First observation of $K_S \rightarrow \pi^0 \mu^+ \mu^-$
and $K_S \rightarrow \pi^0 e^+ e^-$ at NA48/1

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On behalf of the NA48/1 collaboration: Cambridge, Chicago, CERN, Dubna,
Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay,
Siegen, Torino, Warsaw, Wien
Introduction.

First observation of:

\[ K_S \rightarrow \pi^0 \mu^+ \mu^- \] (NEW!!!) and


- Background.
- Signal.
- Branching ratio.

Chiral perturbation theory.

\[ K_L \rightarrow \pi^0 \mu^+ \mu^- \text{ and } K_L \rightarrow \pi^0 e^+ e^- \] CP violating branching ratio predictions.

Summary.
Motivation to search for $K_S \to \pi^0 \mu^+ \mu^-$ and $K_S \to \pi^0 e^+ e^-$:

- Kaon physics could be sensitive to physics beyond the Standard Model.

- Direct CP violation has been measured by NA48 and KTeV, $\epsilon'/\epsilon$. The next goal in kaon physics is to test the Standard Model predictions on CP, this can be achieved testing quantitatively the CKM paradigm (Unitarity triangle) by means of rare kaon decays.
Unitarity triangle

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]
\[ K_L \rightarrow \pi^0 e^+ e^- \]
\[ K_S \rightarrow \pi^0 e^+ e^- \]
\[ K_L \rightarrow \pi^0 \gamma \gamma \]

\[ K_L \rightarrow \mu^+ \mu^- \]
\[ K_L \rightarrow \gamma \gamma, \ K_L \rightarrow e^+ e^- \gamma \]
\[ K_L \rightarrow e^+ e^- e^+ e^-, \ e^+ e^- \mu^+ \mu^- \]

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

Note: Analogous picture for \( K_L \rightarrow \pi^0 \mu^+ \mu^- \) you just need to substitute \( e^+ e^- \) by \( \mu^+ \mu^- \).

\( K_L \rightarrow \pi^0 \nu \bar{\nu} \) and \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) are:

- Very clean theoretically.
- Very difficult experimentally.

\( K_L \rightarrow \pi^0 e^+ e^- \) and \( K_L \rightarrow \pi^0 \mu^+ \mu^- \) are:

- Not so clean theoretically
- But more accessible experimentally.
NA48/1 High intensity $K_S$ beam (2002)

400 GeV protons

SPS flat top 4.8 s/16.8 s

$\sim 5 \times 10^{10}$ protons per pulse

Impinging on a 40 cm long Be target at 4.2 mrad production angle.

24 mm pt absorber between target and sweeping magnet.

5.1 m thick collimator.

120 m vacuum decay volume.

$\sim 2 \times 10^5$ $K_S$ decays per spill in the fiducial volume with a mean energy of 120 GeV.
About the Analysis

- Predicted $\text{BR}(K_S \rightarrow \pi^0 l^+ l^-) \sim 10^{-10} - 10^{-9}$  
  \[ l^+ l^- = \mu^+ \mu^- \text{ or } e^+ e^- \]

- $K_S$ flux expected $\sim$ few $10^{10}$

- This required tight cuts to control the background, but not so tight that they will kill the signal.

Blind analysis

- Signal and control regions masked.
  
  Signal defined in the $m_{\pi^0 l^+ l^-}$ vs $m_{\gamma\gamma}$ plane.
  
  - Cuts tuned with a fraction of the data, while the signal region was masked.
  
  - Unmask control region.
  
  - Unmask signal region.
### Background Summary

**$K_S \rightarrow \pi^0 \mu^+ \mu^-$**

<table>
<thead>
<tr>
<th>Background source</th>
<th>Event in signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^+ \pi^- \pi^0$</td>
<td>$0^{+0.02}_{-0.00}$</td>
</tr>
<tr>
<td>$K_L \rightarrow \mu^+ \mu^- \gamma \gamma$</td>
<td>$0.04 \pm 0.04$</td>
</tr>
<tr>
<td>Accidentals</td>
<td>$0.18^{+0.18}_{-0.11}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$0.22^{+0.19}_{-0.12}$</td>
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</tbody>
</table>

Dominated by accidental background.

**$K_S \rightarrow \pi^0 e^+ e^-$**

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<th>Event in signal region</th>
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<tr>
<td>$K_S \rightarrow \pi_D^0 \pi_D^0$</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>$K_L \rightarrow e^+ e^- \gamma \gamma$</td>
<td>$0.08^{+0.03}_{-0.02}$</td>
</tr>
<tr>
<td>Accidentals</td>
<td>$0.07^{+0.07}_{-0.03}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$0.15^{+0.10}_{-0.04}$</td>
</tr>
</tbody>
</table>

Dominated by $K_L \rightarrow e^+ e^- \gamma \gamma$ and accidental background.

Many backgrounds were studied using both data and MC, here only the non negligible ones are presented.
Accidental background: accidental overlap of particles from two decays that happen to be in-time and fake the signal.

Accidental background can be determined from data extrapolating from the \textit{out of time} side bands.
(note: \textit{out of time} window $\sim 125\text{ns}$, intime window $\pm 1.5\text{ns}$)

Tight cuts imposed to veto on accidental activity.

Major accidental for $K_S \rightarrow \pi^0 \mu^+ \mu^- : K_S \rightarrow \pi^+ \pi^- + K_S \rightarrow \pi^0 \pi^0$ (main), $K_L \rightarrow \pi^\pm \mu^\mp \nu + K_S(K_L) \rightarrow \pi^0 \pi^0(\pi^0)$ (significant)

Major accidental for $K_S \rightarrow \pi^0 e^+ e^- : K_L \rightarrow \pi^\pm e^\mp \nu + K_S(K_L) \rightarrow \pi^0 \pi^0(\pi^0)$

Accidental background $K_S \rightarrow \pi^0 \mu^+ \mu^- : 0.18^{+0.18}_{-0.11}$

Accidental background $K_S \rightarrow \pi^0 e^+ e^- : 0.07^{+0.07}_{-0.03}$
$K_S \rightarrow \pi^0\pi_D^0$ background in $K_S \rightarrow \pi^0e^+e^-$

A cut on the $m_{ee}$ distribution is required to reject $K_S \rightarrow \pi^0\pi_D^0$ ($\pi_D^0 \rightarrow e^+e^-\gamma$) background.

A conservative cut is applied $m_{ee} > 0.165\text{GeV}$

$K_S \rightarrow \pi^0\pi_D^0$ background above 0.165GeV is negligible.
$K_L \rightarrow e^+e^-\gamma\gamma$ background in $K_S \rightarrow \pi^0e^+e^-$

$K_L \rightarrow e^+e^-\gamma\gamma$ background is estimated using 2001 $K_L$ data (10 x 2002 statistics).

$K_L \rightarrow e^+e^-\gamma\gamma$ background = $0.08^{+0.03}_{-0.02}$
First observation of $K_S \rightarrow \pi^0 \mu^+ \mu^-$

6 events found in signal region

- No events found in equivalent same sign distributions
- No accumulation of background close to the signal region by relaxing the cuts.
First observation of $K_S \rightarrow \pi^0 e^+ e^-$

7 events found in signal region

- No events found in equivalent same sign distributions
- No accumulation of background close to the signal region by relaxing the cuts.
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<tr>
<td>$K_S$ Flux</td>
<td>$(2.50 \pm 0.08) \times 10^{10}$</td>
<td>$(3.51 \pm 0.17) \times 10^{10}$</td>
</tr>
<tr>
<td>Acceptance ×</td>
<td>0.081 ± 0.002 ± 0.004</td>
<td>0.065 ± 0.004</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>$0.22^{+0.19}_{-0.12}$</td>
<td>$0.15^{+0.10}_{-0.04}$</td>
</tr>
<tr>
<td>Events</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Branching Ratio</td>
<td>$(2.9^{+1.4}_{-1.2} \pm 0.2) \times 10^{-9}$</td>
<td>$(m_{ee} &gt; 0.165 \text{GeV})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(3.0^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>extrapolated $\star$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$</td>
</tr>
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</table>

The systematic error is one order of magnitude smaller than the statistical error.

$\star$ A vector matrix element with no form factor dependence has been assumed to estimate acceptance and to extrapolate to the full $m_{ee}$ spectrum. The uncertainty in the form factor dependence dominates the systematic error.

Statistical error in flux measurement is completely negligible.
Main source of systematics to determine the Branching Ratio is the unknown form factor \((W(z))\).

\[ W(z) = a_s + b_s \cdot z \quad \text{where} \quad z = \frac{m_{\mu}^2}{m_{K}^2} \]

\(a_s\) and \(b_s\) parameters have to be determined experimentally (theory prediction only available for \(b_s/a_s\)).

Event geometry depends on \(a_s\) and \(b_s\):

- Geometrical acceptance depends on \(a_s\) and \(b_s\).
- To determine \(\text{BR}(K_S \rightarrow \pi^0 e^+ e^-)\) for the whole \(m_{ee}\) spectrum an extrapolation is needed.

![Graph showing acceptance and acceptance trigger efficiency for \(\pi^0 \mu^+ \mu^-\) and \(\pi^0 e^+ e^-\) channels as a function of \(b_s/a_s\).]
**$a_S$ and $b_S$ determination**

\[
Br(K_S \to \pi^0 e^+ e^-) = [0.01 - 0.76a_S - 0.21b_S + 46.5a_S^2 + 12.9a_S b_S + 1.44b_S^2] \times 10^{-10}
\]
\[
Br(K_S \to \pi^0 \mu^+ \mu^-) = [0.07 - 4.52a_S - 1.50b_S + 98.7a_S^2 + 57.7a_S b_S + 8.95b_S^2] \times 10^{-11}
\]

hep-ph/9808289

Assuming VMD ($b_S / a_S = 0.4$) $a_S$ can be extracted independently:

\[
Br(K_S \to \pi^0 e^+ e^-) \approx 5.2 \times 10^{-9} a_S^2 \quad \implies |a_S|_{\pi^0 e^+ e^-} = 1.06^{+0.26}_{-0.21} \pm 0.07
\]

\[
Br(K_S \to \pi^0 \mu^+ \mu^-) \approx 1.2 \times 10^{-9} a_S^2 \quad \implies |a_S|_{\pi^0 \mu^+ \mu^-} = 1.55^{+0.38}_{-0.32} \pm 0.05
\]

$K_S \to \pi^0 \mu^+ \mu^-$ and $K_S \to \pi^0 e^+ e^-$ combined (log-likelihood fit):

- $a_S = -1.4^{+3.6}_{-2.2}$ and $b_S = 9.8^{+5.8}_{-7.6}$
- or
- $a_S = 1.2^{+2.2}_{-2.1}$ and $b_S = -9.2^{+7.9}_{-5.8}$

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Our statistics are too low to determine the $m_{ll}$ distribution.
Results on $\text{BR}(K_S \to \pi^0 \mu^+ \mu^-)/\text{BR}(K_S \to \pi^0 e^+ e^-)$

$\text{BR}(K_S \to \pi^0 \mu^+ \mu^-)/\text{BR}(K_S \to \pi^0 e^+ e^-)$ is interesting because:

\[ \frac{\text{BR}(K_S \to \pi^0 \mu^+ \mu^-)}{\text{BR}(K_S \to \pi^0 e^+ e^-)} \text{ NA48/1 data} = 0.50^{+0.31}_{-0.32} \pm 0.08 \]

\[ \frac{\text{BR}(K_S \to \pi^0 \mu^+ \mu^-)}{\text{BR}(K_S \to \pi^0 e^+ e^-)} \chi_{PT} \text{ prediction} = 0.23 \quad \text{[hep-ph/9808289]} \]

\[ \frac{\text{BR}(K_S \to \pi^0 \mu^+ \mu^-)}{\text{BR}(K_S \to \pi^0 e^+ e^-)} \text{ pure phase space} = 0.21 \]

The decay $K_L \rightarrow \pi^0 l^+ l^-$ ($l = e$ or $\mu$) has three components:

- **CP conserving**
  NA48 measurement $BR(K_L \rightarrow \pi^0 \gamma \gamma)$:
  $$BR(K_L \rightarrow \pi^0 l^+ l^-)_{CPcons} \sim 10^{-12}$$

- **direct CP violating**
  Proportional to $\eta$ or $Im(\lambda_t)$
  $$Im(\lambda_t) = \eta A^2 \lambda^5 \quad \lambda_t = V_{ts}^* V_{td}$$

- **indirect CP violating**
  $$\rightarrow BR(K_L \rightarrow \pi^0 l^+ l^-)_{ind} = |\epsilon|^2 (\frac{\tau_L}{\tau_S}) BR(K_S \rightarrow \pi^0 l^+ l^-)$$

The measured $BR(K_S \rightarrow \pi^0 \mu^+ \mu^-)$ allows the prediction of CPV branching ratio of $K_L \rightarrow \pi^0 \mu^+ \mu^-$ as a function $Im(\lambda_t)$ to within a sign ambiguity.
Branching Ratio Prediction for $K_L$

\[
BR(K_L \rightarrow \pi^0 l^+ l^-)_{CPV} \times 10^{12} = C_{IND} \pm C_{INT} \left( \frac{Im(\lambda_t)}{10^{-4}} \right) + C_{DIR} \left( \frac{Im(\lambda_t)}{10^{-4}} \right)^2
\]

where:

- $C_{DIR}$: Direct CPV component
- $C_{IND} \sim BR(K_S \rightarrow \pi^0 l^+ l^-)$: Indirect CPV component
- $C_{INT} \sim \sqrt{BR(K_S \rightarrow \pi^0 l^+ l^-)}$: Interference DIR-IND

Taking $Im(\lambda_t)$ PDG world average $(1.36 \pm 0.12) \times 10^{-4}$:

\[
BR(K_L \rightarrow \pi^0 \mu^+ \mu^-)_{CPV} \times 10^{12} \approx 9_{\text{indirect}} \pm 6_{\text{interference}} + 1_{\text{direct}}.
\]

\[
BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} \times 10^{12} \approx 17_{\text{indirect}} \pm 9_{\text{interference}} + 5_{\text{direct}}.
\]

KTeV measurement: $BR(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10} (90\% CL)$

KTeV measurement: $BR(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10} (90\% CL)$
First observation of $K_S \to \pi^0 \mu^+ \mu^- : 6$ events. (NEW!!!)

First observation of $K_S \to \pi^0 e^+ e^- : 7$ events.

$$\text{BR}(K_S \to \pi^0 \mu^+ \mu^-) = (2.9_{-1.2}^{+1.4}(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-9} \text{(NEW!!!)}$$

$$\text{BR}(K_S \to \pi^0 e^+ e^-)_{(m_{ee}>0.165\text{GeV})} = (3.0_{-1.2}^{+1.5}(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-9}$$

$$\text{BR}(K_S \to \pi^0 e^+ e^-) = (5.8_{-2.3}^{+2.8}(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-9}$$

hep-ex/0309075
\(K_S\) BR results together with \(\chi_{PT}\) predict:

\[B(K_L \rightarrow \pi^0 \mu^+ \mu^-)_{CPV} \approx (0.4 \, \text{to} \, 1.6) \times 10^{-11} \quad \text{(NEW!!!)}\]

\[B(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} \approx (1.3 \, \text{to} \, 3.1) \times 10^{-11}\]

Higher statistics are needed to have a precision \(\chi_{PT}\) test.
Other rare decays results from NA48
NEW!!!
\[ K_L \rightarrow \pi^\pm \pi^0 e^\pm \nu_e (\overline{\nu}_e) \]

\[ BR(Ke4) = [5.21 \pm 0.07(stat) \pm 0.09(syst)] \times 10^{-5} \]

**Ke4 form factors:**

\[ f_s = 0.052 \pm 0.006 \pm 0.002 \]

\[ f_p = -0.051 \pm 0.011 \pm 0.005 \]

\[ \lambda_g = 0.087 \pm 0.019 \pm 0.006 \]

\[ h = -0.32 \pm 0.12 \pm 0.07 \]

Ke4 sample: 5464 events with 62 background events. Form factors agree with previous measurements with improved accuracy. Coupling parameter of the chiral Lagrangian \( L_3 = (-4.1 \pm 0.2) \times 10^{-3} \) evaluated from data.
$K_L \rightarrow \pi^\pm \pi^0 e^\pm \nu_e (\bar{\nu}_e)$

![Graph 1: Distribution of $m_{\pi\pi}$ vs. events.](image1)

![Graph 2: Distribution of $\cos(\theta_{\pi\pi})$ vs. events.](image2)
$K_L \to \pi^\pm \pi^0 e^\pm \nu_e (\bar{\nu}_e)$
$$K_0 \to \pi^\pm e^\mp \nu(\bar{\nu}) \gamma$$

$$BR(Ke3\gamma, E_\gamma^* > 30 Mev, \theta_{e\gamma}^* > 20deg) = [0.962 \pm 0.007 (stat) ^{+0.012}_{-0.011} (syst)]%$$

**Data sample:**
- More than 18000 $Ke3\gamma$ events.
- Normalization: $5 \times 10^6$ $Ke3$
- Result compatible with theoretical predictions.
- Result disagrees with the previous high statistic experimental measurement.