

Rare Kaon Decays from KTeV

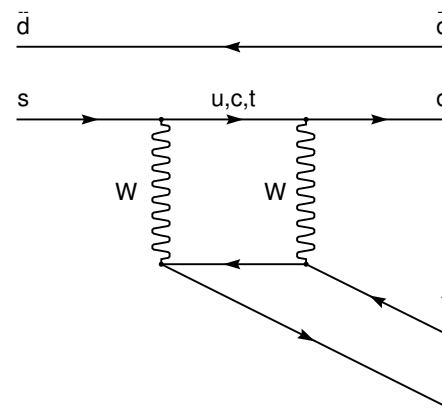
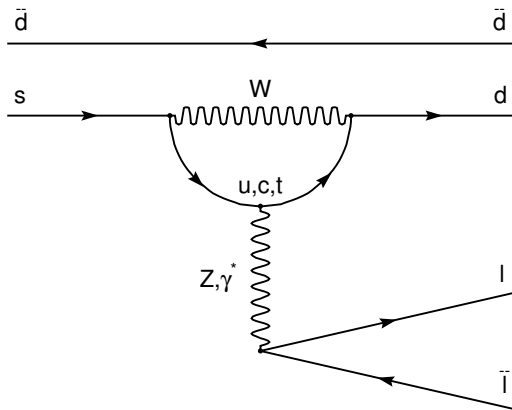
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- Direct CP violation in $K_L \rightarrow \pi^0 l^+ l^-$
- The KTeV Detector
- KTeV Measurements of $K_L \rightarrow \pi^0 l^+ l^-$
- Summary

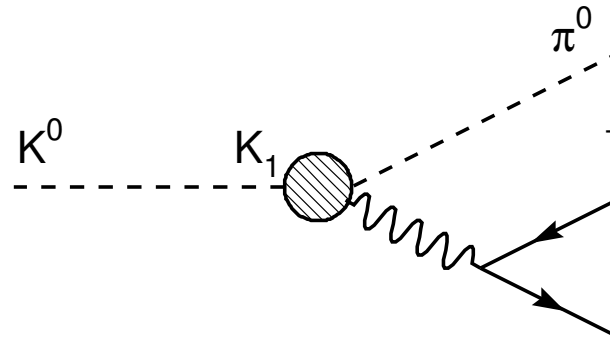
Direct CP Violation in $K_L \rightarrow \pi^0 l^+ l^-$

- Direct CP violation: $K_2 \rightarrow$ CP even state.
 - $K_2 \rightarrow \pi^0 \gamma^*$ and $K_2 \rightarrow \pi^0 Z$
 - $K_2 \rightarrow \pi^0 W^* W^*$

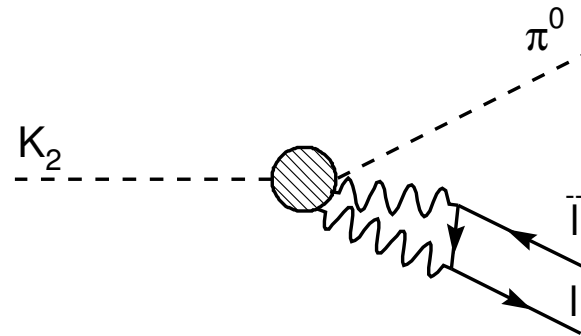


Other contributions to $K_L \rightarrow \pi^0 l^+ l^-$

- Indirect CP violation,
 - $K_L \rightarrow \epsilon K_1 \rightarrow \pi^0 \gamma^*, \pi^0 Z$
 - Interference
 - New K_S results from NA48.



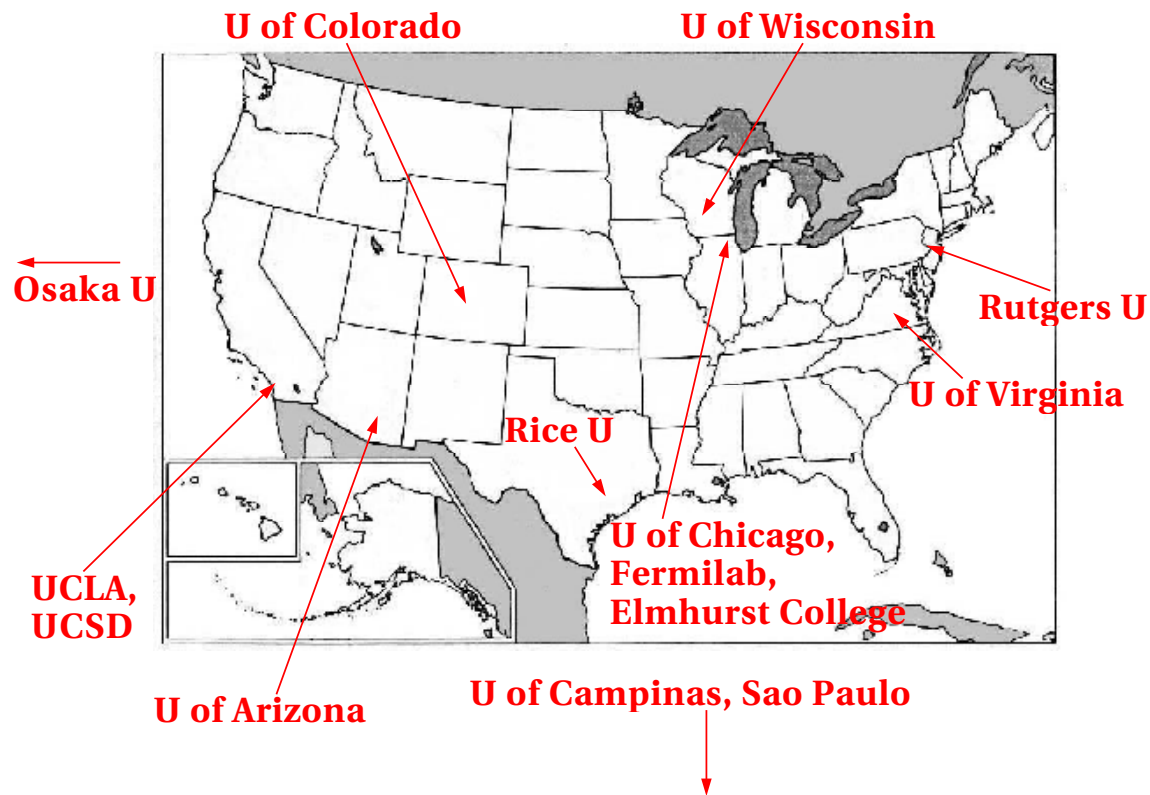
- CP conserving decays.
 - $K_L \rightarrow \pi^0 \gamma^* \gamma^*$
 - Input from theory and $K_L \rightarrow \pi^0 \gamma \gamma$



Theoretical Predictions

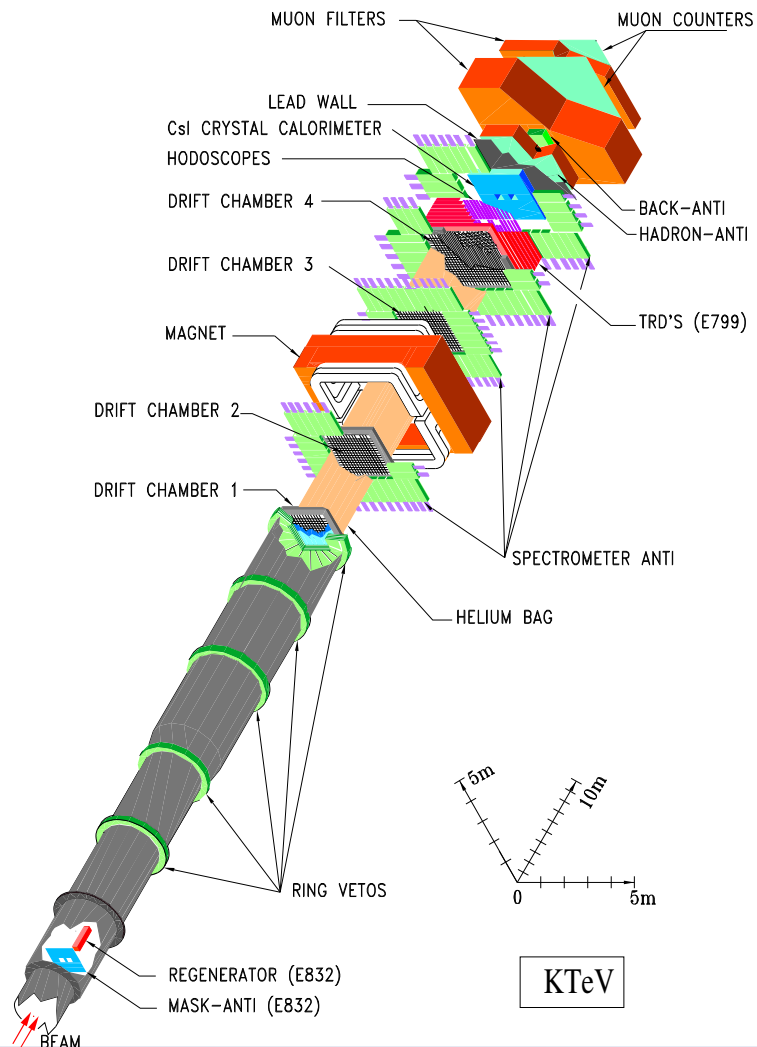
- CP Violating terms
 - $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) \sim (17 \pm 10) \times 10^{-12}$
 - $\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) \sim (9 \pm 6) \times 10^{-12}$
- CP Conserving terms
 - $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) \sim 0.5 \times 10^{-12}$
 - $\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) \sim 5 \times 10^{-12}$
- Total [Buras hep-ph/0405132]
 - $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim (3.0 \pm 0.6) \times 10^{-11}$
 - $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) \sim (3.7 \pm 1.0) \times 10^{-11}$
 - $\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) \sim (1.5 \pm 0.3) \times 10^{-11}$
- New Physics [Isidori et al. hep-ph/0404127]
 - $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) \sim (9.0 \pm 1.6) \times 10^{-11}$
 - $\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) \sim (4.3 \pm 0.7) \times 10^{-11}$

The KTeV Collaboration



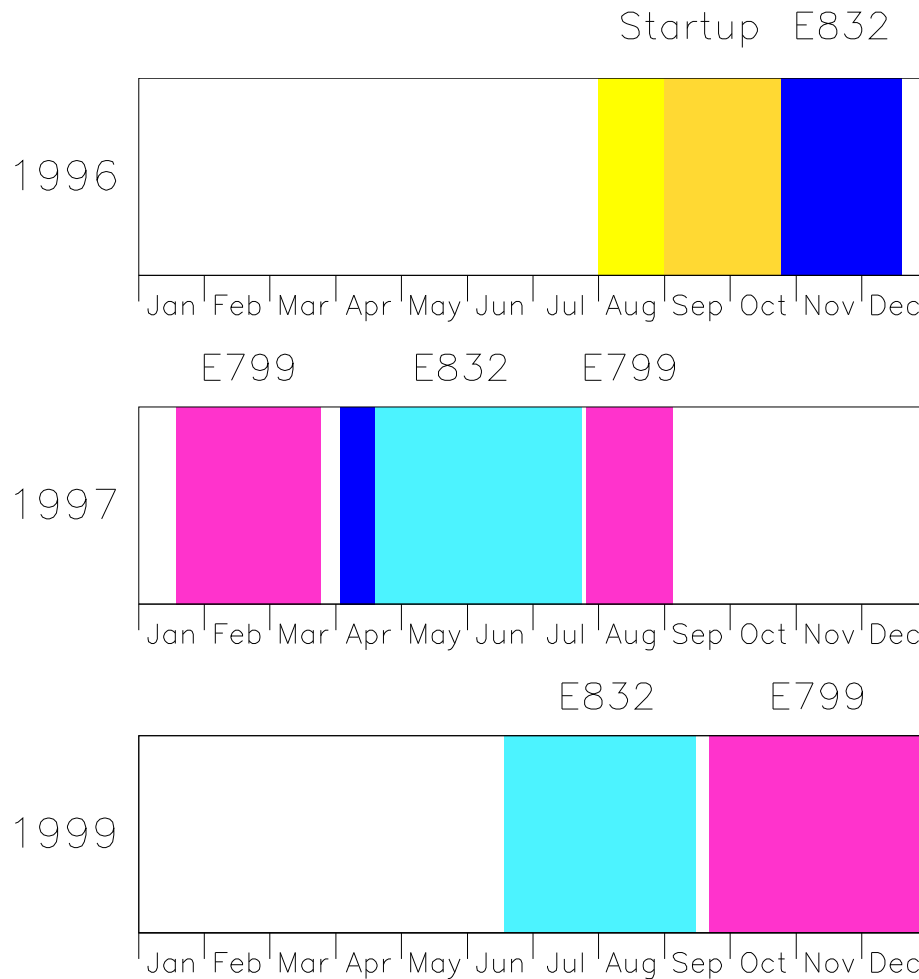
- 14 institutions.
- ~ 80 physicists.

The KTeV Detector



- Excellent particle ID
 - CsI calorimeter
 - Planar TRDs
- Good Tracking
 - Better than $100\mu m$ resolution
- Clean beams.

KTeV Data Taking



● Rare decay data (E799)

● Three running periods

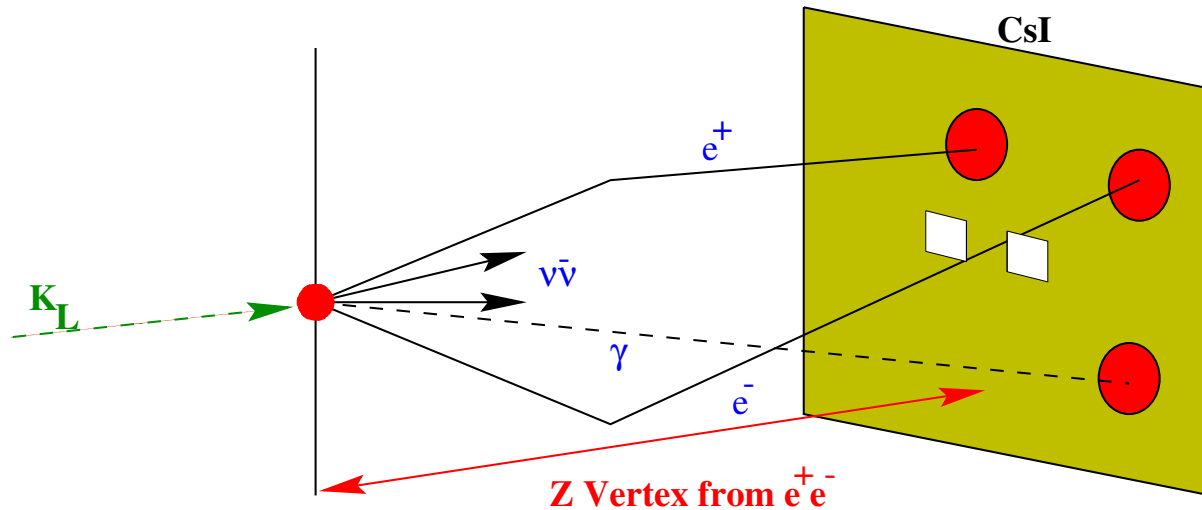
● 1997 data:
 $2.7 \times 10^{11} K_L$ decays.

● 1999 data:
 $3.6 \times 10^{11} K_L$ decays.

KTeV Physics Program

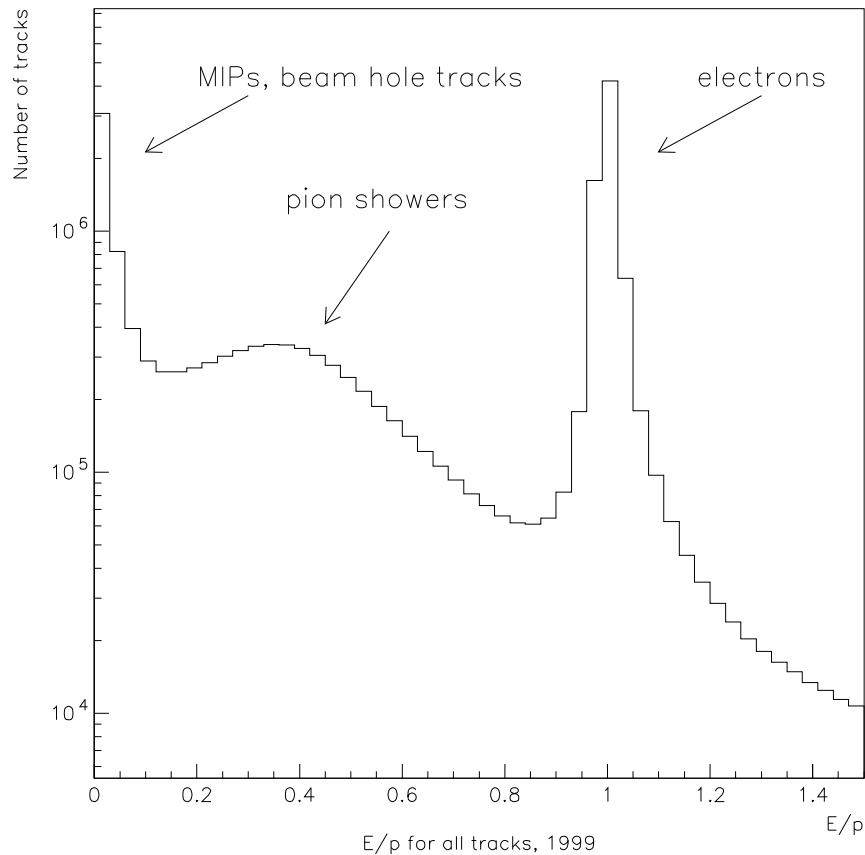
	E832	E799
CP Violation	$Re(\epsilon'/\epsilon)$	$K_L \rightarrow \pi^0 l^+ l^-$
	Charge Asymmetry	$K_L \rightarrow \pi^+ \pi^- e^+ e^-$
	$\Phi_{+-}, \Phi_{+-\gamma}$	
New Phenomena	$\Delta\Phi$	$K_L \rightarrow \pi^0 e^\pm \mu^\mp$
	R^0 Search	H dibaryon search
CKM Physics	$K_L \rightarrow \pi^0 \gamma\gamma$	$K_L \rightarrow l^+ l^- l^+ l^-$
	V_{us} Measurement	$K_L \rightarrow l^+ l^- \gamma$
		$K_L \rightarrow l^+ l^- \gamma\gamma$
		$\pi^0 \rightarrow e^+ e^-, e^+ e^- e^+ e^-$
		Hyperon Decays

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Analysis



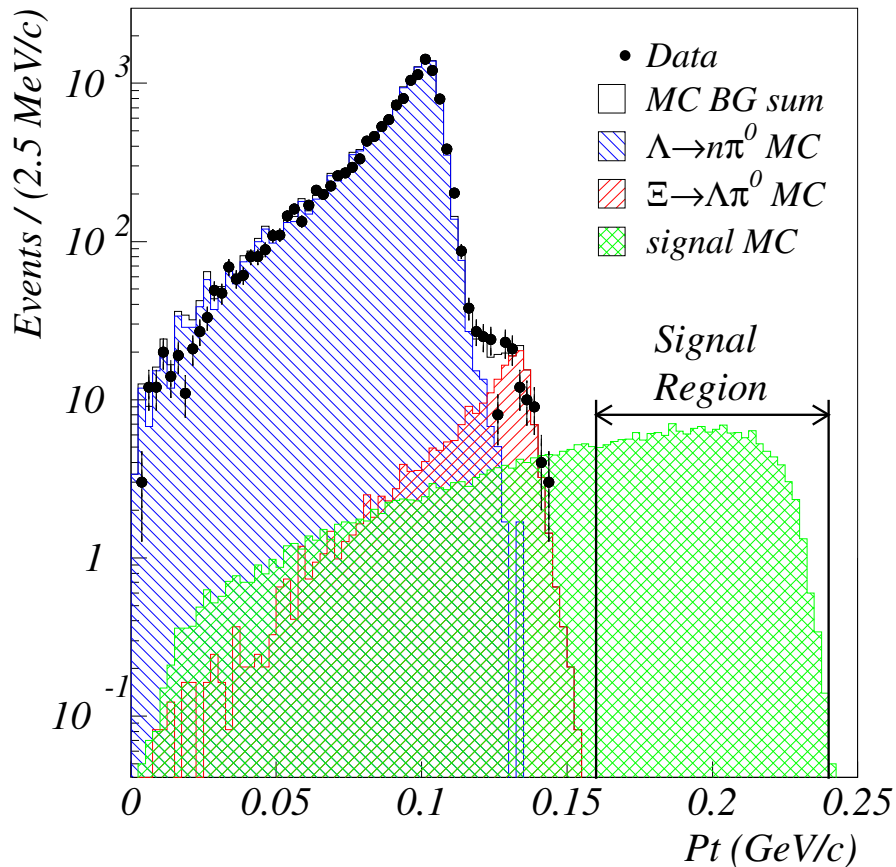
- Theoretical uncertainties $\sim 1\%$.
- Theory: 3×10^{-11}
- Search for large missing p_T .
 - $\pi^0 \rightarrow e^+e^-\gamma$
 - Two tracks, electron id, and one γ .

Calorimeter Performance



- Resolution.
 - Energy: $< 1\%$ over all energies of interest.
 - Position: $\sim 1.8\text{mm}/1.0\text{mm}$ for large/small crystals.
- Rejection.
 - E/p cut $\rightarrow 500:1$ rejection.

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Result



Backgrounds

● $\Lambda \rightarrow \pi^0 n$

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

● $\Xi \rightarrow \Lambda\pi^0$

Normalized to

$K_L \rightarrow e^+ e^- \gamma$.

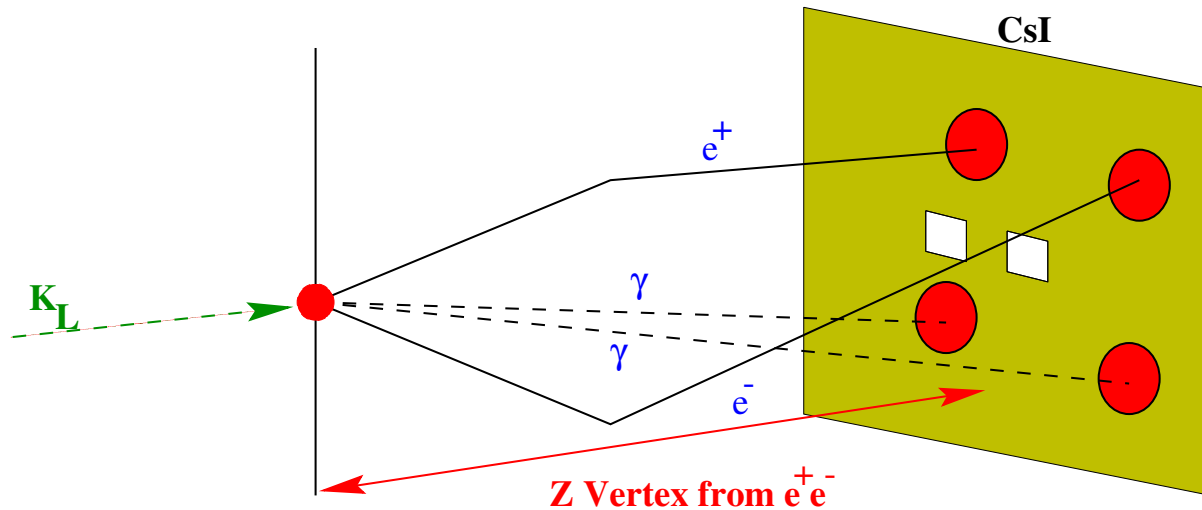
● No events in signal region.

$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 5.9 \times 10^{-7}$ (1997 data)

The $K_L \rightarrow \pi^0 e^+ e^-$ Decay

- Pros:
 - Reconstruct total decay (cf $K_L \rightarrow \pi^0 \nu \bar{\nu}$)
- Cons:
 - Backgrounds from $K_L \rightarrow e^+ e^- \gamma \gamma$.
 - Contributions from indirect and CP conserving terms.
- Previous best limit: E799-I
 - $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 4.3 \times 10^{-9}$
- New Physics \rightarrow BR enhancement.

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



● Two oppositely charged tracks + electron id.

● Two photons.

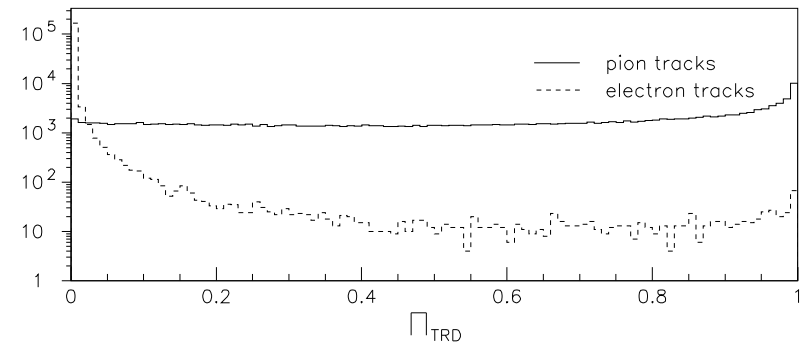
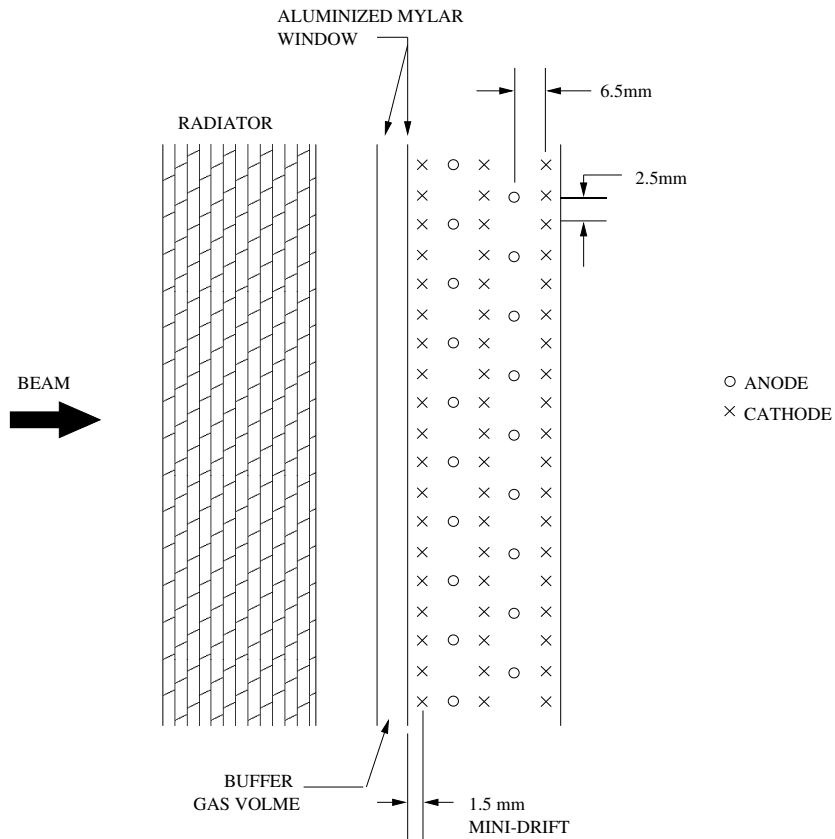
● Backgrounds

● $K_L \rightarrow \pi^0 \pi_D^0 \pi_d^0$

● $K_L \rightarrow \pi e \nu + \gamma_{acc} + \gamma_{rad}$

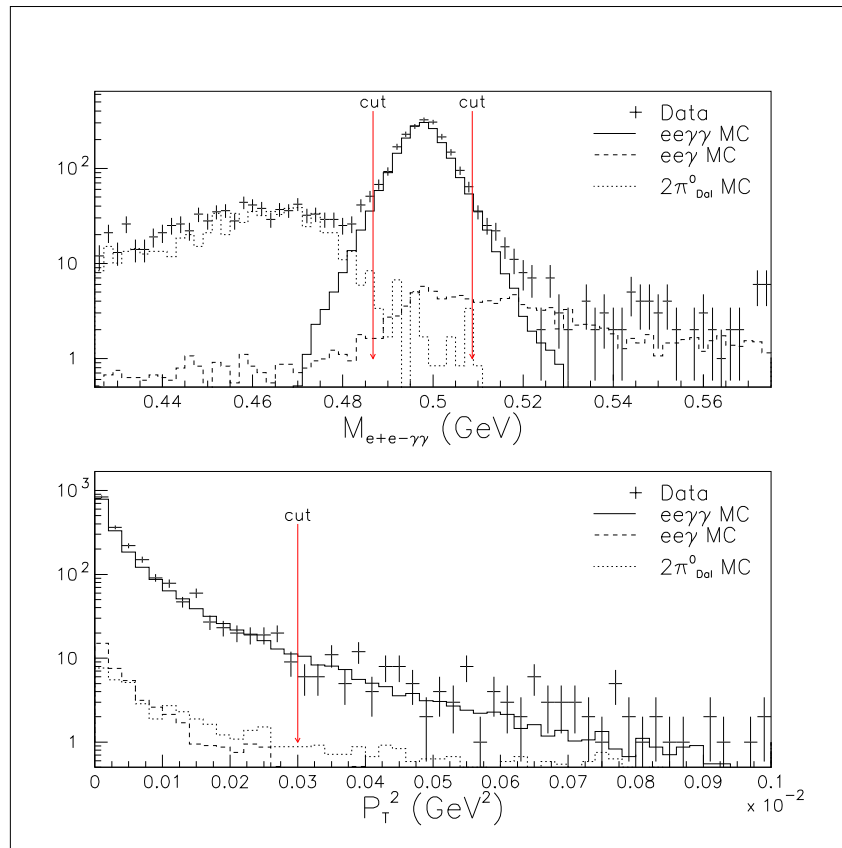
● $K_L \rightarrow e^+ e^- \gamma \gamma$

TRD performance



Better than 200:1 rejection
with 90% electron efficiency.

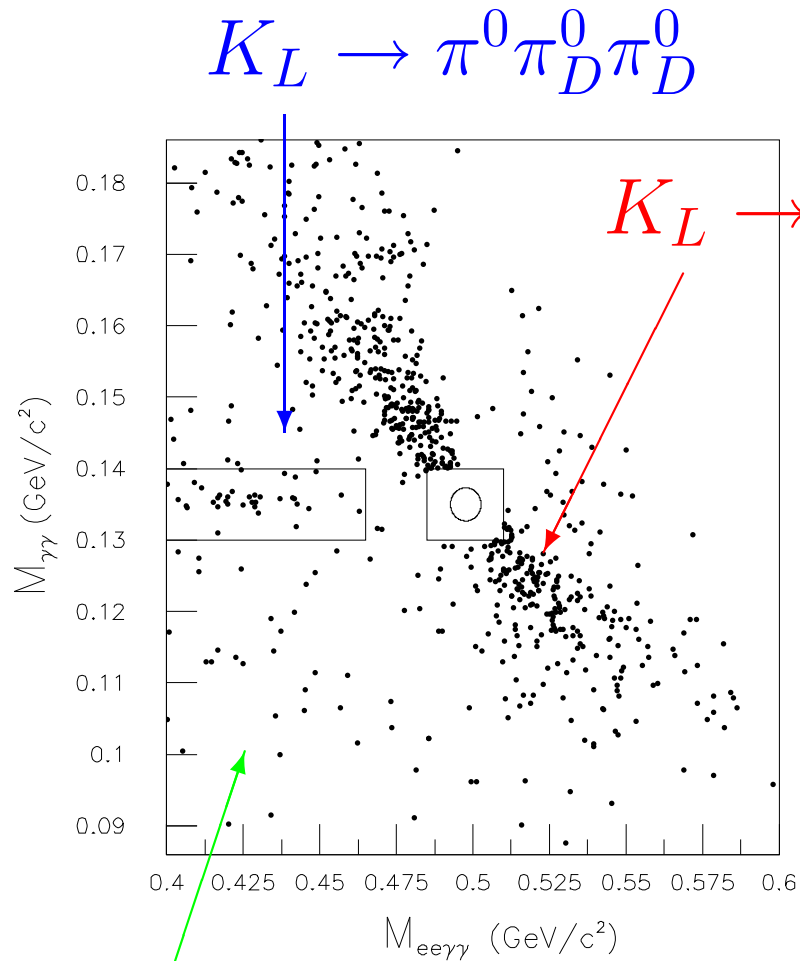
$K_L \rightarrow e^+ e^- \gamma \gamma$ Analysis



- Exclude events with a good m_{π^0} .
- Total: 1988 events
 - Previous result: 58 events
- Background: 77 ± 3
- Serious background to $K_L \rightarrow \pi^0 e^+ e^-$

$$\text{BF}(K_L \rightarrow e^+ e^- \gamma \gamma) = (6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$$

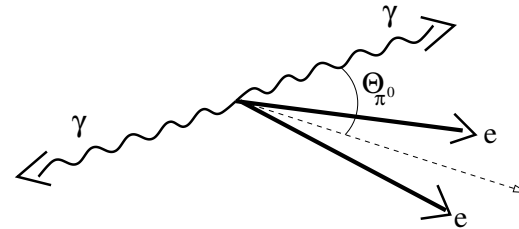
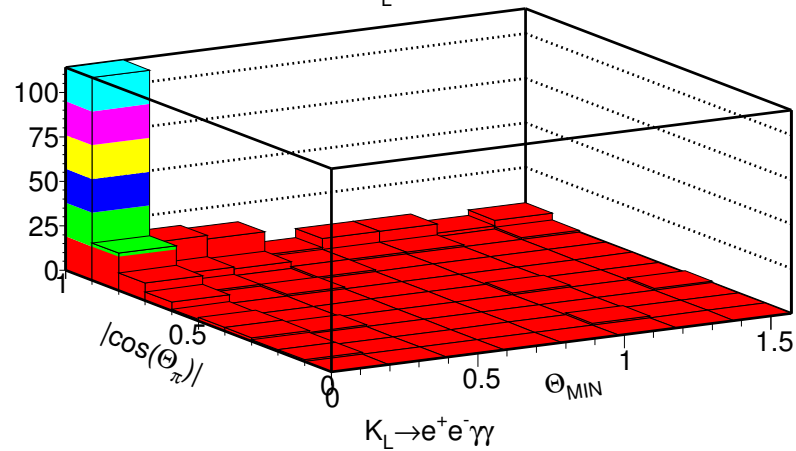
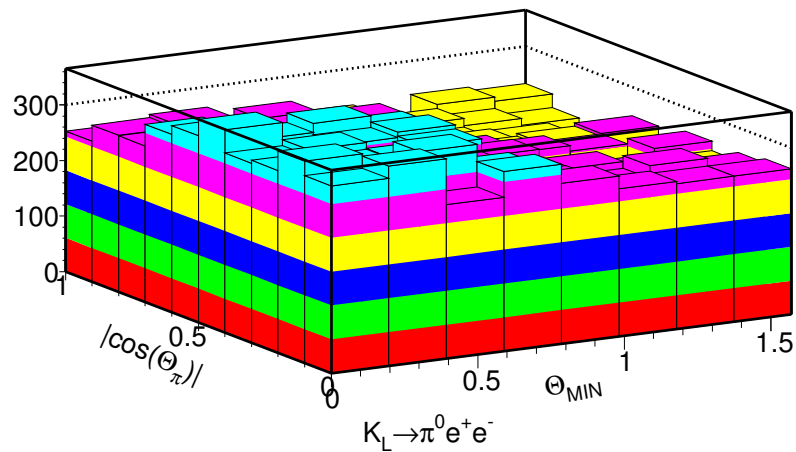
$K_L \rightarrow \pi^0 e^+ e^-$ Analysis



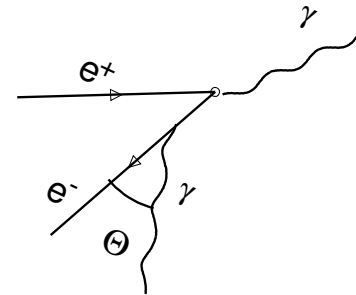
$K_L \rightarrow \pi e \nu + \gamma_{acc} \gamma_{rad}$

- $m_{\gamma\gamma}$ constrained to be m_{π^0} .
- Box region used in blind analysis.
- Rectangular regions excluded from bkg fits.
- Ellipse → signal region.

$K_L \rightarrow \pi^0 e^+ e^-$ Kinematic Variables

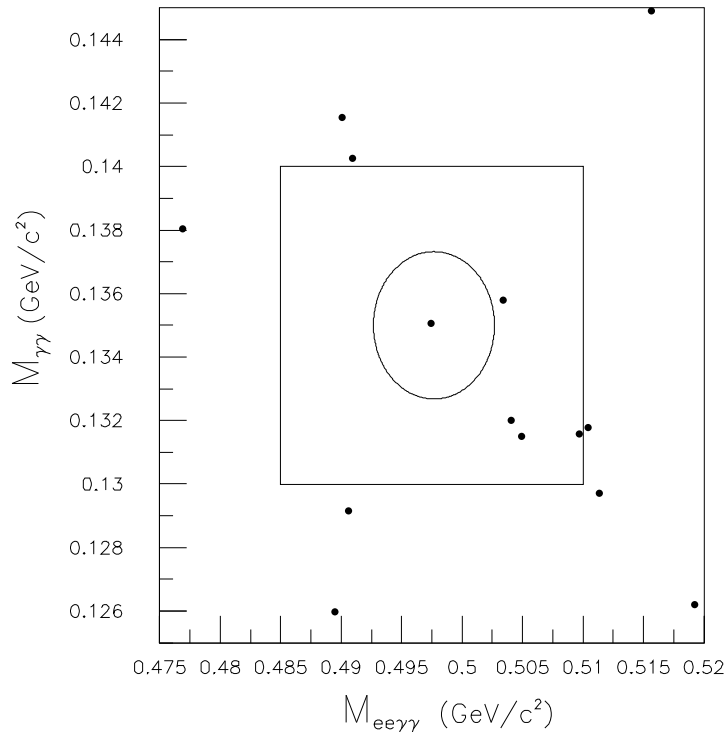


Angle btwn $p_{e^+e^-}$ and γ in $\gamma\gamma$ CM.
Signal is uniform due to π^0 spin.



Smallest angle between photon and e^\pm in K_L CM.
Bkg angle small: bremsstrahlung.

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

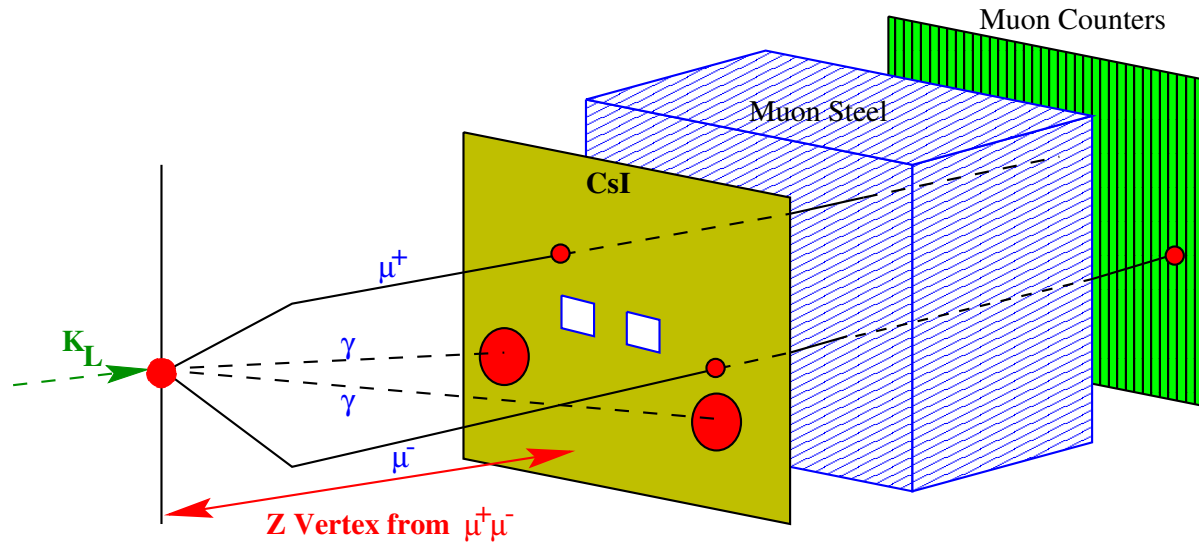


- One candidate event.
- Background Estimate:
 - Ellipse: 0.99 ± 0.35
 - Box: 3.9 ± 1.4
- Acceptance: Lower by 30% from 1997
 - Higher accidental rates in 1999.

$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 3.5 \times 10^{-10}$ (1999) [Accepted by PRL]

$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ (1997+1999)

$K_L \rightarrow \pi^0 \mu^+ \mu^-$ Analysis



● Two oppositely charged tracks + μ id.

● Two photons.

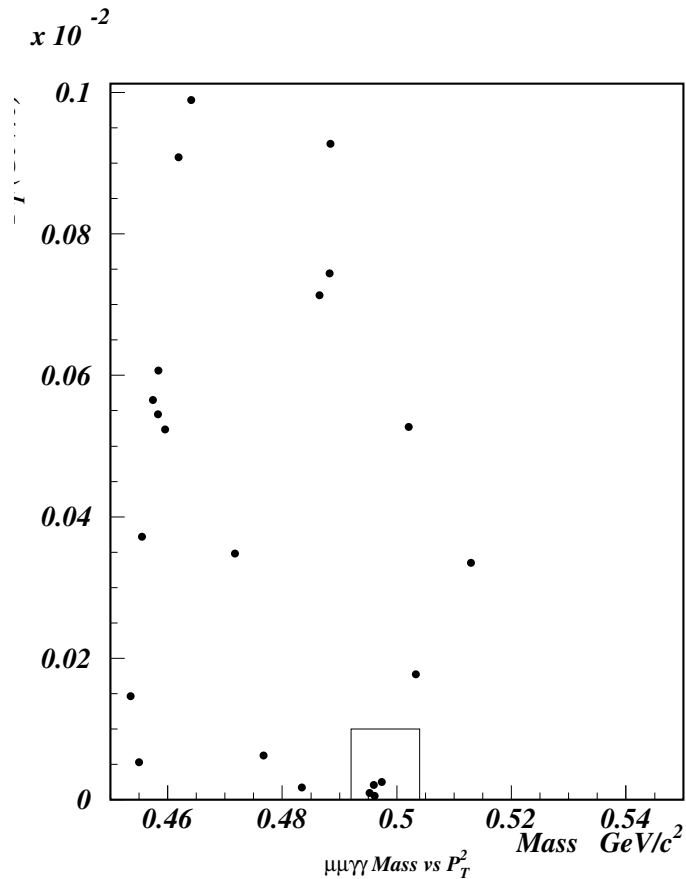
● Backgrounds

● $K_L \rightarrow \pi^+ \pi^- \pi^0$

● $K_L \rightarrow \pi \mu \nu + 2\gamma_{acc}$

● $K_L \rightarrow \mu^+ \mu^- \gamma \gamma$

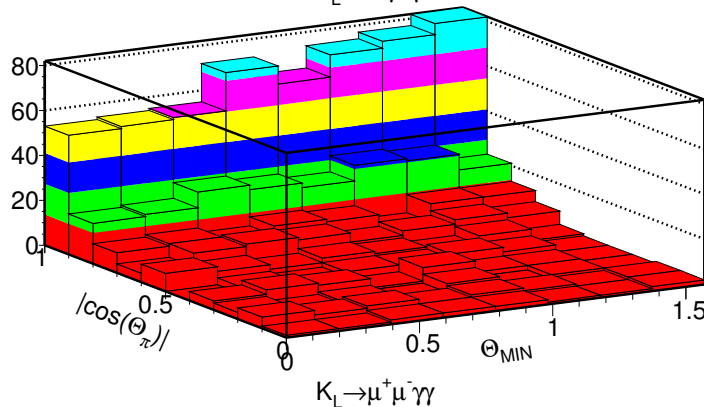
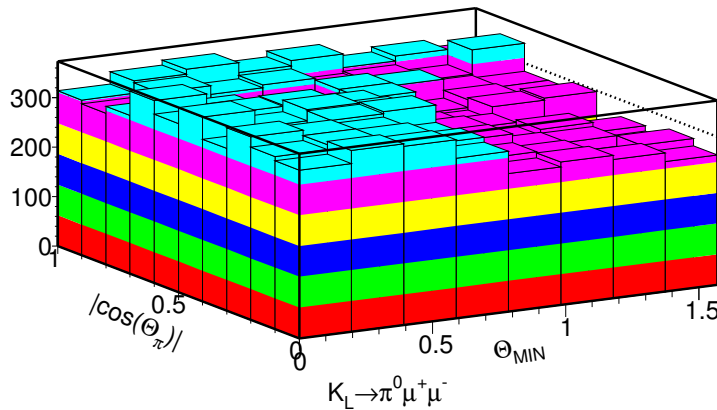
$K_L \rightarrow \mu^+ \mu^- \gamma \gamma$ Result



- First observation.
- Four events with 0.16 ± 0.08 background events.
- QED calculation: $(9.1 \pm 0.8) \times 10^{-9}$
- Dangerous background to $K_L \rightarrow \pi^0 \mu^+ \mu^-$.

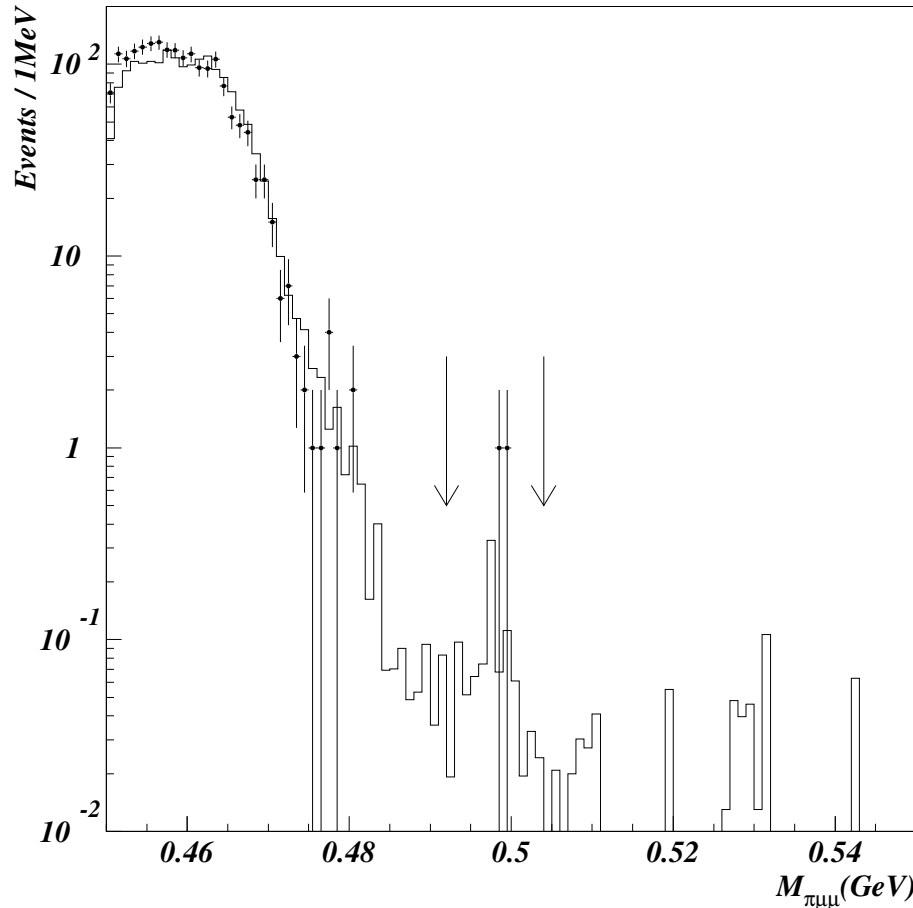
$$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = (10.4_{-5.9}^{+7.5} \pm 0.7) \times 10^{-9} \text{ with } m_{\gamma\gamma} \geq 1 \text{ MeV}/c^2$$

$K_L \rightarrow \pi^0 \mu^+ \mu^-$ Kinematic Variables



- Same definitions as $K_L \rightarrow \pi^0 e^+ e^-$
- $\cos \Theta_\pi$
 - π^0 spin \rightarrow uniform in signal.
- Θ_{min}
 - Less effective in this mode.
 - μ have less radiation.

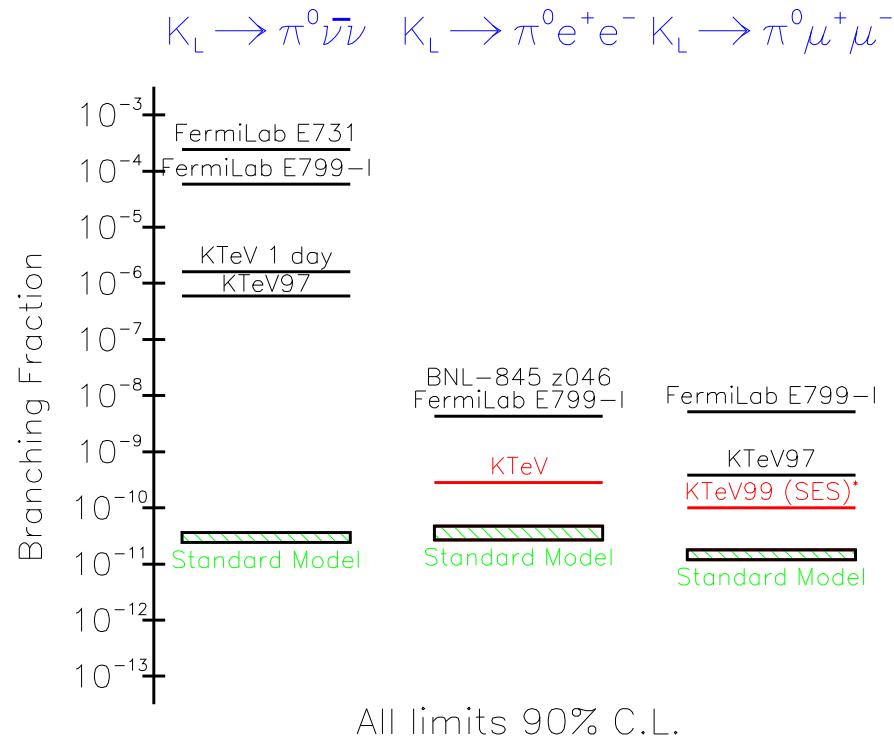
$K_L \rightarrow \pi^0 \mu^+ \mu^-$ Result



- MC and data agree.
- Two events in signal box.
- Expect 0.87 ± 0.15 background events.
- 40% from $K_L \rightarrow \mu^+ \mu^- \gamma \gamma$
- Remaining from $K_L \rightarrow \pi^+ \pi^- \pi^0$ and $K_L \rightarrow \pi \mu \nu$.

$$\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10} \text{ (90\% C.L.)}$$

Current Status of $K_L \rightarrow \pi^0 l^+ l^-$



Summary

- Successful program of rare decay searches and measurements.
- KTeV improved upon $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ by two orders of magnitude.
 - New experiments: KOPIO, E391A
- $K_L \rightarrow \pi^0 e^+ e^-$ approaching SM value.
 - Possibility to search for new physics.
- $K_L \rightarrow \pi^0 \mu^+ \mu^-$
 - Full analysis of KTeV 1997+1999 data soon.
 - Expected SES $\sim 1 \times 10^{-10}$