Rare Kaon Decays from KTeV

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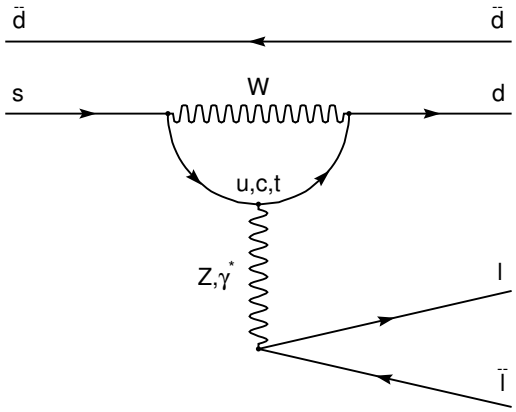
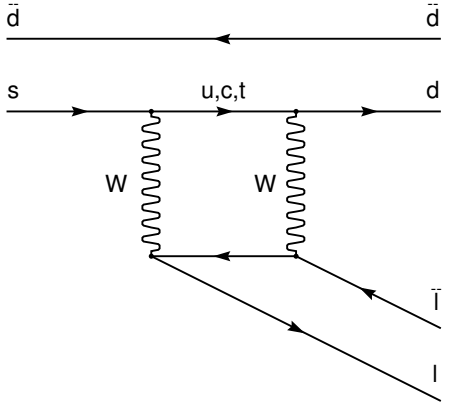
- Direct CP violation in $K_L \to \pi^0 l^+ l^-$
- The KTeV Detector
- KTeV Measurements of $K_L \to \pi^0 l^+ l^-$
- Summary

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

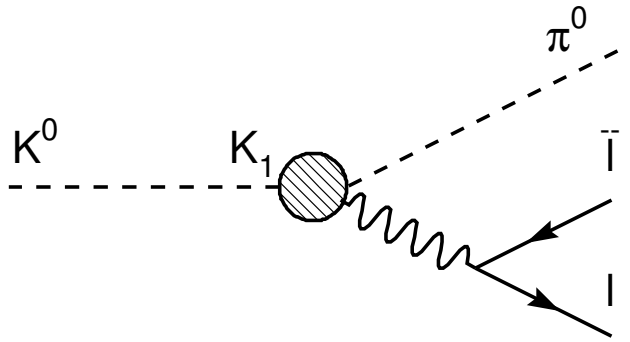
- Direct CP violation: $K_2 \to$ CP even state.
  - $K_2 \to \pi^0 \gamma^*$ and $K_2 \to \pi^0 Z$
  - $K_2 \to \pi^0 W^* W^*$



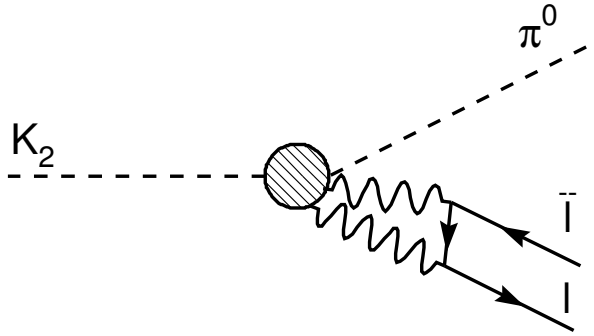


Other contributions to $K_L \to \pi^0 l^+ l^-$

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



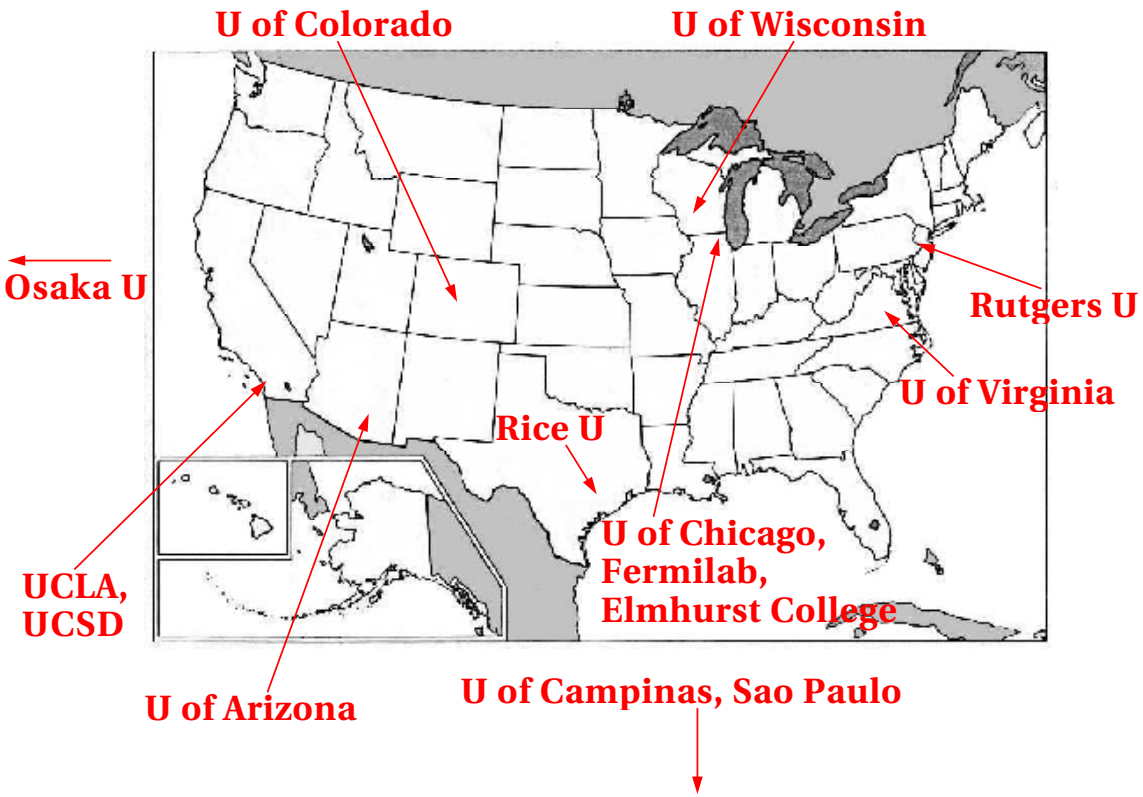
- CP conserving decays.
  - $K_L \to \pi^0\gamma^*\gamma^*$
    - Input from theory and $K_L \to \pi^0\gamma\gamma$



Theoretical Predictions

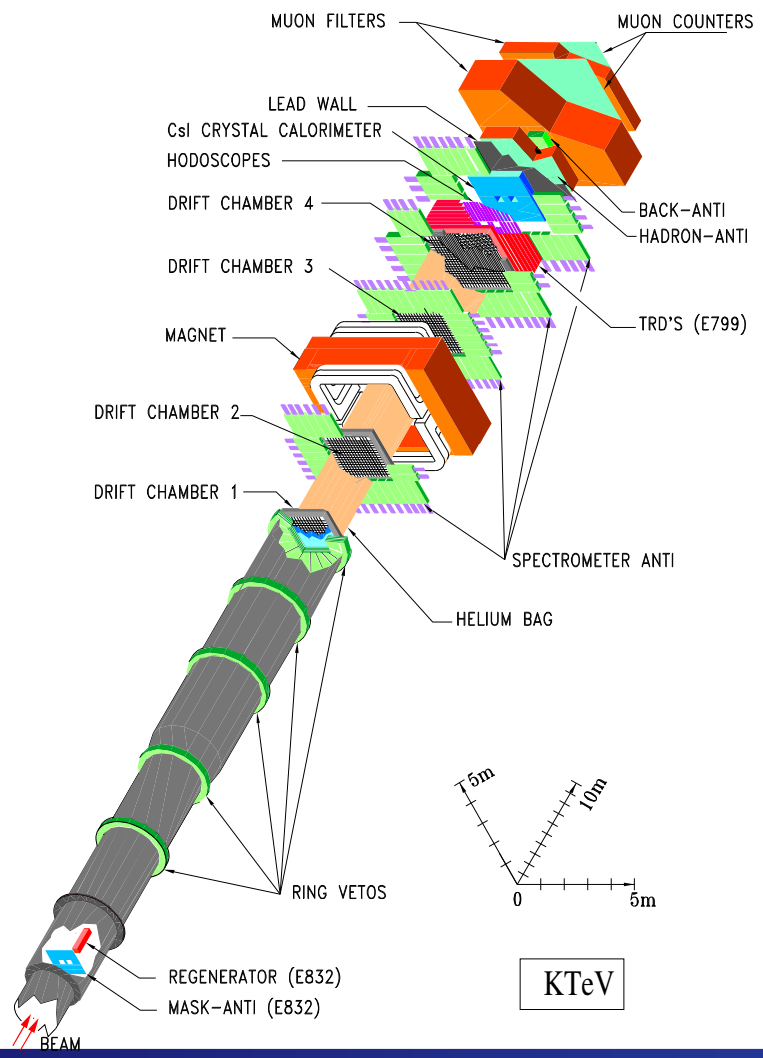
- CP Violating terms
  - BR($K_L \to \pi^0 e^+ e^-$) $\sim (17 \pm 10) \times 10^{-12}$
  - BR($K_L \to \pi^0 \mu^+ \mu^-$) $\sim (9 \pm 6) \times 10^{-12}$
- CP Conserving terms
  - BR($K_L \to \pi^0 e^+ e^-$) $\sim 0.5 \times 10^{-12}$
  - BR($K_L \to \pi^0 \mu^+ \mu^-$) $\sim 5 \times 10^{-12}$
- Total
  - BR($K_L \to \pi^0 \nu \bar{\nu}$) $\sim (2.6 \pm 1.2) \times 10^{-11}$
  - BR($K_L \to \pi^0 e^+ e^-$) $\sim (2 \pm 1 \times 10^{-11}$
  - BR($K_L \to \pi^0 \mu^+ \mu^-$) $\sim (1.5 \pm 0.5) \times 10^{-11}$

The KTeV Collaboration



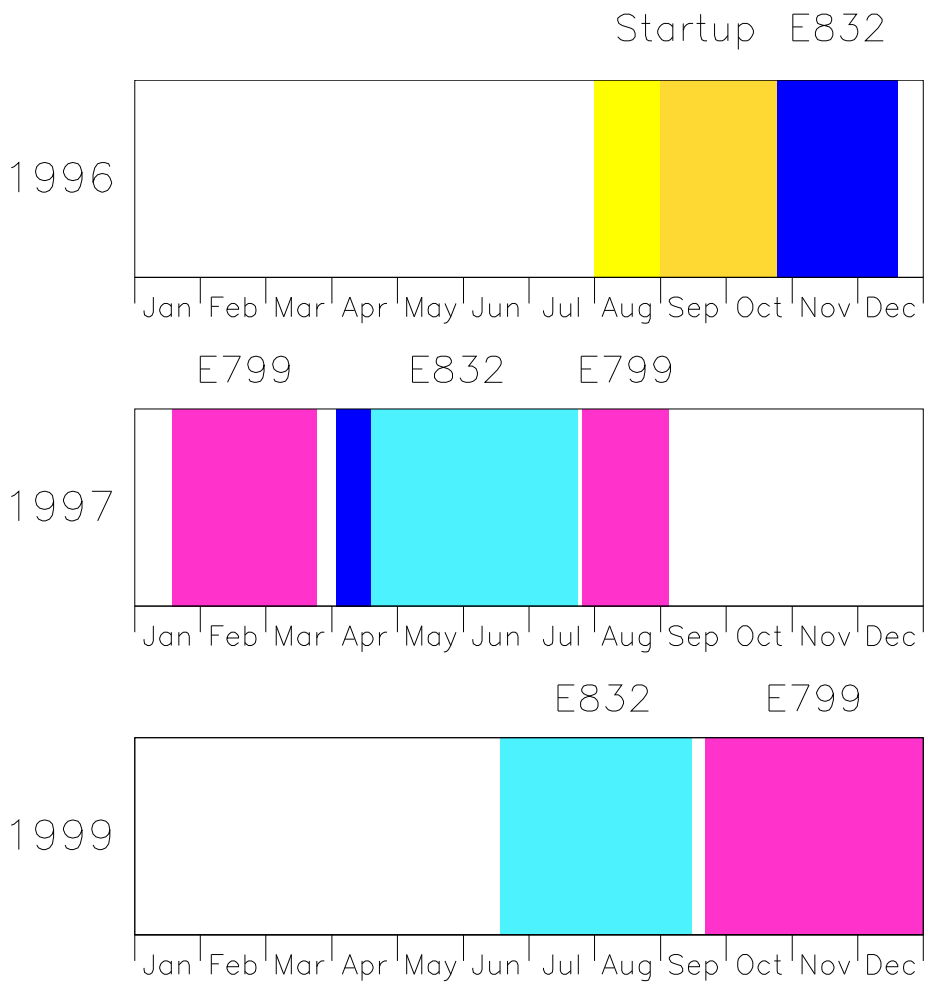
- 14 institutions.
- $\sim$ 80 physicists.

The KTeV Detector



- Excellent particle ID
  - CsI calorimeter
  - Planar TRDs
- Good Tracking
  - Better than 100μm resolution
- Clean beams.

KTeV Data Taking

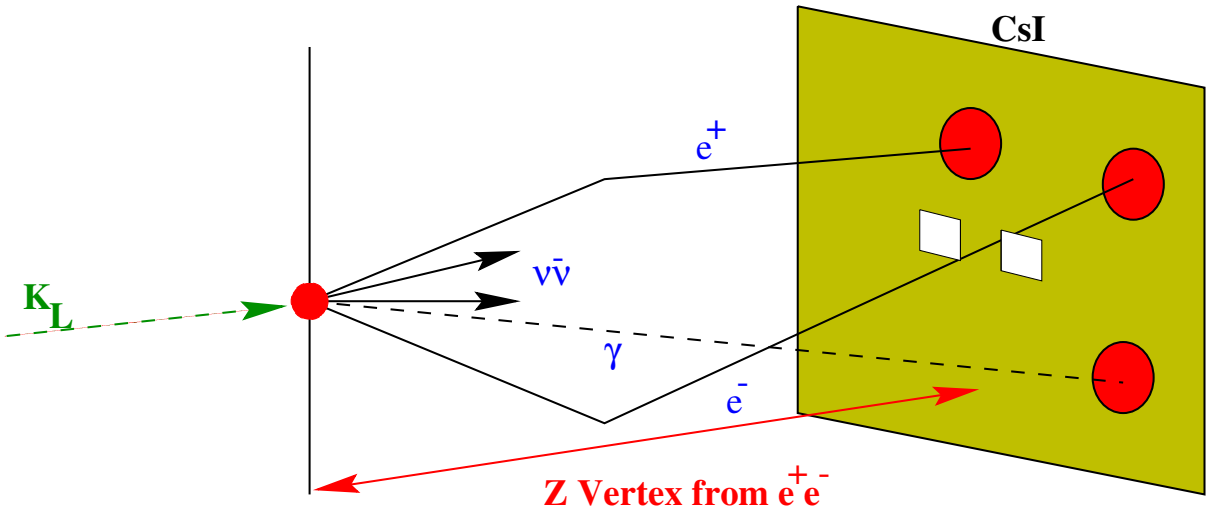


- Rare decay data (E799)
- Three running periods
  - 1997 data: 2.7×10^{11} K_L decays.
  - 1999 data: 3.6×10^{11} K_L decays.

KTeV Physics Program

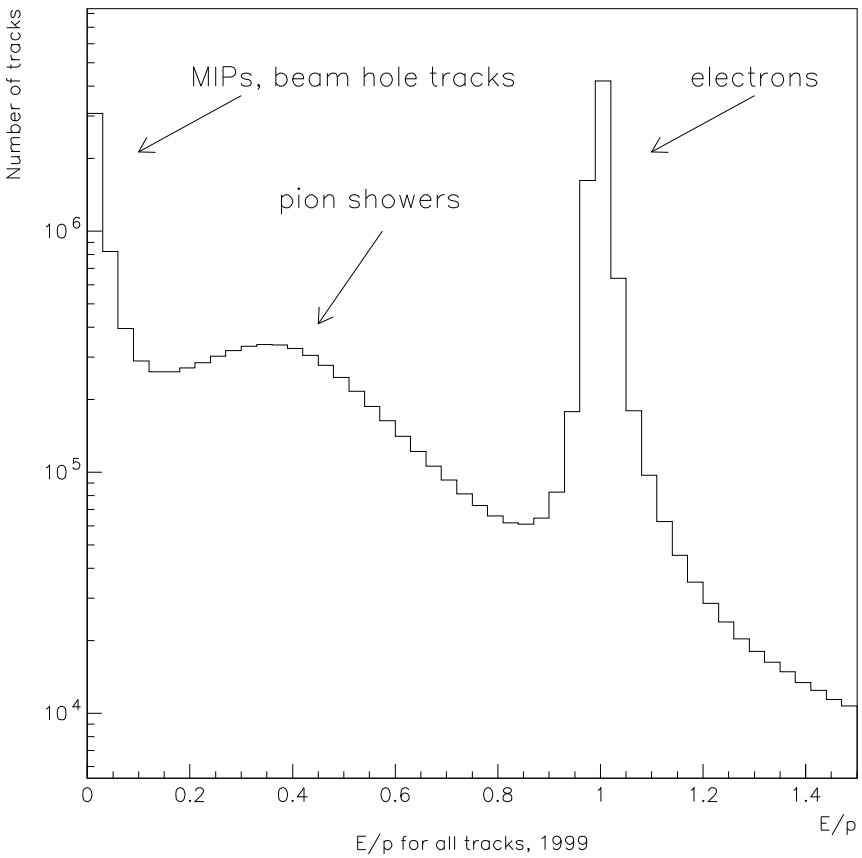
	E832	E799
CP Violation	$Re(\epsilon'/\epsilon)$	$K_L \to \pi^0 l^+ l^-$
	Charge Asymmetry	$K_L \to \pi^+ \pi^- e^+ e^-$
	Φ_{+-}, $\Phi_{+-\gamma}$	
New Phenomena	$\Delta\Phi$	$K_L \to \pi^0 e^\pm \mu^\mp$
	R^0 Search	H dibaryon search
CKM Physics	$K_L \to \pi^0 \gamma\gamma$	$K_L \to l^+ l^- l^+ l^-$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

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



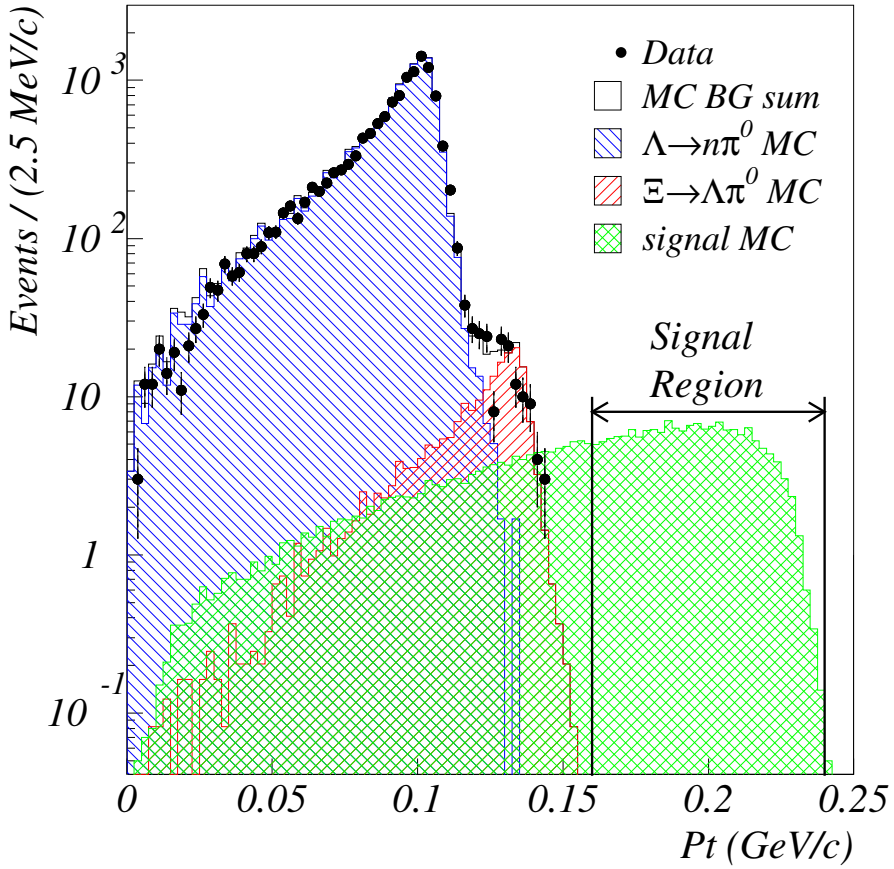
- Theoretical uncertainties $\sim$ 1%.
- Theory: 3×10^{-11}
- Search for large missing p_T.
  - $\pi^0 \to e^+e^-\gamma$
  - Two tracks, electron id, and one γ.

Calorimeter Performance



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

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



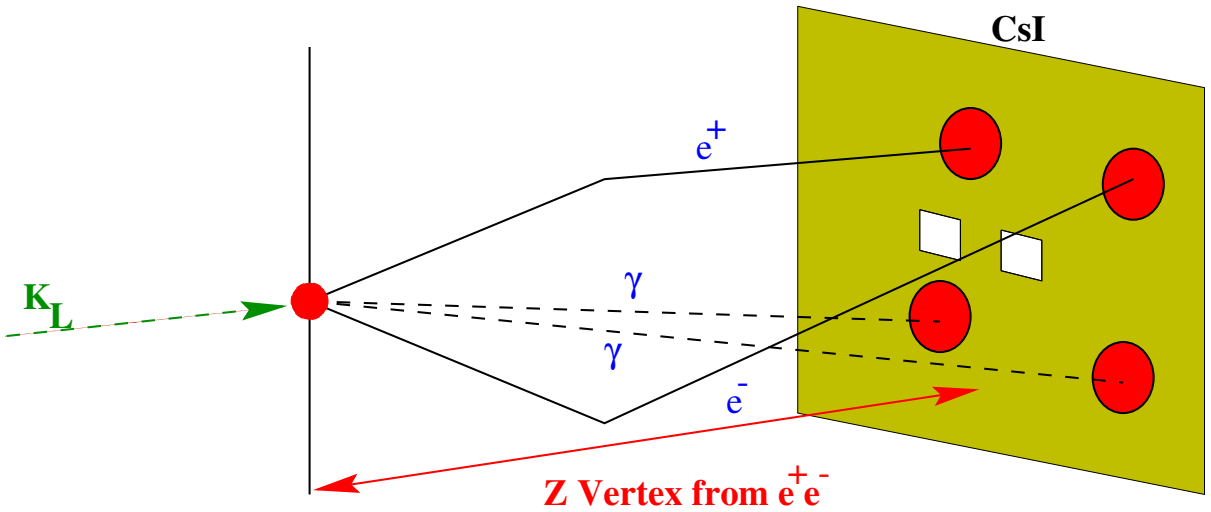
- Backgrounds
  - $\Lambda \to \pi^0 n$
  - $K_L \to \pi^0\pi^0$, $K_L \to \pi^0\pi^0\pi^0$
  - $\Xi \to \Lambda\pi^0$
- Normalized to $K_L \to e^+e^-\gamma$.
- No events in signal region.

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

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

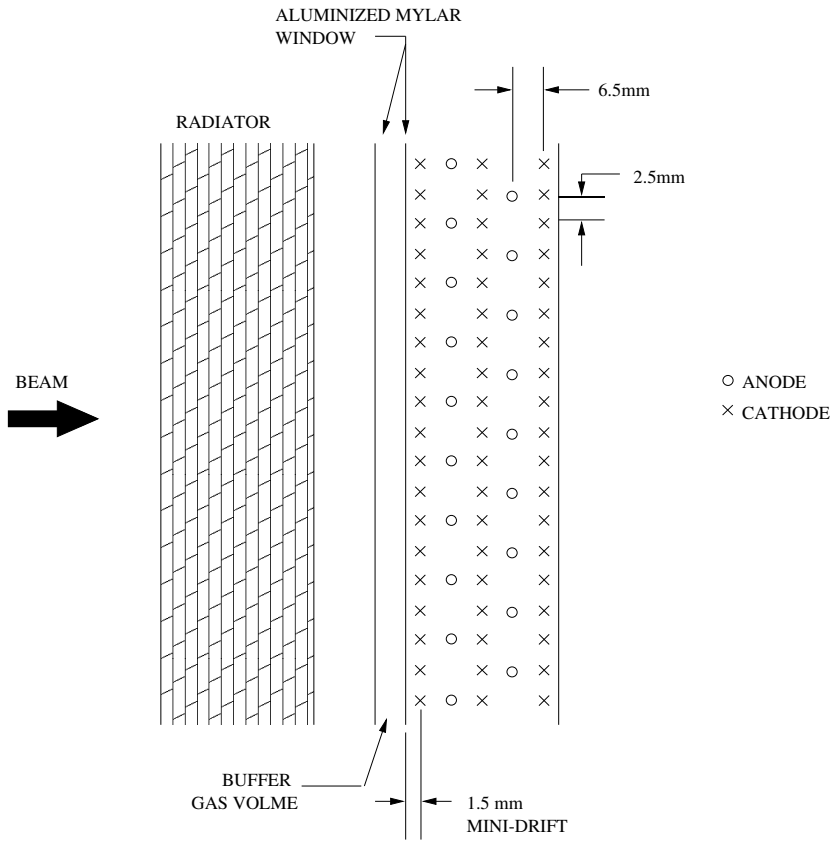
- Pros:
  - Reconstruct total decay (cf $K_L \to \pi^0 \nu\bar{\nu}$)
- Cons:
  - Backgrounds from $K_L \to e^+ e^- \gamma\gamma$.
  - Contributions from indirect and CP conserving terms.
- Previous best limit: E799-I
  - BR($K_L \to \pi^0 e^+ e^-$)$< 4.3 \times 10^{-9}$
- New Physics $\to$ BR enhancement.

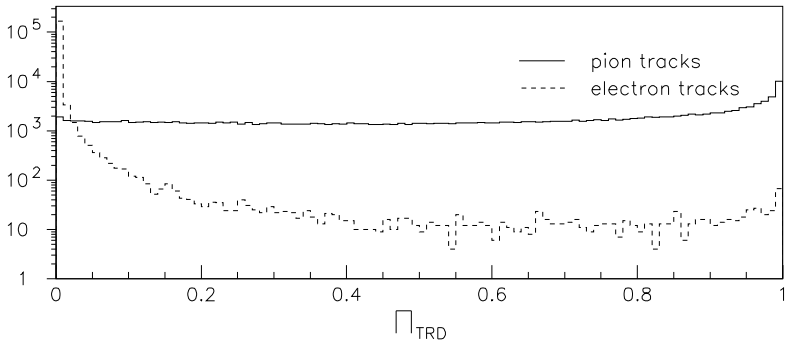
$K_L \to \pi^0 e^+ e^-$ Analysis



- Two oppositely charged tracks + electron id.
- Two photons.
- Backgrounds
  - $K_L \to \pi^0 \pi^0_D \pi^0_d$
  - $K_L \to \pi e \nu + \gamma_{acc} + \gamma_{rad}$
  - $K_L \to e^+ e^- \gamma\gamma$

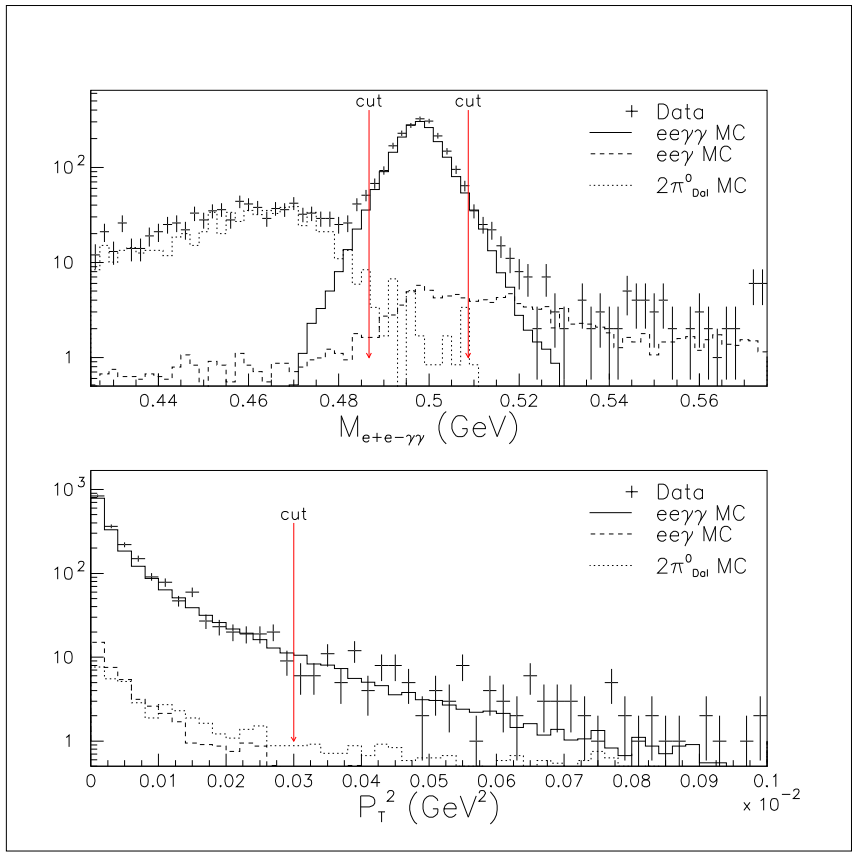
TRD performance





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

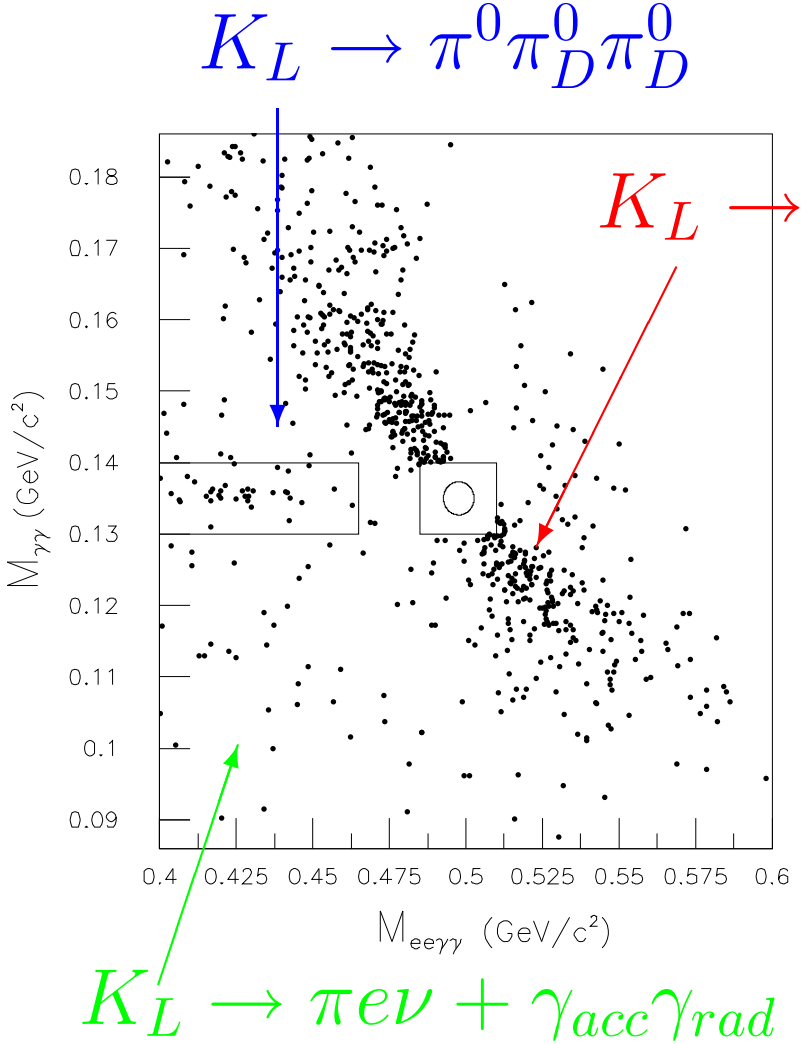
$K_L \to e^+e^-\gamma\gamma$ Analysis



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

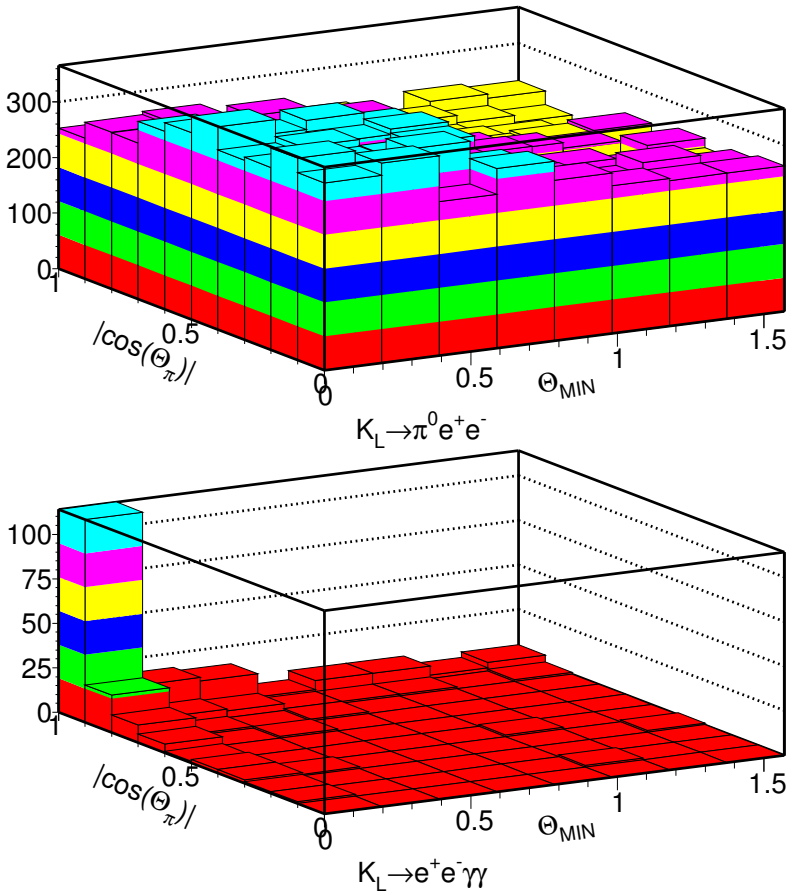
BF($K_L \to e^+e^-\gamma\gamma$) = $(6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$

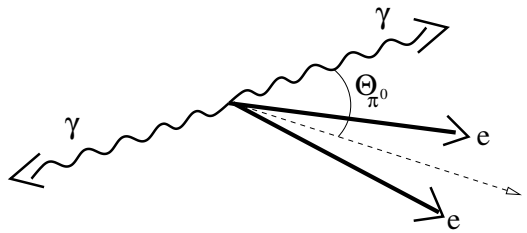
$K_L \to \pi^0 e^+ e^-$ Analysis



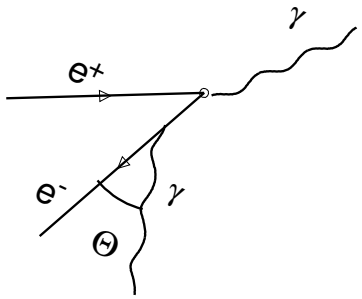
- $m_{\gamma\gamma}$ constrained to be m_{π^0}.
- Box region used in blind analysis.
  - Rectangular regions excluded from bkg fits.
- Ellipse $\to$ signal region.

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



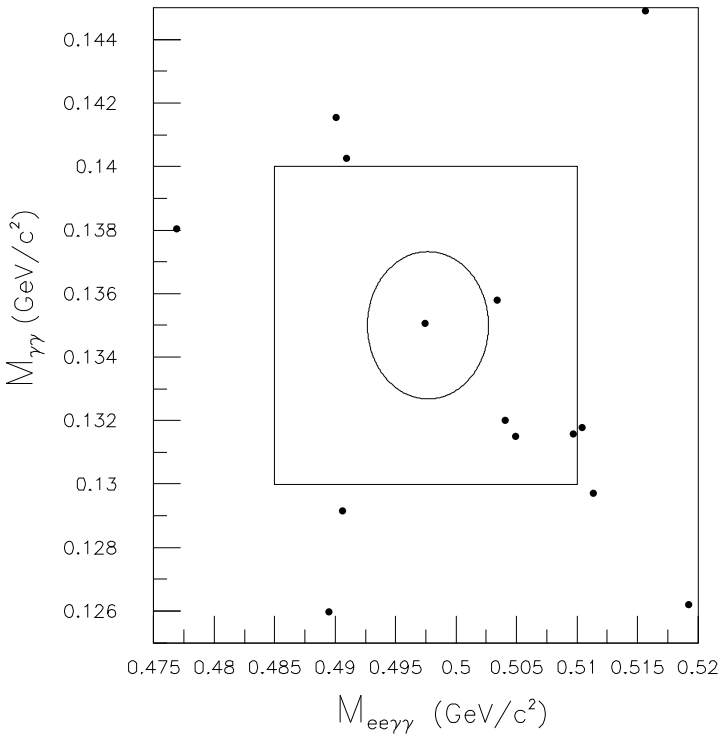


Angle btwn $p_{e^+e^-}$ and γ in $\gamma\gamma$ CM.
Signal is uniform due to π^0 spin.



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

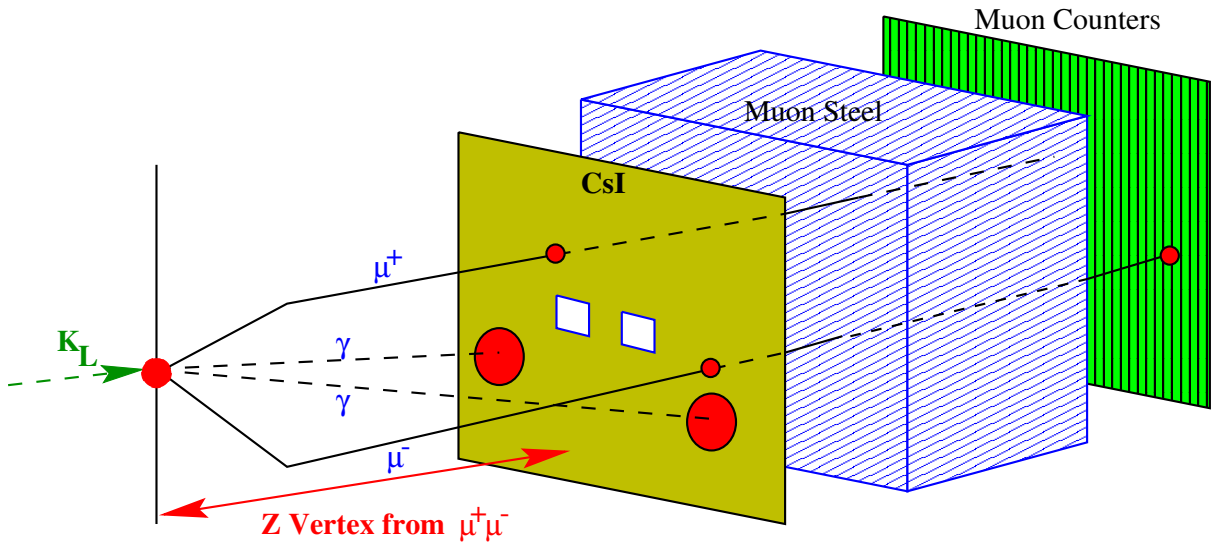
$K_L \to \pi^0 e^+ e^-$ Result



- 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.

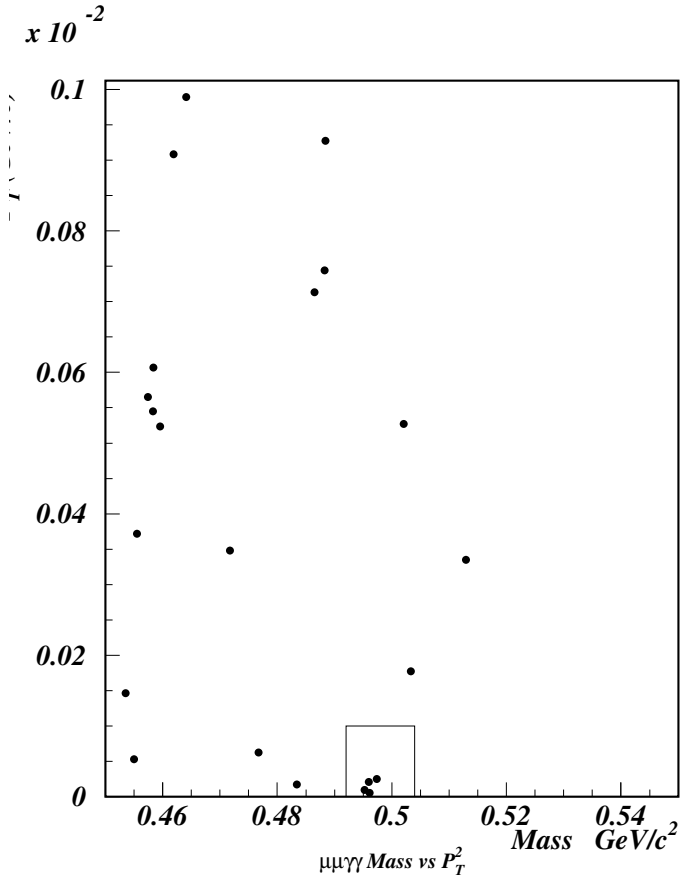
BR($K_L \to \pi^0 e^+ e^-$) $< 3.5 \times 10^{-10}$ (1999) [Accepted by PRL]
BR($K_L \to \pi^0 e^+ e^-$) $< 2.8 \times 10^{-10}$ (1997+1999)

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



- Two oppositely charged tracks + μ id.
- Two photons.
- Backgrounds
  - $K_L \to \pi^+\pi^-\pi^0$
  - $K_L \to \pi\mu\nu + 2\gamma_{acc}$
  - $K_L \to \mu^+\mu^-\gamma\gamma$

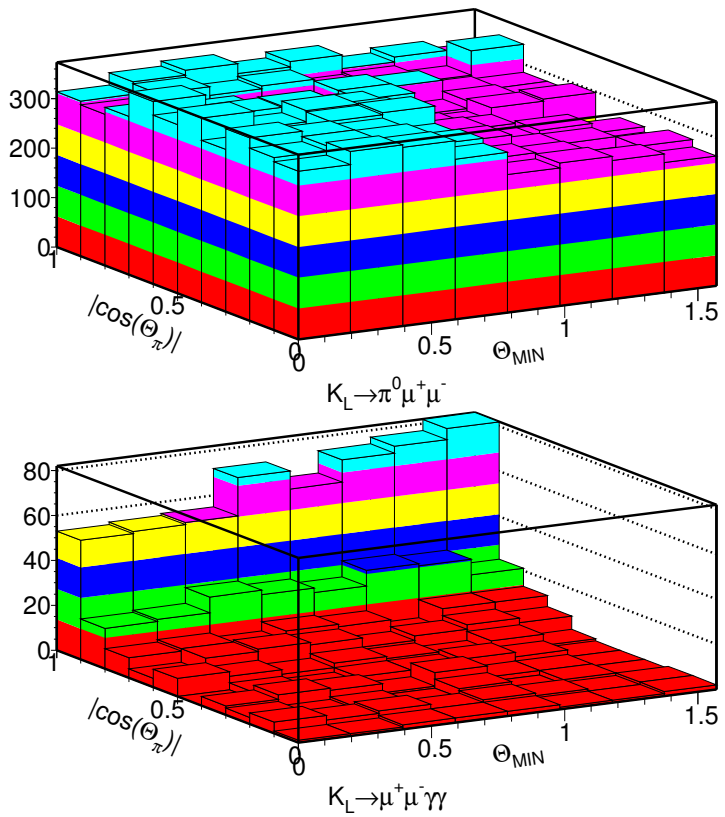
$K_L \to \mu^+\mu^-\gamma\gamma$ Result



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

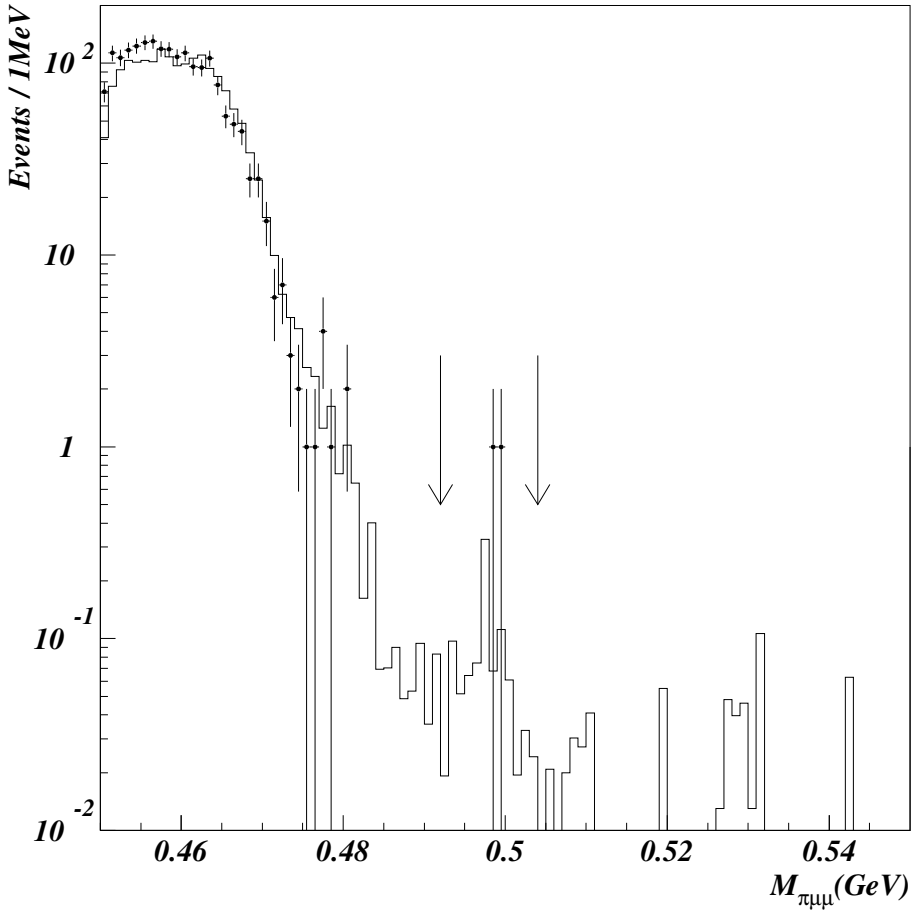
BR$(K_L \to \mu^+\mu^-\gamma\gamma) = (10.4^{+7.5}_{-5.9} \pm 0.7) \times 10^{-9}$ with $m_{\gamma\gamma} \geq 1$ MeV/c^2

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



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

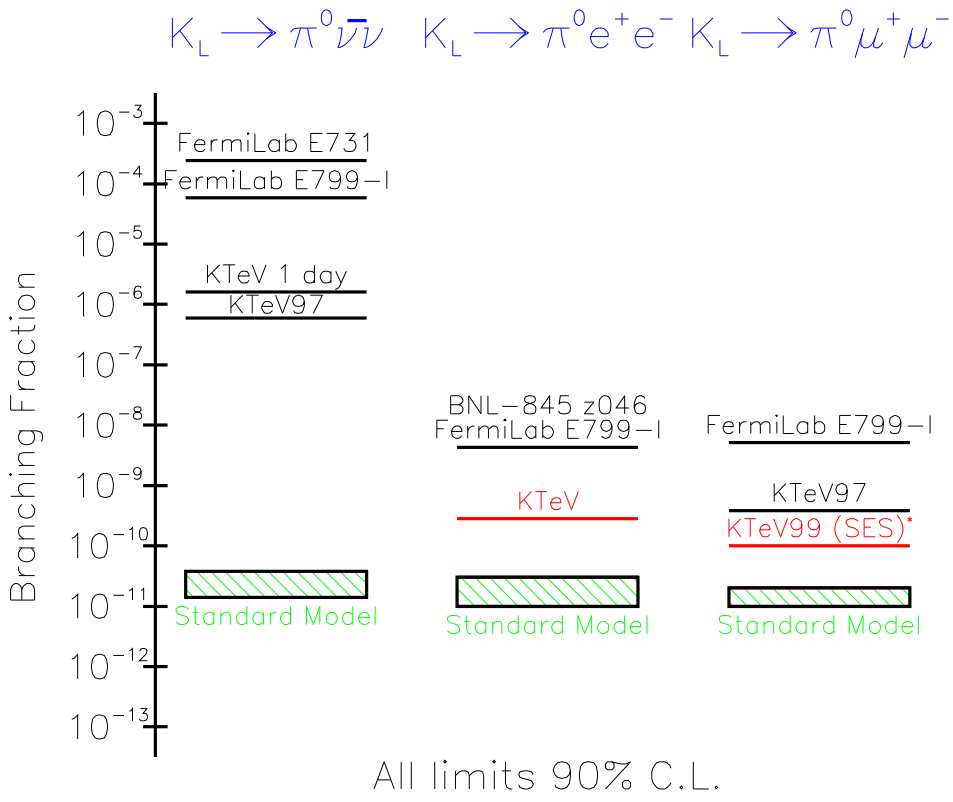
$K_L \to \pi^0\mu^+\mu^-$ Result



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

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

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



Summary

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