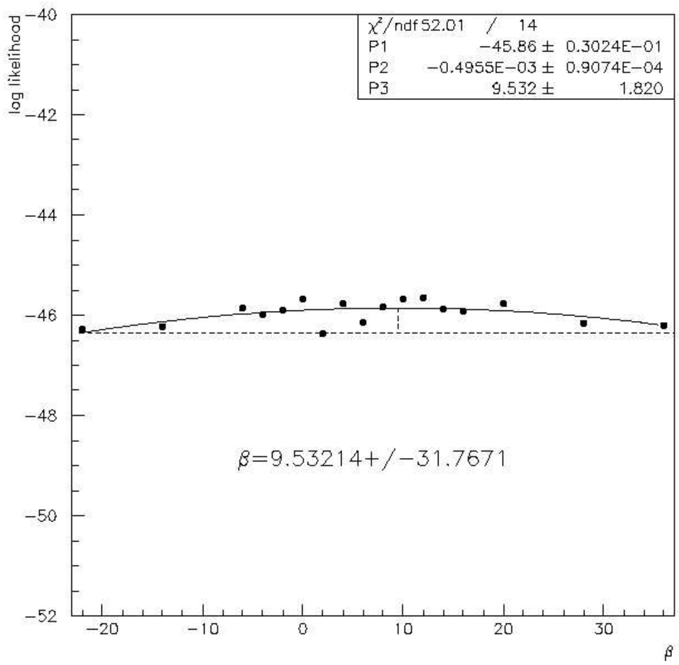
$$BR(K_L \rightarrow e^+e^-\mu^+\mu^-) =$$
$$2.69 \pm 0.24_{stat} \pm 0.12_{sys} \times 10^{-9}$$

Thesis work of Jason Hamm

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

The hope is to extract the DIP form factor β from these data. We fix α_{DIP} to the value detemined from $K_L \rightarrow \mu\mu\gamma$ and attempt a fit for β_{DIP}.

But...the statistics are too low and the sensitivity is too low...

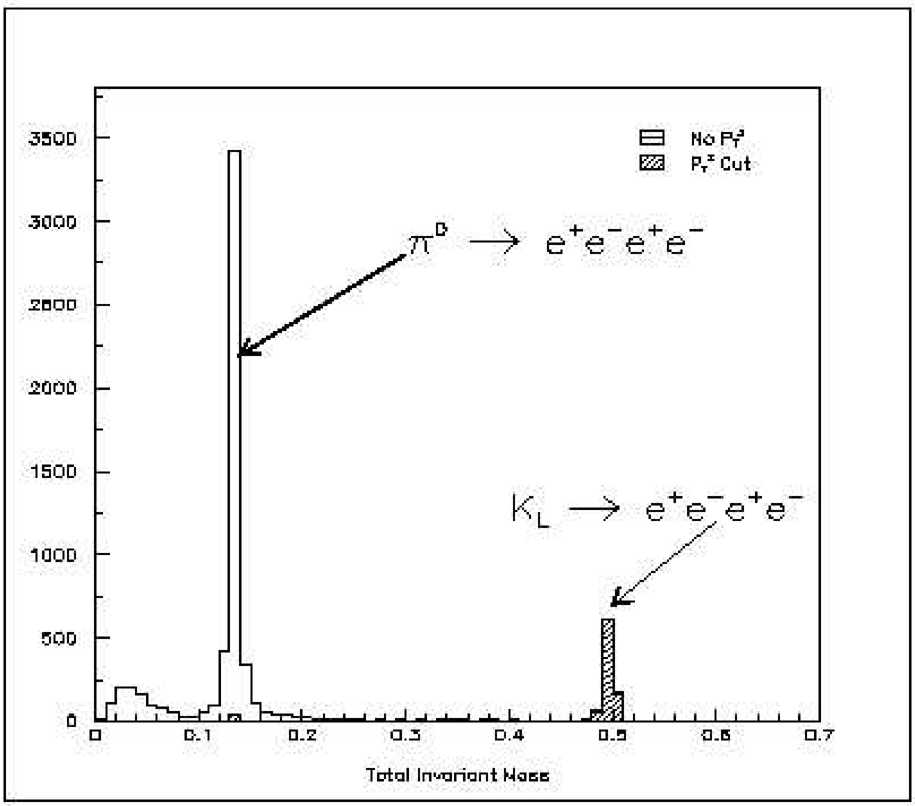


Log likelihood vs. β_{DIP}

$\beta_{DIP} = 9.5 \pm 31.8$

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

In the full KTeV data set there are 1056 $K_L \to e^+e^-e^+e^-$ events. This mode can also be used to extract the form factors, including β_{DIP}.



$$M_{eeee}$$

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

(External systematic is due to error on π^0_D BR)
With 1056 events, we still have no sensitivity to β_{DIP}

Thesis work of Jason LaDue

Conclusions on $K_L \to \gamma^*\gamma^{(*)}$ physics

Branching Ratios:

$BR(K_L \to \mu^+\mu^-\gamma) = (3.62 \pm 0.04_{stat} \pm 0.08_{sys}) \times 10^{-7}$

$BR(K_L \to e^+e^-\gamma) =$
$(10.192 \pm 0.036_{stat} \pm 0.073_{sys} \pm 0.285_{ext\ sys}) \times 10^{-6}$

$BR(K_L \to e^+e^-\mu^+\mu^-) =$
$(2.69 \pm 0.24_{stat} \pm 0.12_{sys}) \times 10^{-9}$

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

α_{K^*}:

From $K_L \to \mu\mu\gamma$ $\quad -0.160^{+0.026}_{-0.028}$

From $K_L \to ee\gamma$ $\quad -0.186 \pm 0.011$

α_{DIP}:

From $K_L \to \mu\mu\gamma$ $\quad -1.54 \pm 0.10$

From $K_L \to e^+e^-\gamma$ $\quad -1.63 \pm 0.047$

From $K_L \to e^+e^-\mu^+\mu^-$ $\quad -1.59 \pm 0.37$

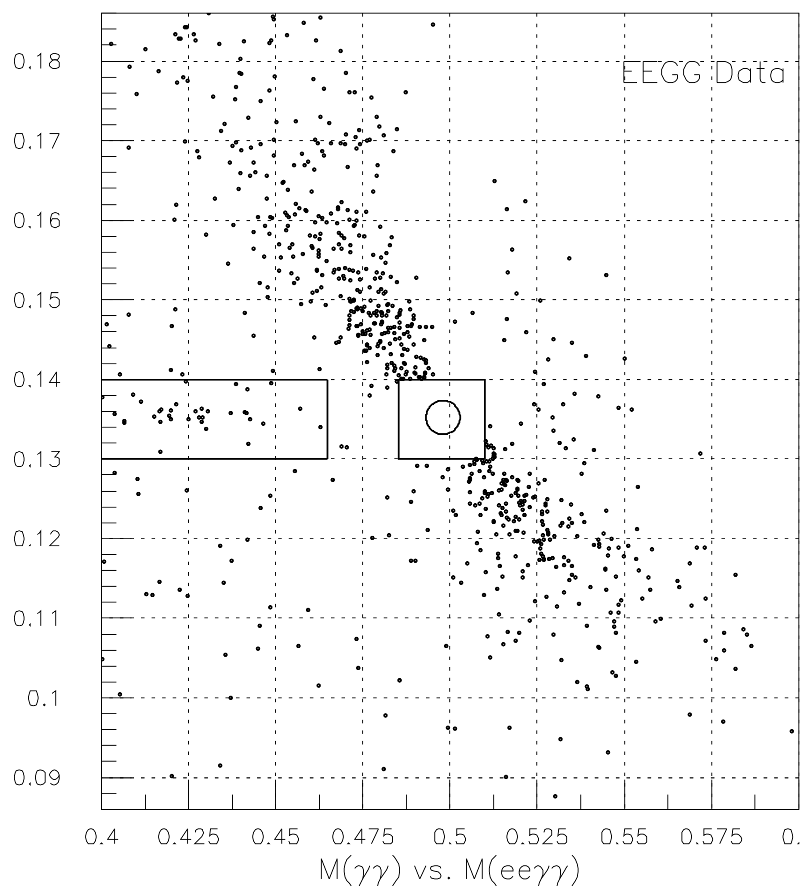
β_{DIP} :

From $K_L \to e^+e^-\mu^+\mu^-$ $\quad 9.5 \pm 32$

From $K_L \to e^+e^-e^+e^-$ $\quad 13 \pm 70$

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

This mode is of interest because of the possible direct CP violating contribution. The CP conserving decay $K_S \to \pi^0 ee$ has recently been seen by NA48.

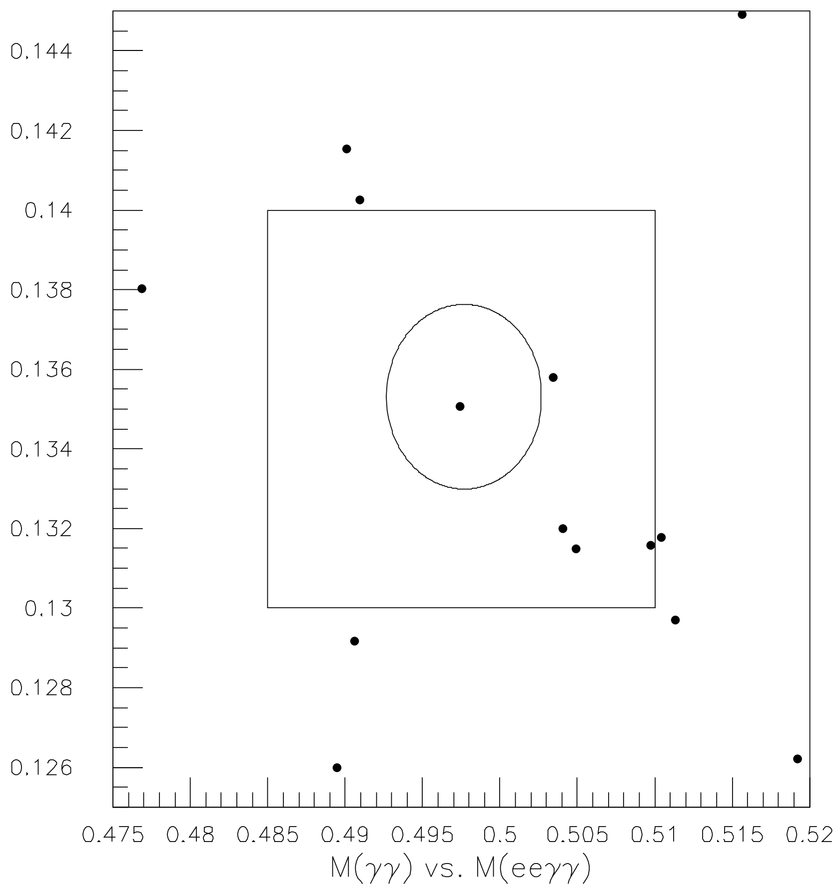


$M_{\gamma\gamma}$ vs $M_{ee\gamma\gamma}$

The diagonal swath is the primary background $K_L \to ee\gamma\gamma$. Kinematic cuts reduce the expected background to 0.99 ± 0.35 events.

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

In the 99 data set we observe one event, giving a 90% CL limit of 3.5 $\times 10^{-10}$

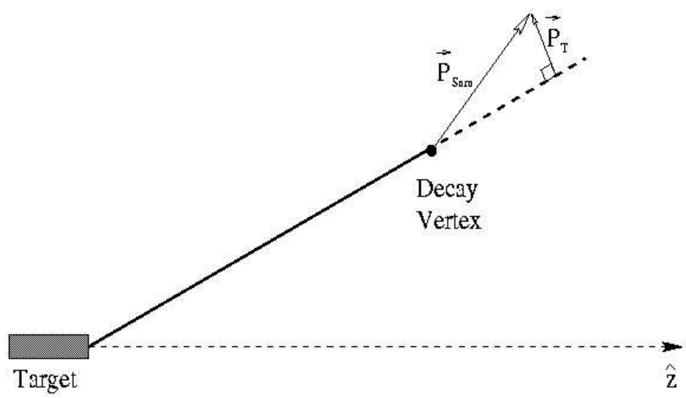


Combining with the 97 data gives the final KTeV limit

$BR(K_L \to \pi^0 ee) < 2.8 \times 10^{-10}$ at 90% CL

Search for Lepton Flavor violation in $K_L \to \pi^0 \mu e$

The procedure is to define a signal box in the 2-D space of $M_{\pi^0 \mu e}$ and p_t^2, the momentum of the final particles with respect to the initial flight direction of the Kaon (should be close to zreo).

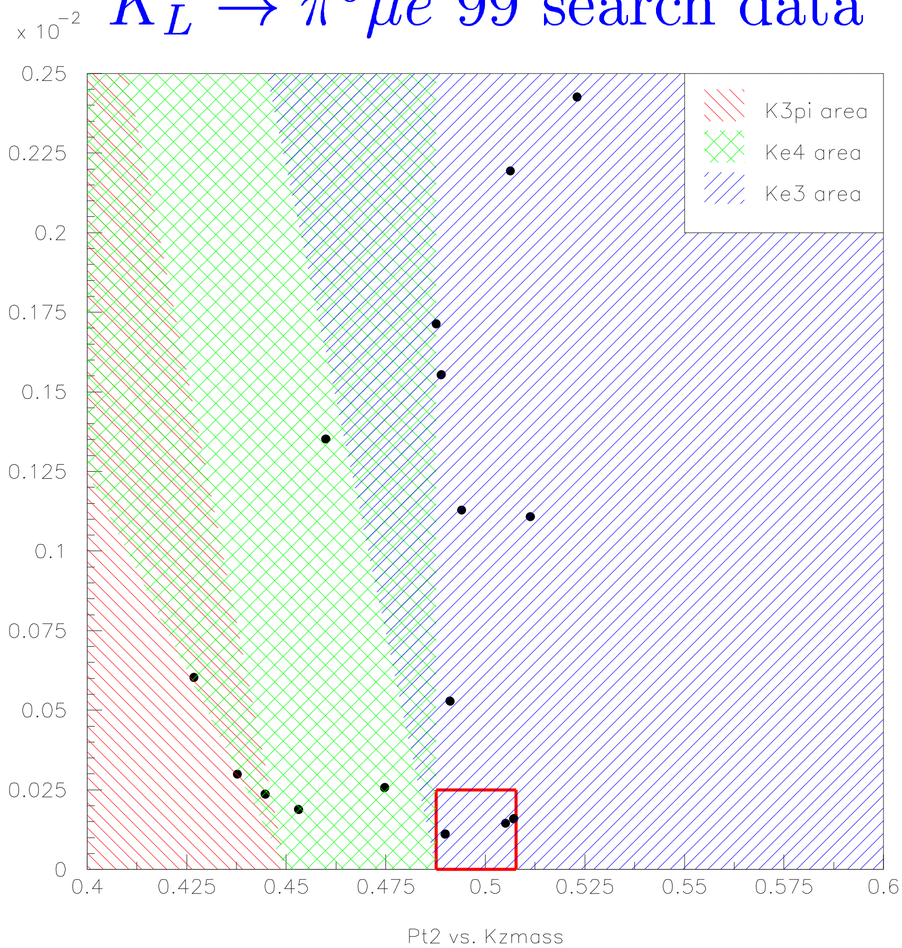


Definition of p_t^2

A study region, about 100x larger, is defined in the same variables to study the backgrounds.

The limiting background for this mode turned out to be K_{e3} with accidental photons

$K_L \to \pi^0 \mu e$ 99 search data



p_t^2 vs $M_{\pi^0 \mu e}$

Our result was limited by background from K_{e3} with accidental photons, which we could not eliminate. The final KTeV result, for both 97 and 99 (still preliminary) is

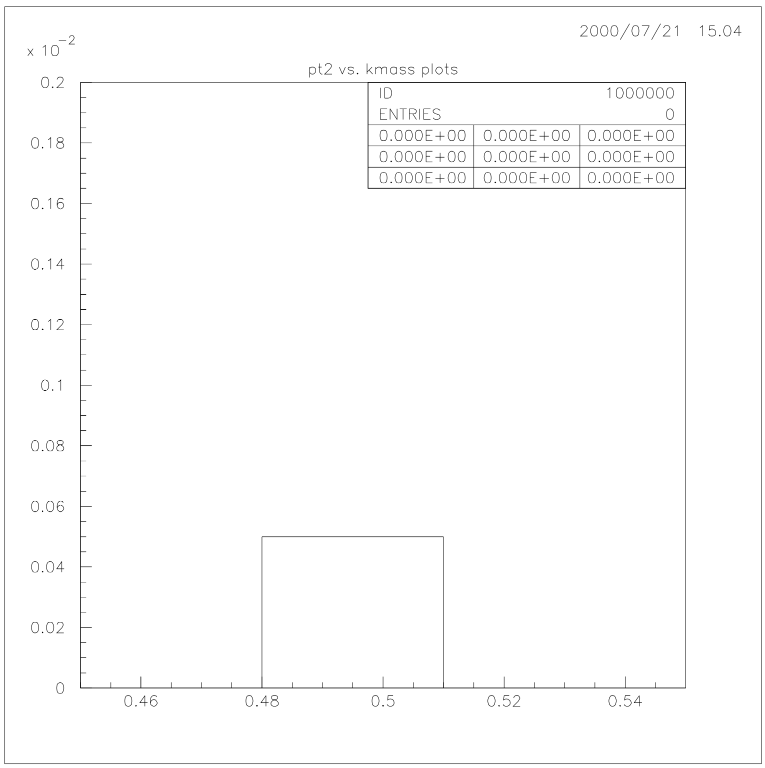
$BR(K_L \to \pi^0 \mu^\pm e^\mp) < 3.3 \times 10^{-10}$ at 90% CL

Previous limit was 6.2×10^{-9}

Thesis work of Angela Bellavance

Search for Lepton Flavor violation in $\pi^0 \to \mu e$ from $K_L \to \pi^0\pi^0\pi^0$

Again define a signal region in p_t^2 vs mass and look for background events in a region around it. For this mode, since 2 π^0s are required, the background is greatly suppressed.



p_t^2 vs Kaon mass

No events are found in the signal region or surrounding region (97 data only) giving a limit

$BR(\pi^0 \to \mu^\pm e^\mp) < 7.85 \times 10^{-10}$ at 90% CL

Work of undergraduate Collin Wolfe

Summary of LFV Limits

$BR(K_L \to \pi^0 \mu^\pm e^\mp) < 3.3 \times 10^{-10}$ (90% CL)

$BR(\pi^0 \to \mu^\pm e^\mp) < 7.85 \times 10^{-10}$(90% CL)
Will be improved by 99 statistics

$BR(K_L \to \mu^\pm \mu^\pm e^\mp e^\mp) < 1.36 \times 10^{-10}$ (90% CL)
From the $K_L \to e^+ e^- \mu^+ \mu^-$ study

Other modes KTeV is looking at now:

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

$K_L \to \pi^+ \pi^- \mu^\pm e^\mp$

and the $\Delta L = 2$ mode
$K_L \to \pi^\pm \pi^\pm \mu^\mp e^\mp$

How might one do better?

- Measurement of β_{DIP} through $K_L \to e^+e^-\mu^+\mu^-$ and $K_L \to e^+e^-e^+e^-$ is limited only by rate. You probably need 100,000 events to measure β_{DIP}. With branching ratios of 10^{-8} and 10^{-9}, this is a challenge. But a worthy goal.

- Measurement of $K_L \to \pi^0 ee$ and $K_L \to \pi^0 \mu\mu$ are ultimately limited by the $K_L \to ee\gamma\gamma$ and $K_L \to \mu\mu\gamma\gamma$ backgrounds. But we're not there yet, so there is some room for improvement.

- Our results on LFV modes were limited by accidental activity and total luminosity. An e^+e^- collider should be a much cleaner environment.