First observation of the decay

\[ K_S \rightarrow \pi^0 e^+ e^- \]

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

- Physics Motivation

- The NA48/1 beamline and detector in 2002

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

- Background Studies

- Preliminary result and conclusions
**CP violation in rare kaon decays**

A unitarity triangle in the kaon system:

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]
\[ K_L \rightarrow \pi^0 e^+ e^- \left\{ \begin{array}{l}
K_S \rightarrow \pi^0 e^+ e^- \\
K_L \rightarrow \pi^0 \gamma \gamma \\
K_L \rightarrow e e \gamma \gamma 
\end{array} \right. \]

\[ K_L \rightarrow \mu^+ \mu^- \left\{ \begin{array}{l}
K_L \rightarrow \gamma \gamma, K_L \rightarrow e^+ e^- \gamma \\
K_L \rightarrow e^+ e^- e^+ e^-, e^+ e^- \mu^+ \mu^- 
\end{array} \right. \]

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

Theoretical error 2-5 %

Together determine unitarity triangle

Extremely difficult experiments

\( K_L \rightarrow \pi^0 e^+ e^- \) experimentally more constrained (limited by background)
$K_L \to \pi^0 e^+ e^-$

The decay $K_L \to \pi^0 e^+ e^-$ has three components:

- **CP conserving**
  
  NA48 measurement $BR(K_L \to \pi^0 \gamma \gamma)$ :
  
  $BR(K_L \to \pi^0 e^+ e^-)_{CP\ cons} = 0.47^{+0.22}_{-0.18} \times 10^{-12}$

  [PL B536 229]

- **direct CP violating**
  
  Proportional to $\eta$ or $Im(\lambda_t)$

  $Im(\lambda_t) = \eta A^2 \lambda^5 \quad \lambda_t = V_{ts}^* V_{td}$
  
  $BR(K_L \to \pi^0 e^+ e^-)_{dir} \sim few \times 10^{-12}$

- **indirect CP violating**

  $BR(K_L \to \pi^0 e^+ e^-)_{ind} = |\epsilon|^2 \left(\frac{\tau_L}{\tau_S}\right) BR(K_S \to \pi^0 e^+ e^-)$

$BR(K_S \to \pi^0 e^+ e^-)$ and $BR(K_L \to \pi^0 \gamma \gamma)$ determine whether it will be possible to extract $\eta$ from a measurement of $BR(K_L \to \pi^0 e^+ e^-)$
\[ K_L \to \pi^0 e^+ e^- \text{ and } K_S \to \pi^0 e^+ e^- \]

Theory \( BR(K_S \to \pi^0 e^+ e^-) = 5 - 50 \times 10^{-10} \)

(Ecker, Pich, de Rafael [NP B291 692])

Direct/indirect CP violating components of \( K_L \to \pi^0 e^+ e^- \) interfere:

\[
BR(K_L \to \pi^0 e^+ e^-)_{CPV} = 1 \times 10^{-12} \left( 15.3 a_s^2 \pm 6.8 \frac{\text{Im}(\lambda_t)}{10^{-4}} |a_s| + 2.8 \left( \frac{\text{Im}(\lambda_t)}{10^{-4}} \right)^2 \right)
\]

\[
BR(K_S \to \pi^0 e^+ e^-) = 5 \times 10^{-9} |a_s|^2 \Rightarrow \text{determines } |a_s|
\]

(D’Ambrosio, Ecker, Isidori, Portoles [JHEP 08 (1998) 004])

Current limits:

\[
BR(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10} \text{ (KTeV, [PRL 86 397])}
\]

2 events with background of 1.1 event

\[
BR(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7} \text{ (NA48, [PL B514 253])}
\]

2-days test run in 1999
The NA48 simultaneous $K_S$ and $K_L$ beams

Used for $\text{Re}(\varepsilon'/\varepsilon)$ measurement until 2001

2002 data-taking: $K_S$ target only
2002 Beamline

$5 \times 10^{10}$ ppp from SPS in 4.8s spill

400 GeV/c protons onto 40 cm Beryllium target, 4.2 mrad production angle

Photon converter downstream of target and a sweeping magnet after the defining collimator

Intensity on target increased by factor $\sim 1000$ compared to running conditions used for the measurement of $\varepsilon'/\varepsilon$

$\sim 4 \times 10^{10} K_S$ decays in 89 days with energy 40-240 GeV and within 2.5 $K_S$ lifetimes from the final collimator

(proposal: $3 \times 10^{10} K_S$ in 105 days; 8% loss due to duty cycle but factor 2 gain in read-out)
**NA48 Detector**

- **Magnetic spectrometer:** charged particles
  \[ \sigma(p)/p \simeq 0.5\% \oplus 0.009\ p[GeV/c]\% \]
  \[ (P_{\perp}^\text{kick} \sim 265\text{MeV}/c) \]

- **Liquid Krypton electromagnetic calorimeter:** photons and electrons
  high granularity \((13212\ 2 \times 2\ \text{cm}^2\ \text{cells})\)
  \[ \sigma(E)/E = 3.2\%/\sqrt{E} \oplus (9\%)/E \oplus 0.42\% \]
  \[ \sigma(t) \simeq 265\text{ps} \text{ for 50 GeV } e^- \]
- Detector performance

\[ \sigma(m_{\gamma \gamma}) \approx 1 \text{ MeV} \]

\[ \sigma(m_{\pi^+ \pi^-}) \approx 3 \text{ MeV} \]

- 50k events read out per burst:
  40 MHz read-out \( \pm 100 \text{ ns} \)
  LKr electromagnetic calorimeter read-out upgraded
  New drift chamber read-out: removal of dead time due to read-out overflow
  Active Level III trigger reduced data volume 120 TB \( \rightarrow 40 \text{ TB} \)
Trigger

The trigger used to select $\pi^0 e^+ e^-$ candidates required:

- Energy deposited in LKr $> 30$ GeV
- Energy centre of gravity $< 15$ cm from beam axis at LKr
- Proper decay time $< 6$ $K_S$ lifetimes from the end of the final collimator
- Number of hits in DCH1 compatible with at least one track

Trigger efficiency measured using $\pi^0 \pi^0_D$ events: 99.0%
**Analysis Strategy**

Rare decay analysis strategy ⇒ understand and minimise all possible background processes, without cutting away the signal

“Blind analysis procedure” → signal and control regions masked:

- **Signal region**: \(2.5\sigma_{m_{K}} \times 2.5\sigma_{m_{\pi_{0}}}\)
- **Control region**: \(6.0\sigma_{m_{K}} \times 6.0\sigma_{m_{\pi_{0}}}\)

Study backgrounds using the data and a Monte Carlo simulation

Fix analysis cuts on the basis of these studies

Unmask control region → final background estimate

Unmask signal region → result
$K_S \rightarrow \pi^0 e^+ e^-$ signal selection

Select decays within 2.5 $K_S$ lifetimes of final collimator and with energy $40 < E_{kaon} < 240\text{GeV}$:

- 4 clusters in calorimeter within 3ns of the average time
- 2 tracks, one +, one - forming a good vertex
- Charged vertex downstream of collimator region
- Electron id : $0.95 < \frac{E}{p} < 1.05$
- No signal from muon detector
- Energy centre of gravity (cog) < 6cm from beam axis at LKr
- No energy deposited in hadron calorimeter
- Remove events with additional clusters/tracks in-time
- $m_{ee\gamma\gamma} = m_{kaon}$ assuming $\gamma\gamma$ originate from charged vertex
  2.5$\sigma_{m_K}$ cut used ($\sigma_{m_K} = 4.7\text{MeV}$)
- $m_{\gamma\gamma} = m_{\pi^0}$ assuming $\gamma\gamma$ originate from vertex reconstructed
  imposing $m_K$
  2.5$\sigma_{m_{\pi^0}}$ cut used ($\sigma_{m_{\pi^0}} = 1.0\text{MeV}$)
Backgrounds to the search for $K_S \rightarrow \pi^0e^+e^-$

$K_S$ decays

$K_S \rightarrow \pi^0\pi^0_{Dalitz}$
$K_S \rightarrow \pi^0\pi^0_D + \text{conversion(s)}$
$K_S \rightarrow \pi^0\pi^0_{DalitzDalitz}$
$K_S \rightarrow \pi^0\pi^0(e^+e^-)$
$K_S \rightarrow \pi^0_{Dalitz}\pi^0_{Dalitz}$

$K_L$ decays

$K_L \rightarrow \pi^0\pi^+\pi^-$
$K_L \rightarrow \pi^0\pi^\pm e^{\mp}\nu$
$K_L \rightarrow ee\gamma + \text{bremsstrahlung}$
$K_L \rightarrow ee\gamma\gamma$

$\Xi^0$ decays

$\Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0$
$\Xi^0 \rightarrow \Lambda(pe^-\nu)\pi^0$
$\Xi^0 \rightarrow \Sigma^+(p\pi^0)e^-\nu$

Overlapping fragments of two decays

from the same proton interaction
$p \rightarrow \phi(K_SK_L)$

from different proton interactions
$p \rightarrow K_S \quad p \rightarrow K_L$
Background from $K_S \rightarrow \pi^0 \pi^0_{Dalitz}$

$3 \times 10^8 \ K_S \rightarrow \pi^0 \pi^0_{Dalitz}(e^+ e^- \gamma)$ decays in $\ 0 < \frac{c_T}{c_T S} < 2.5$

Rejected using:

- extra $\gamma$ $\Leftrightarrow m_K$ cut / additional activity cut
- $\theta_{e^+ e^-}$ small $\Leftrightarrow$ track separation at 1st drift chamber $> 2$ cm
- $m_{ee} < m_{\pi^0}$ $\Leftrightarrow$ require $\pi^0 e^+ e^-$ candidates have $m_{ee} > 0.165$ GeV/$c^2$
Background from $K_S \to \pi^0\pi^0_D$ (cont’d)

$m_{ee}$ resolution studied extensively with both data and Monte Carlo

- ‘regular’ $\pi^0\pi^0_D$ events:

  $$K_S \to \begin{cases} 
  \pi^0 \to \{ \gamma, \gamma \} \\
  \pi^0_D \to \{ \gamma', e, e \}
\end{cases}$$

- $\pi^0\pi^0_D$ decay + conversion in detector

  $$K_S \to \begin{cases} 
  \pi^0 \to \{ \gamma, \gamma \} \\
  \pi^0_D \to \{ \gamma \stackrel{\text{conversion}}{\rightarrow} e^+e^- \stackrel{(\text{lost})}{\rightarrow} e^+e^- \}
\end{cases}$$

- Analogous processes e.g. $\pi^0\pi^0_{DD}$, $\pi^0(\gamma\gamma)\pi^0(\gamma_{\text{conv}}(e\bar{e}^\ast)\gamma_{\text{conv}}(e\bar{e}^\ast))$
Background from $K_S \rightarrow \pi^0\pi_D^0$: Data/MC in low $m_{ee}$ region

Events with $m_{ee}$ mis-measured: $m_{ee} > m_{\pi^0} \rightarrow m_{ee\gamma\gamma} > m_K$

Apply conservative cut $m_{ee} > 0.165\text{GeV}$
**Background from $K_S \rightarrow \pi^0\pi^0_D$: Same sign data**

![Graph showing distribution of $m_{ee}$ vs $m_K$ for different categories of events]

Events with $m_{ee} \sim m_{\pi^0}$ contain $e^+e^-e^+e^-$

Check $m_{ee}$ distribution of $\pi^0 e^+ e^+$ and $\pi^0 e^- e^-$ events:

- worse $m_{ee}$ resolution
- have high $m_{ee}$

→ same sign events used as a check of $m_{ee}$ tail before freezing analysis cuts and unmasking control and signal regions
Background from $K_S \rightarrow \pi_D^0 \pi_D^0$

$2 \times 10^6$ $K_S \rightarrow \pi_D^0 (e^+ e^- \gamma) \pi_D^0 (e^+ e^- \gamma)$ decays in $0 < \frac{cT}{cT_S} < 2.5$

$e^+$ and $e^-$ lost from different $\pi_D^0$ decays can have $m_{ee} > m_{\pi^0}$

Suppressed by requirement $m_{\gamma\gamma} \sim m_{\pi^0}$
Background from $K_S \rightarrow \pi_0^D\pi_0^D$ (cont’d)

Lost $e^+$, $e^-$ low energy $\Rightarrow$ $m_{ee\gamma\gamma} \sim m_K$

$m_K$ cut $\Rightarrow$ $(m_{e\gamma}, m_{e\gamma}) \sim (m_{\pi^0}, m_{\pi^0})$

$\pi_0^D\pi_0^0(\gamma\gamma) +$ conversion $\Rightarrow$ tails $m_{e\gamma} < m_{\pi^0}$

Reject events with $(m_{e\gamma}, m_{e\gamma}) < 0.165 \text{ GeV}/c^2$
No events found in the signal region in $30 \times 2002$ statistics
1 event found in control region
Background summary so far ...

Backgrounds from $K_S$ decays $\rightarrow$ additional cuts:

$$m_{ee} > 0.165\text{GeV} \quad (m_{e\gamma}, m_{e\gamma}) > 0.165\text{GeV}/c^2$$

$\Rightarrow K_S \rightarrow \pi_D^0\pi_D^0$ contributes 0.007 event in $\pm 2.5\sigma$ signal region

Now consider backgrounds from $K_L$ decays:

$K_L$ decays

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

$K_L \rightarrow \pi^0\pi^\pm e^{\mp}\nu$

$K_L \rightarrow ee\gamma + $ bremsstrahlung

$K_L \rightarrow ee\gamma\gamma$
Backgrounds from $K_L$ decays

$\sim 5 \times 10^8$ $K_L$ decay in the $0 < \frac{ct}{c\tau_S} < 2.5$ fiducial region

$K_L$ decay primarily to final states with $\pi^\pm$ rather than $e^\pm$

$\rightarrow$ need efficiency of electron id : $0.95 < E/p < 1.05$

Pions can charge exchange in calorimeter : $\pi^- p \rightarrow \pi^0 n$

$\rightarrow$ pions mis-identified as electrons

Select $K_L \rightarrow \pi^0 \pi^+ \pi^-$ decays from 2001 data :

- Measure mis-identification probability $\rightarrow \sim 10^{-2}$

- Study kinematic rejection

using events from data

Starting from $5 \times 10^8$ $K_L$ decays we expect :

- $6 \times 10^3$ $\pi^0 \pi^+ \pi^-$ decays
- $2 \times 10^6$ $\pi^0 \pi^\pm e^\mp \nu$ decays

with two charged particles that look like $e^+ e^-$
**Backgrounds from** $K_L \to \pi^0 \pi^+ \pi^-$ **and** $K_L \to \pi^0 \pi^\pm e^\mp \nu$

To study rejection from kinematics, selected $\pi^0 \pi^+ \pi^-$ and $\pi^0 \pi^\pm e^\mp \nu$ from 2001 data:

- **2001 DATA**
  - $K_L \to \pi^0 \pi^+ \pi^-$ with $m_{\pi^+} = m_e$
  - $m_{\gamma\gamma} / \text{GeV}$ vs $m_K / \text{GeV}$

No events were found in the signal region in either channel
**Background from $K_L \rightarrow ee\gamma\gamma$**

Expect 300 $K_L \rightarrow ee\gamma\gamma$ decays in $0<\frac{ct}{c\tau_S}<2.5$ ($BR = 6 \times 10^{-7}$)

Strongly suppressed by $m_{ee} > 0.165\text{GeV}$ requirement and $m_{\gamma\gamma} = m_{\pi^0}$ cut ($\sigma_{m_{\pi^0}} = 1\text{MeV}$ in $K_S \rightarrow \pi^0 e^+e^-$)

$K_L \rightarrow ee\gamma\gamma$ candidates selected from 2001 data ($K_L$ beam) used to estimate background ($10 \times$ number of $K_L$ decays in 2002 data)

Extrapolate from low $m_{\gamma\gamma}$ region to signal region (assuming flat in $m_{\gamma\gamma}$)
Background summary so far ...

Backgrounds from $K_S$ decays:
$\Rightarrow K_S \rightarrow \pi^0_D \pi^0_D$ contributes 0.007 event in $\pm 2.5\sigma$ signal region

Backgrounds from $K_L$ decays:
- Mis-identification $\pi^{\pm} \leftrightarrow e^{\pm}$, kinematic rejection studied with data
  $\Rightarrow K_L \rightarrow ee\gamma\gamma$ contributes 0.075 event in $\pm 2.5\sigma$ signal region

Now consider backgrounds from $\Xi^0$ decays:

\[ \Xi^0 \text{ decays} \]
\[ \Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0 \]
\[ \Xi^0 \rightarrow \Lambda(p\pi^+\nu)\pi^0 \]
\[ \Xi^0 \rightarrow \Sigma^+(p\pi^0)e^-\nu \]
Backgrounds from $\Xi^0$ decays

Expect $\sim 2 \times 10^9 \Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0$ decays in $0 < \frac{cT}{c\tau_S} < 2.5$

Probability of proton mis-identification as $e^+$ measured from 2001 data using $\Lambda$ decays $\rightarrow \sim 10^{-4}$

Expect $2 \times 10^3 \Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0$ decays in 2002 data with two charged particles that look like $e^+e^-$
Backgrounds from $\Xi^0$ decays (cont’d)

$\Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0$ acceptance $\sim 2\% \Rightarrow$ background already small

Exploit momentum asymmetry in $\Xi^0$ and $\Lambda$ decay - additional cut on:

$$ASP_{(\pi^0,\pm)} = \frac{p_{\pi^0} - (p_+ + p_-)}{p_{\pi^0} + (p_+ + p_-)} \quad \text{and} \quad ASP_{(+,\pm)} = \frac{p_+ - p_-}{p_+ + p_-}$$

reduces background to negligible level

$\Xi^0 \rightarrow \Lambda(pe^-\nu)\pi^0$, $\Xi^0 \rightarrow \Sigma^+(p\pi^0)e^-\nu$ decays rejected in same way

![Graphs](https://example.com/graph1.png)  
![Graphs](https://example.com/graph2.png)
Background summary so far ...

Backgrounds from $K_S$ decays:
$\Rightarrow K_S \rightarrow \pi_D^0\pi_D^0$ contributes 0.007 event in $\pm 2.5\sigma$ signal region

Backgrounds from $K_L$ decays:
$\Rightarrow K_L \rightarrow ee\gamma\gamma$ contributes 0.075 event in $\pm 2.5\sigma$ signal region

Backgrounds from $\Xi^0$ decays $\rightarrow$ additional cut:
Cut on momentum asymmetry in $\Xi^0$ and $\Lambda$ decay
$\Rightarrow$ Negligible contribution from $\Xi^0$ decays

Now consider backgrounds from overlapping fragments of two decays:

from different proton interactions
$p \rightarrow K_S \quad p \rightarrow K_L$
**Background from overlapping fragments of two decays**

Two p interactions accidentally close together in time look like one event: \( p_1 + \text{Be} \rightarrow K_S + X \) and \( p_2 + \text{Be} \rightarrow K_L + X \)

Rate measured using events with two fragments well separated in time

Control region: time between fragments \( \Delta t : 3 < \Delta t < 50 \text{ ns} \)

Signal region: \( \Delta t < 3 \text{ ns} \)

Extrapolate from out-of-time control region to in-time signal region
Background from overlapping fragments of two decays (cont’d)

Major component:

$$ee(\pi^{\pm}e^{\mp}\nu) + \gamma\gamma(\pi^0\pi^0(\pi^0))$$

confirmed by relaxing E/p and cτ
No events in $2.5\sigma$ signal region in $(3 < \Delta t < 50\text{ ns})$ time sidebands

Toy MC $\Rightarrow (m_K, m_{\pi^0})$ distribution of $(\pi^\pm e^\mp \nu) + (\pi^0 \pi^0 (\pi^0))$

Events in $6\sigma$ control region extrapolated into signal region using shape from toy MC

Linear extrapolation from $(3 < \Delta t < 50\text{ ns})$ time sidebands to $(\Delta t < 3\text{ ns})$ in-time signal region
**Total background**

Significant contributions to the background in the signal region:

<table>
<thead>
<tr>
<th>Source</th>
<th>control region</th>
<th>signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S \rightarrow \pi^0_D \pi^0_D$</td>
<td>0.03</td>
<td>0.007</td>
</tr>
<tr>
<td>$K_L \rightarrow e\bar{e}\gamma\gamma$</td>
<td>0.11</td>
<td>0.075</td>
</tr>
<tr>
<td>$(\pi^\pm e^\mp \nu) + (\pi^0 \pi^0 (\pi^0))$</td>
<td>0.19</td>
<td>0.069</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td>$0.33^{+0.18}_{-0.11}$</td>
<td>$0.15^{+0.05}_{-0.04}$</td>
</tr>
</tbody>
</table>
Toward opening the box ...
Unmasking the control region
Finally we can open the box!

7 events found in the signal region:
Negligible probability that all 7 events are consistent with background ($\sim 10^{-10}$)

→ presence of signal well established

No events found in equivalent same sign distributions
The box is open!

<table>
<thead>
<tr>
<th></th>
<th>control region</th>
<th>signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Total background</td>
<td>$0.33^{+0.18}_{-0.11}$</td>
<td>$0.15^{+0.05}_{-0.04}$</td>
</tr>
</tbody>
</table>

Have checked that there is no accumulation of background close to the signal region by relaxing cuts:

- E/p  \hspace{1cm} 0.95 < E/p < 1.05 \rightarrow E/p > 0.85
- cτ  \hspace{1cm} 0 < \frac{cτ}{cτS} < 2.5 \rightarrow 0 < \frac{cτ}{cτS} < 5
- m_{ee}  \hspace{1cm} m_{ee} > 0.165\text{GeV} \rightarrow m_{ee} > 0.150\text{GeV}
- centre-of-gravity  \hspace{1cm} cog < 6\text{cm} \rightarrow cog < 10\text{cm}
- ASP cut  \hspace{1cm} reversed: try to select Ξ^0 decays
$K_S \rightarrow \pi^0 e^+ e^-$ events

1 background event seen $17\sigma_{m_K}$, $20\sigma_{m_{\gamma\gamma}}$ from the signal region

Monte Carlo mass distribution : solid line
$K_S \rightarrow \pi^0 e^+ e^-$ events (cont’d)
Branching ratio measurement - Acceptance

Model independent acceptance, $\alpha$:

$\alpha$ computed in bins of $m_{ee}$

take weighted mean according to distribution of $7 \, K_S \rightarrow \pi^0 e^+ e^-$

events found

$\rightarrow \alpha(m_{ee} > 0.165 \text{GeV}) = 6.6\%$

Shape given by vector matrix element [JHEP 08 (1998) 004]
Branching ratio measurement - Flux

$K_S$ flux measured using $K_S \rightarrow \pi^0\pi^0_D$ decays:

- topologically similar to $K_S \rightarrow \pi^0 e^+e^-$ taken by the same trigger

Cross-checked using $K_S \rightarrow \pi^0\pi^0$ decays

→ Difference found between the two fluxes: 18.8%

Half the discrepancy is understood (common to $\pi^0 e^+e^-$, $\pi^0\pi_D^0$):

- inefficiencies due to the drift chamber read-out (at start of run)
- accidental losses

To account for the remaining unexplained difference (10%):

$K_S$ flux measured with $\pi^0\pi_D^0$ decays increased by 5%

systematic error of 5% assigned
Branching ratio measurement

7 events observed with a background 0.15 event

- Acceptance \((m_{ee}>0.165 \text{ GeV})= 6.6 \%\)
- Taking \(\pi^0\pi_D^0\) flux

Preliminary result :

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

Acceptance calculated using vector matrix element
(D’Ambrosio, Ecker, Isidori, Portoles [JHEP 08 (1998) 004])

Form factor: $w(z) = (1 + \frac{b}{a} z)$ where $z = m_{ee}^2/m_K^2$, and $b/a = 1.12$
(from fitting $K^+ \rightarrow \pi^+ e^+ e^-$ including the $\pi\pi$ loop [PRL 83 (1999) 4482])

Extrapolation to full acceptance done using $w(z) = 1$
Preliminary results

Measured branching ratio:

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

Extrapolating to all $m_{ee}$ (*) :

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(\text{stat}) \pm 0.3(\text{syst}) \pm 0.8(\text{theor})) \times 10^{-9}$$

$\chi$PT prediction: $BR(K_S \rightarrow \pi^0 e^+ e^-) = 5 \times 10^{-9} |a_s|^2$  →

Preliminary measurement of $|a_s|$:

$$|a_s| = 1.08^{+0.26}_{-0.21}$$

* Matrix element from [JHEP 08 (1998) 004] used with form factor $w(z) = 1$
Implications for $K_L \rightarrow \pi^0 e^+ e^-$

Measurement of $|a_s|$ allows $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-)$ to be predicted as a function of $\text{Im}(\lambda_t)$ to within a sign ambiguity:

$$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} = \left( 15.3a_s^2 \pm 6.8 \frac{\text{Im}(\lambda_t)}{10^{-4}} |a_s| + 2.8 \left( \frac{\text{Im}(\lambda_t)}{10^{-4}} \right)^2 \right) \times 10^{-12}$$

indirect interference direct

$$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} = (17.7 \pm 9.5 + 4.7) \times 10^{-12}$$

(Global fit $\Rightarrow$ $\text{Im}(\lambda_t) = (1.30 \pm 0.12) \times 10^{-4}$ Kettell, Landsberg, Nguyen [hep-ph/0212321])

$$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-)_{CP\text{\,cons}} = (0.47^{+0.22}_{-0.18}) \times 10^{-12}$$
Implications for $K_L \rightarrow \pi^0 e^+ e^-$ (cont’d)

$$\Rightarrow BR(K_L \rightarrow \pi^0 e^+ e^-) = 1 - 4 \times 10^{-11}$$
Conclusions

$4.2 \times 10^{10}$ $K_S$ decays collected in the fiducial region during 89 days

$7$ $K_S \rightarrow \pi^0 e^+ e^-$ decays found in region $m_{ee} > 0.165$ GeV with 0.15 event background

⇒ well established evidence for signal

Preliminary results:

Measured branching ratio:

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

Extrapolating to all $m_{ee}$:

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(\text{stat}) \pm 0.3(\text{syst}) \pm 0.8(\text{theor})) \times 10^{-9}$$

$$|a_s| = 1.08^{+0.26}_{-0.21}$$
Spares
Background from overlapping fragments of two decays (cont’d)

Two fragments from a single proton interaction → always close together in time

Resonances → $K+(K,\Lambda)$ e.g. $\phi(K_S K_L)$

Estimated number of $\phi$ by searching for $K_S(\pi^+\pi^-)K_L(\pi^0\pi^0\pi^0)$ events in 2002 data

- No evidence for in-time peak above accidental background → assumed all decays found in-time from a $\phi$ (upper limit)
- Computed background from all partially reconstructed $K_S+K_L$ decays modes

Also searched for in-time sources of $K_S+K_S$, $K_S+\Lambda$, $K_L+\Lambda$

Total contribution to background negligible
Checks

DATA $\pm E/p > 0.85$

$E/p +$
Checks (cont’d)

DATA +- 0 < $c\tau$ < 5

DATA +- reverse asymmetry cut
0.9 < $E/p$ < 1.1
$K_S \rightarrow \pi^0 e^+ e^-$ events (cont’d)
**NA48 and KTeV measurements of $K_L \rightarrow \pi^0\gamma\gamma$**

**NA48**: 
\[ \text{BR}(K_L \rightarrow \pi^0\gamma\gamma) = (1.36 \pm 0.05) \times 10^{-6} \text{ [PL B536 229]} \]
\[ \rightarrow a_V = -0.46 \pm 0.05 \]
\[ \rightarrow \text{BR}(K_L \rightarrow \pi^0 e^+ e^-)_{CP cons} = 0.47^{+0.22}_{-0.18} \times 10^{-12} \]

**KTeV**: 
\[ \text{BR}(K_L \rightarrow \pi^0\gamma\gamma) = (1.68 \pm 0.10) \times 10^{-6} \text{ [PL 83 917]} \]
\[ \rightarrow a_V = -0.72 \pm 0.08 \]
\[ \rightarrow \text{BR}(K_L \rightarrow \pi^0 e^+ e^-)_{CP cons} \sim 2 \times 10^{-12} \]
\( \pi^0 \) reconstruction

- Vertex position along beam line found by imposing the Kaon mass

\[
D = Z_{LKr} - Z_{decay} = \sqrt{\sum (E_i E_j \times r_{ij})^2} / M_K
\]

\( Z_{vtx} \) resolution \( \approx 50 \text{ cm} \)

\( \Rightarrow \) Correlation between \( Z_{vtx} \) and energy scale