Recent KTeV Results on Rare and LFV Decays

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

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Fermilab

Electroweak Moriond 2007
Outline

KTeV was constructed primarily to measure the direct CPV parameter $\varepsilon'/\varepsilon$.

Ran in 1997 and 1999 at Fermilab.

Rich number of other physics topics from KTeV due to excellent detector acceptance to many rare K decay modes.

For this talk, I present recent KTeV measurements of:

- $\text{BR}(\pi^0 \to \text{ee}\gamma)$ “Dalitz decay”

- $\text{BR}(K_L \to \pi^0\gamma\gamma)$ and $\text{BR}(K_L \to \pi^0\text{ee}\gamma)$

- LFV limits on $K_L \to \pi^0\pi^0\mu e$ and $\pi^0 \to \mu e$
Large acceptance for nearly all neutral kaon decays

Spectrometer:
\[ \sigma(P)/P = 0.38\% + 0.16\%P \]

CsI calorimeter:
\[ \sigma(E)/E = 0.45\% + 2%/\sqrt{E} \]

Transition Radiation Detector for additional particle-ID

Ran in 1997 and 1999 at Fermilab, with an exposure of \(~10^{12}\) \(K_L\) decays in the fiducial volume
A New Measurement of $\text{BR}(\pi^0 \rightarrow ee\gamma)$ “Dalitz decay”

An important engineering measurement for HEP. Many measurements use $\text{BR}(\pi^0 \rightarrow ee\gamma)$ as a scale factor (ie. an external systematic error).

Current Measurements of $\text{BR}(\pi^0 \rightarrow ee\gamma)/\text{BR}(\pi^0 \rightarrow \gamma\gamma)$

$(1.17 \pm 0.15)\%$ 27 events Budagov 1960 – JETP 11
$(1.166 \pm 0.047)\%$ 3071 events Samios 1961 – Phys. Rev. 121
$(1.25 \pm 0.04)\%$ $\sim10^3$ events Schardt 1981 – Phys. Rev. D 23
$(1.213 \pm 0.030)\%$ PDG Average (2.5% relative uncertainty)

Theory

1.196% D. Joseph 1960 – Nuovo Cimento 16
**Analysis Technique**

**Signal Mode**

\[ K_L \rightarrow \pi^0\pi^0\pi^0 \]

\[ \gamma\gamma \gamma\gamma \text{ee}\gamma \]

7 clusters in CsI

2 tracks, well-separated in the drift chambers

**Normalization Mode**

\[ K_L \rightarrow \pi^0\pi^0\pi^0 \rightarrow 6\gamma \]

6 clusters in CsI

**Reconstruction**

Fully reconstructed

Choose among 15 photon pairings by requiring the 3 pions to have decayed at the same z position

Decay must occur in 40 m vacuum region

**66,000 Dalitz Decays!**
Dalitz Signal

3\pi^0\text{ Normalization Mode}

- Data
- MC

Reconstructed 3\pi^0_d\text{ Mass (GeV/c}^2\text{)}

Reconstructed 3\pi^0\text{ Mass (GeV/c}^2\text{)}
$e^+e^-$ Track Separation Requirement to Ensure Good Acceptance Measurement

Track Cell Separation Requirement: >3 cells

Drift Chamber Cells

Sense Wire

6.35 mm

Effective $e^+e^-$ Mass Cutoff

Graph showing the distribution of generated $e^+e^-$ mass with different cuts.
Relative Acceptance

Good Match between Data and MC is essential

Shapes match to better than 1.5σ
<table>
<thead>
<tr>
<th>Source of Systematic Error</th>
<th>Preliminary Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative Corrections</td>
<td>1.02%</td>
</tr>
<tr>
<td>Tracking Inefficiency</td>
<td>0.68%</td>
</tr>
<tr>
<td>Detector Material</td>
<td>0.37%</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.10%</td>
</tr>
<tr>
<td>Trigger Inefficiency</td>
<td>0.14%</td>
</tr>
<tr>
<td>Trigger 6 Prescale</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Form Factor</td>
<td>0.07%</td>
</tr>
<tr>
<td>Photon Inefficiency</td>
<td>0.01%</td>
</tr>
<tr>
<td>Background</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Cut Variations</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Monte Carlo Statistics</td>
<td>0.19%</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>1.32%</td>
</tr>
</tbody>
</table>

66,432 Dalitz events

0.39% relative statistical uncertainty
Radiative corrections lowers the acceptance by ~5%

Width of $e^+e^-\gamma$ mass distribution disagrees with data

Conservatively assign a systematic error of ~1% of the acceptance
New KTeV Measurement of $\frac{\text{BR}(\pi^0 \rightarrow e^+ e^- \gamma)}{\text{BR}(\pi^0 \rightarrow \gamma \gamma)}$

$$(1.1539 \pm 0.0045 \pm 0.0152)\%$$

Consistent with previous measurements and with theory

Half the uncertainty of current PDG average

2.5 times better than best previous measurement
Physics of $K_L \rightarrow \pi^0\gamma\gamma$

Relevant for untangling the CP decomposition of $K_L \rightarrow \pi^0\text{ee}$ (related to $\text{Im} V_{TD}$)

- $O(p^4)$ $\chi$PT predicts $\text{BR} \sim 10^{-6}$ and small contribution to $K_L \rightarrow \pi^0\text{ee}$. Prediction low by factor of 2-3.

- $O(p^6)$ $\chi$PT and the VMD parameter $a_v$ can accommodate the measurements. Large contribution to $K_L \rightarrow \pi^0\text{ee}$. 
Signature is 4 EM showers in CsI

Underconstrained system!

3 possible pairing of $2\gamma$ to form $\pi^0$

Use Kaon Mass constraint to create 3 possible hypothesis for the $K_L$ decay vertex location.

Select hypothesis with best possible $\pi^0$ mass
Serious Background from $K_L \rightarrow \pi^0\pi^0\pi^0 \rightarrow 6\gamma$

Background tendencies:
- reconstructs downstream
- bad cluster shapes

2 lost $\gamma$'s

1 lost $\gamma$
1 merged $\gamma$

2 merged $\gamma$

$K_L$ decay vertex region

ID 206002
Entries 91605

Signal events

background
$K_L \rightarrow \pi^0\pi^0\pi^0 \rightarrow 6\gamma$ Background from Published Result

Due to DATA/MC mismatch in the cluster shape variable, we underestimated the $K_L \rightarrow \pi^0\pi^0\pi^0$ background in this publication.
Improved Simulation of the Cluster Shape Variable

Better Data/MC agreement in the tails.
Result: Increased Background Level.
Updated Result on $\text{BR}(K_L \rightarrow \pi^0 \gamma \gamma)$

1982 events observed from full data set

$\text{BR}(K_L \rightarrow \pi^0 \gamma \gamma) = (1.30 \pm 0.03(\text{stat}) \pm 0.04(\text{sys})) \cdot 10^{-6}$

Normalized to $\text{BR}(K_L \rightarrow \pi^0 \pi^0)$
<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_V$ dependence</td>
<td>1.5</td>
</tr>
<tr>
<td>$3\pi^0$ background</td>
<td>1.3</td>
</tr>
<tr>
<td>MC statistics</td>
<td>1.0</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.9</td>
</tr>
<tr>
<td>Photon Shape</td>
<td>1.1</td>
</tr>
<tr>
<td>Tracking Chambers</td>
<td>0.9</td>
</tr>
<tr>
<td>$2\pi^0$ branching ratio</td>
<td>0.9</td>
</tr>
<tr>
<td>Photon vetoes</td>
<td>0.9</td>
</tr>
<tr>
<td>Kaon Energy</td>
<td>0.7</td>
</tr>
<tr>
<td>Decay Vertex</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.9</strong></td>
</tr>
</tbody>
</table>
Measurement of BR($K_L \to \pi^0 e e \gamma$)

Similar Physics to $K_L \to \pi^0 \gamma\gamma$ but much easier event topology.

Can fully reconstruct event.

χPT Predictions

- $O(P^4)$: $1.0 \cdot 10^{-8}$
- $O(P^6)$: $2.4 \cdot 10^{-8}$

(KTeV published result [PRL87, 21801(2001)]

$(2.34 \pm 0.35 \pm 0.13) \cdot 10^{-8}$
Preliminary Result on $\text{BR}(K_L \to \pi^0 \text{ee} \gamma)$

\[
\text{BR} = (1.90 \pm 0.16 \pm 0.12) \cdot 10^{-8}
\]

139 signal events

14.4 background events from $K_L \to \pi^0 \pi^0_D$

$K_L \to \pi^0 \pi^0 \pi^0_D$
# Lepton Flavor Violating Decays

LFV is permitted within SM by presence of neutrino mixing, but heavily suppressed. Therefore, LFV decays are sensitive to new physics.

LFV decays in the kaon sector is expected in many new scenarios.

Mass scale probed by LFV kaon decays through a hypothetical LFV vector boson $X$.

<table>
<thead>
<tr>
<th>Branching Fraction Limit</th>
<th>Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(K_L \to \mu e) &lt; 4.7 \cdot 10^{-12}$</td>
<td>150 TeV/c$^2$</td>
</tr>
<tr>
<td>$B(K^+ \to \pi^+ \mu^+\mu^-) &lt; 1.3 \cdot 10^{-11}$</td>
<td>31 TeV/c$^2$</td>
</tr>
<tr>
<td>$B(K_L \to \pi^0 \mu e) &lt; 3.4 \cdot 10^{-10}$</td>
<td>37 TeV/c$^2$</td>
</tr>
</tbody>
</table>

(KTeV Preliminary)
New KTeV Limits on Lepton Flavor Violating Decays

- KTeV has good sensitivity to a number of LFV decays

\[ K_L \rightarrow \pi^0\mu e \]
\[ K_L \rightarrow \pi^0\pi^0\mu e \]
\[ \pi^0 \rightarrow \mu e \text{ (from } K_L \rightarrow 3\pi^0) \]

\{ New Preliminary Results \}

- KTeV's large kaon flux and well understood beam and detector make this an ideal environment to search for rare decays.
$K_L \rightarrow \pi^0\pi^0\mu e$ decay signature is clean due to multiple constraints.

- **Vertex location is constrained by charged tracks and $2\pi^0$ mass constraint.**
- **Identify electrons using $E/p$**
- **Identify CsI clusters > 2 GeV that are “in-time” and have good electromagnetic shower shape**
- **Identify muons by $E_\mu > 8 \text{ GeV}/c$ with < 1 GeV in CsI, hits in $\mu$ counters, and Transition Radiation Hits.**
- **Kaon Mass and Transverse Momentum Constraint**
Backgrounds

• $K_L \rightarrow \pi\mu\nu$ with 4 accidental photons

• $K_L \rightarrow \pi\nu\nu e$ with 4 accidental photons and the $\pi$ misidentified as a $\mu$

• $K_L \rightarrow \pi^0 \pi^0 \pi^0 D$ with accidental $\mu$

The square of the $\pi^0$ momentum in the $K_L$ rest frame is a good discriminant against this background.
• Blind analysis

• Signal region defined by $p_t^2$ and kaon mass

• Final cuts made on the likelihood variable based on PDFs of the $p_t^2$ and kaon mass.

• Signal acceptance ~2% after all cuts.

• Cut at 10 preserves 95% of the signal events remaining after all cuts.
### Background Estimate

- We don’t trust the MC to estimate background to 1 part in $10^{10}$. Use data.
- Relax kinematic, PID, and accidental cuts, and fit for background in the likelihood distribution.
- Determine suppression factors of each of the cuts.
- Final background estimate is suppressed by the cuts. However, technique works if the cuts are relatively independent.

<table>
<thead>
<tr>
<th>Cut set</th>
<th>Suppression factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic</td>
<td>0.092 ± 0.016</td>
</tr>
<tr>
<td>Particle ID</td>
<td>0.273 ± 0.024</td>
</tr>
<tr>
<td>Accidental</td>
<td>0.261 ± 0.024</td>
</tr>
<tr>
<td>Kinematic * ID (actual)</td>
<td>0.012 ± 0.009</td>
</tr>
<tr>
<td>Kinematic * ID (estimated)</td>
<td>0.025 ± 0.005</td>
</tr>
<tr>
<td>Kinematic * Accidental (actual)</td>
<td>0.025 ± 0.009</td>
</tr>
<tr>
<td>Kinematic * Accidental (estimated)</td>
<td>0.024 ± 0.005</td>
</tr>
<tr>
<td>ID * Accidental (actual)</td>
<td>0.077 ± 0.015</td>
</tr>
<tr>
<td>ID * Accidental (estimated)</td>
<td>0.071 ± 0.009</td>
</tr>
</tbody>
</table>
Expected background = 0.44 ± 0.12 events

Box opened

No events in signal or blind region

PRELIMINARY result using Feldman-Cousins method

\[ \text{BR}(K_L \rightarrow \pi^0\pi^0\mu e) < 1.58 \times 10^{-10} \ (90\% \text{ CL}) \]

\[ KL \rightarrow \pi^0\pi^0\pi^0_D \text{ used as Normalization Mode} \]
\[ \pi^0 \rightarrow \mu e \quad \text{from} \quad K_L \rightarrow 3\pi^0 \]

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

*Expected background* = \( 0.03 \pm 0.02 \) events

Box opened. No events in signal or blind region.

**PRELIMINARY** result using Feldman-Cousins method

\[ \text{BR}(\pi^0 \rightarrow \mu e) < 3.63 \times 10^{-10} \quad (90\% \text{ CL}) \]

Previous results

\[ \begin{align*}
\text{BR}(\pi^0 \rightarrow \mu e) & < 1.72 \times 10^{-8} \quad (90\% \text{ CL}) \quad \text{PL B320 407 (94)} \\
\text{BR}(\pi^0 \rightarrow \mu^+e^-) & < 3.8 \times 10^{-10} \quad (90\% \text{ CL}) \quad \text{PRL 85 2450 (00)} \\
\text{BR}(\pi^0 \rightarrow \mu^-e^+) & < 3.4 \times 10^{-9} \quad (90\% \text{ CL}) \quad \text{PRL 85 2877 (00)}
\end{align*} \]
Summary

Preliminary measurements of:

- $\text{BR}(\pi^0 \to \text{ee}\gamma)/\text{BR}(\pi^0 \to \gamma\gamma)$
  
  $(1.1539 \pm 0.0045 \pm 0.0152)\%$

- $\text{BR}(K_L \to \pi^0\gamma\gamma)$ and $\text{BR}(K_L \to \pi^0\text{ee}\gamma)$
  
  $\text{BR}(K_L \to \pi^0\gamma\gamma) = (1.30 \pm 0.03\text{(stat)} \pm 0.04\text{(sys)}) \cdot 10^{-6}$
  $\text{BR}(K_L \to \pi^0\text{ee}\gamma) = (1.90 \pm 0.16 \pm 0.12) \cdot 10^{-8}$

- LFV limits on $K_L \to \pi^0\pi^0\mu\text{e}$ and $\pi^0 \to \mu\text{e}$
  
  $\text{BR}(K_L \to \pi^0\pi^0\mu\text{e}) < 1.58 \times 10^{-10}$ (90% CL)
  $\text{BR}(\pi^0 \to \mu\text{e}) < 3.63 \times 10^{-10}$ (90% CL)
Backup Slides
Analysis Cuts for $K_L \rightarrow \pi^0\pi^0\mu e$

- 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 $\pi^0$ momentum in K rest frame between 0 and 0.025 (GeV/c)$^2$
- $\pi^0$ masses between 0.132 and 0.138 GeV/c$^2$

- E/p for electron between 0.95 and 1.05
- TRD signal for $\mu$ track is not consistent with electron (prob$_\mu$ > 0.015)
- Fusion $\chi^2 < 10$ for electron and neutral clusters (eliminates overlapping clusters)
- $\mu$ momentum > 8 GeV. $\mu$ 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