Measurement of the
$\pi^0 \rightarrow e^+e^-$ branching ratio

by Rune Niclasen
University of Colorado at Boulder
on behalf of the KTeV collaboration

PANIC 2005
Outline

- Basic structure of the decay $\pi^0 \rightarrow e^+ e^-$
- Interference with the Dalitz decay ($\pi^0 \rightarrow e^+ e^- \gamma$)
- The KTeV detector
- The measurement technique
- Signal and background
- Systematic errors
- Preliminary result
The decay $\pi^0 \rightarrow e^+ e^-$

- $\pi^0 \rightarrow e^+ e^-$ is a rare electromagnetic decay that proceeds through a loop process at lowest order.
- It is suppressed by two factors of the electromagnetic coupling $\alpha$ and is also helicity suppressed by a factor $(2m_{ee}/m_{\pi^0})^2$. 

![Diagram of the decay process](image)
The decay $\pi^0 \rightarrow e^+ e^-$

Assuming a pion form factor the branching ratio to lowest order is (Bergström, 82):

$$\frac{\Gamma(\pi^0 \rightarrow e^+ e^-)}{\Gamma(\pi^0 \rightarrow \gamma \gamma)} = 2\sqrt{1 - \left(\frac{2m_e}{m_\pi}\right)^2 \left(\frac{\alpha}{\pi m_\pi}\right)^2} |R|^2$$

with

$$R = -\frac{2i}{\pi^2 m_\pi^2} \int d^4k \frac{q^2 k^2 - (q \cdot k)^2 F(k^2, (q - k)^2)}{(k^2 + i\epsilon)((q - k)^2 + i\epsilon)((k - p)^2 - m_e^2 + i\epsilon)}$$

The contribution from on-shell photons comes from the imaginary part of $R$ and sets a lower limit, the unitary bound, on the decay rate which is independent of the form factor model:

$$\frac{\Gamma(\pi^0 \rightarrow e^+ e^-)}{\Gamma(\pi^0 \rightarrow \gamma \gamma)} \geq 4.75 \times 10^{-8}$$

Chiral perturbation and meson dominance models for the form factor predict a lowest order rate in the range:

$$\frac{\Gamma(\pi^0 \rightarrow e^+ e^-)}{\Gamma(\pi^0 \rightarrow \gamma \gamma)} = 6 - 9 \times 10^{-8}$$
Radiative corrections are introduced in next to leading order treatments. A detailed treatment was done by Bergström(83), calculating both the virtual and the radiative corrections.

The total correction to the rate from next to leading order terms is $-3.4\%$. 

![Diagram showing electron pair production in electron-positron annihilation process with virtual and radiative corrections.]
Interference with the Dalitz decay

- The $\pi^0 \to e^+e^-$ decay with radiation only distinguishes itself from the much more common Dalitz decay in the region of very soft photons.

- So define branching ratio where there is only soft radiation:

$$BR(\pi^0 \to e^+e^-, \ x > 0.95), \quad x = \frac{m_{ee}^2}{m_{\pi^0}^2}$$

- The actual quantum mechanical interference between the two modes have been found to be negligible in the high $e^+e^-$ mass region.
The KTeV E799 experiment

- The spectrometer consists of 4 drift chambers and a magnet which measures charged tracks with momentum resolution

\[ \sigma(P)/P = 0.38\% \oplus 0.016\% \cdot P \]

- The CsI calorimeter measures electromagnetic cluster energies with resolution

\[ \sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E} \]

and positions with resolution in the millimeter range.
Measurement technique

- We measured:

\[
\frac{\text{BR}(\pi^0 \to e^+e^-, \; x > 0.95)}{\text{BR}(\pi^0 \to e^+e^-\gamma, \; x > 0.232)}
\]

where \( x = \frac{m_{ee}^2}{m_{\pi}^2} \).

- Both modes were extracted by fully reconstructing kaons from the following decay chains:

\[
K_L \to \pi^0 \pi^0 \pi^0 \to \gamma\gamma\gamma\gamma \; e^+e^- \\
K_L \to \pi^0 \pi^0 \pi^0 \to \gamma\gamma\gamma\gamma \; e^+e^-\gamma
\]

- We required 2 tracks pointing to calorimeter clusters and 4 (5) additional clusters.

- The photon pairing with the best agreeing decay vertex was used.

![Diagram with particles and vertices labeled Pairing 1, Pairing 2, Pairing 3]
Data-MC comparisons

$e^+e^- \text{ mass}$

$\chi^2/\text{dof} = 37.8 / 49$

$e^+e^-\gamma \text{ mass}$

$\chi^2/\text{dof} = 419.4 / 99$
Backgrounds

Backgrounds to the signal all originated from $K_L \rightarrow 3\pi^0$ decays.

- $K_L \rightarrow 3\pi^0 \rightarrow \gamma\gamma\gamma e^+e^-\gamma$
- $K_L \rightarrow 3\pi^0 \rightarrow \gamma\gamma\gamma e^+e^-e^+e^-$
- $K_L \rightarrow 3\pi^0 \rightarrow \gamma\gamma e^+e^-\gamma e^+e^-\gamma$
- $K_L \rightarrow 3\pi^0 \rightarrow \gamma\gamma\gamma e^+e^-\gamma$

with 1 photon converting to an $e^+e^-$ pair.

- $K_L \rightarrow 3\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ with 2 photons converting to $e^+e^-$ pairs.
Signal and background

A comparison of the reconstructed $e^+e^-$-mass for data and background MC is shown. Black histogram is data, red line is MC.

We found 714 events in the signal region with an estimated background of $39.9 \pm 12.3$ event.

The statistical uncertainty becomes 4.0%
Systematic errors

The main systematic uncertainty comes from the background estimate which suffers from a couple issues.

The main sources are:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty associated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background normalization</td>
<td>1.4%</td>
</tr>
<tr>
<td>$e^+e^-$ mass modeling</td>
<td>1.0%</td>
</tr>
<tr>
<td>Background MC statistics</td>
<td>0.8%</td>
</tr>
<tr>
<td>Photon pairing $\chi^2$ modeling</td>
<td>0.7%</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>2.1%</td>
</tr>
</tbody>
</table>
Preliminary branching ratio

From the 714 signal events and 1,619,561 normalization events we measure:

$$\frac{\text{BR}(\pi^0 \rightarrow e^+e^-, \ x > 0.95)}{\text{BR}(\pi^0 \rightarrow e^+e^-\gamma, \ x > 0.232)} = (1.721 \pm 0.068\text{(stat)} \pm 0.036\text{(sys)}) \times 10^{-4}$$

Using the Dalitz branching ratio and the fraction of Dalitz events with $m_{ee} > 65$ MeV the sought branching ratio can be extracted:

$$\text{BR}(\pi^0 \rightarrow e^+e^-, \ x > 0.95) = (6.56 \pm 0.26\text{(stat)} \pm 0.23\text{(sys)}) \times 10^{-8}$$

The systematic error now includes the 2.7% uncertainty in the Dalitz branching ratio and a 0.5% uncertainty from the uncertainty in the $\pi^0$ slope parameter.

The old KTeV result using less than half the data was:

$$\text{BR}(\pi^0 \rightarrow e^+e^-, \ x > 0.95) = (6.09 \pm 0.40\text{(stat)} \pm 0.24\text{(sys)}) \times 10^{-8}$$
Preliminary branching ratio

The result can be recast in terms of just the lowest order rate which can be used to compare with theoretical predictions:

\[
\frac{\Gamma^0_{ee}}{\Gamma_{\gamma\gamma}} = (7.67 \pm 0.30\text{(stat)} \pm 0.27\text{(sys)}) \times 10^{-8}
\]
Conclusion

A new preliminary result for the branching ratio has been obtained from the complete KTeV E799 dataset:

\[ \text{BR}(\pi^0 \rightarrow e^+ e^-, \ x > 0.95) = (6.56 \pm 0.26 \text{(stat)} \pm 0.23 \text{(sys)}) \times 10^{-8} \]

The new result has a statistical uncertainty of 4.0% and a systematic uncertainty of 3.4%.

In its final version it will supersede the old 1999 KTeV result.