Recent results on Rare Kaon Decays by the NA48 experiment at CERN

Edoardo Mazzucato
CEA-Saclay, DAPNIA/SPP

WIN’03 Workshop, Lake Geneva, WI, U.S.A.
October 6th - 11th, 2003

On behalf of the NA48 Collaboration:
Cagliari-Cambridge-CERN-Chicago-Dubna-Edinburgh-Ferrara-Firenze-Mainz-
Northwestern-Orsay-Perugia-Pisa-Saclay-Siegen-Torino-Vienna-Warsaw
NA48 Detector and Neutral Kaon Beam Lines

- $K_S \rightarrow \pi^0 e^+ e^-$
- $K_S \rightarrow \pi^0 \pi^0 \pi^0$
- $K_S \rightarrow \pi^0 \gamma \gamma$
- $K_S \rightarrow \gamma \gamma$
- $K_L,S \rightarrow \pi^+ \pi^- e^+ e^-$

Charged Kaon Decays

Summary and Outlook
The NA48 Detector

Two main components:

✦ Magnetic Spectrometer*

\[ \frac{\sigma_P}{P} \simeq 0.5\% \oplus 0.009\% P(\text{GeV/c}) \]

✦ LKr Electromagnetic Calorimeter

\[ \frac{\sigma_E}{E} \simeq \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\% \ (E \text{ in GeV}) \]

* unavailable in 2000

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The $K_L$ and $K_S$ beam lines

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Recent results on Rare Kaon Decays by the NA48 experiment at CERN (page 4)

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$K_S \rightarrow \pi^0 e^+ e^-$
A measurement of the $K_S \to \pi^0 e^+ e^-$ decay allows to improve SM predictions of the CP violating part of the $K_L \to \pi^0 e^+ e^-$ decay rate...

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

- **CP conserving**
  - dominated by the two-photon process $K_L \to \pi^0 \gamma^* \gamma^*$
  - can be obtained from the low $m_{\gamma \gamma}$ tail in $K_L \to \pi^0 \gamma \gamma$
  - **NA48**: $\text{BR}(K_L \to \pi^0 e^+ e^-)_{\text{CPC}} = 0.47^{+0.22}_{-0.18} \times 10^{-12}$

- **Direct CP violating**
  - probe of short-distance effects
  - amplitude proportional to $\text{Im}(\lambda_t) = \text{Im}(V_{ts}^* V_{td})$
  - expected $\text{BR}(K_L \to \pi^0 e^+ e^-)_{\text{CPVdir}} \approx 2 - 3 \times 10^{-12}$

- **Indirect CP violating**
  - $\text{BR}(K_L \to \pi^0 e^+ e^-)_{\text{CPVind}} = \frac{\tau_L}{\tau_S} |\varepsilon|^2 \text{BR}(K_S \to \pi^0 e^+ e^-)$
Interference between direct and indirect CP violation amplitudes in the $K_L \to \pi^0 e^+ e^-$ decay can give rise to sizeable effects...

✦ Theoretical predictions:

$$\text{BR}(K_L \to \pi^0 e^+ e^-)_{\text{CPV}} \times 10^{12} = 15.3 \ a_S^2 - 6.8 \left( \frac{\text{Im}(\lambda_t)}{10^{-4}} \right) a_S + 2.8 \left( \frac{\text{Im}(\lambda_t)}{10^{-4}} \right)^2$$
$$\text{BR}(K_S \to \pi^0 e^+ e^-) \times 10^9 = 5.2 \ a_S^2 \quad \text{with} \ a_S \sim O(1)$$


✦ Experimental published limits (@ 90% CL):

$$\text{BR}(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10} \quad \text{KTeV} \ [\text{PRL 86 (2001) 397}]$$
$$\text{BR}(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7} \quad \text{NA48} \ [\text{PLB 514 (2001) 253}]$$

NA48/1 measures both $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ modes (2002 data)...

Theory: \( \frac{\text{BR}(K_S \to \pi^0 \mu^+ \mu^-)}{\text{BR}(K_S \to \pi^0 e^+ e^-)} \simeq 0.23 \) in the VDM framework [AEIP]

* See also G. Buchalla, G. D’Ambrosio and G. Isidori, hep-ph/0308008 [BDI]
$K_S \rightarrow \pi^0 e^+ e^-$

2002 High Intensity $K_S$ run...

- $5 \times 10^{10}$ p/spill (@ 400 GeV/c)
- spill: 4.8 s every 16.2 s
- 4.2 mrad production angle
- $4 \times 10^{10}$ $K_S$ decays in 89 days
- modified $K_S$ target+collimator region
- LKr and DCH read-out upgraded
- 50 K events/spill
- 40 Tbytes data volume

Trigger efficiency $> 99\%$ measured with $K_S \rightarrow \pi^0 \pi^0_D$ reconstructed decays.
$K_S \rightarrow \pi^0 e^+ e^-$

**Event selection**
- Select candidates with $40 < E_K < 240$ GeV and $\tau < 2.5 \tau_S$ of final collimator
- 4 in-time clusters in LKr with 2 tracks forming one good $e^+e^-$ vertex
- Particle id.: $|E/P - 1| < 0.05$ and no signal in $\mu$VETO or HAC
- Energy COG at LKr $< 6$ cm from beam axis
- No extra in-time track or cluster
- $m_{ee\gamma\gamma}: m_K \pm 2.5 \sigma_{m_K}$ assuming $\gamma\gamma$ pair originates from charged vertex
- $m_{\gamma\gamma}: m_{\pi^0} \pm 2.5 \sigma_{m_{\pi^0}}$ assuming $\gamma\gamma$ pair originates from vertex imposing $m_K$
  \[ (\sigma_{m_K} = 4.6 \text{MeV/c}^2 \text{ and } \sigma_{m_{\pi^0}} = 1.0 \text{MeV/c}^2) \]

**Background sources:**
- $K_S \rightarrow \pi^0 \pi_D^0, \pi^0 \pi_D^0 + \text{conversion(s)}$, $\pi^0 \pi_D^0 \pi_D^0$, $\pi^0 \pi_D^0 (ee)$, $\pi_D^0 \pi_D^0$
- $K_L \rightarrow ee\gamma\gamma$, $ee\gamma + \text{bremsstrahlung}$, $\pi^0 \pi^+ \pi^-$, $\pi^0 \pi^0 \pm e^\pm \nu$
- $\Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0$, $\Lambda(p\nu)e^-\nu$, $\Sigma^+(p\pi^0)e^-\nu$
- **Accidental activity**: $\phi(K_SK_L)$, $K_L + K_S$ from different proton interactions

*Perform blind analysis ... Keep expected background level in signal region small!*

**Signal region**: $2.5 \sigma_{m_K} \times 2.5 \sigma_{m_{\pi^0}}$  
**Control region**: $6.0 \sigma_{m_K} \times 6.0 \sigma_{m_{\pi^0}}$
Reject huge $K_S \to \pi^0 \pi_0^0 (e^+e^-\gamma)$ background ($3 \times 10^8$ in $0 < \tau < 2.5\tau_S$):

- $d_{ee}^{DCH1} > 2$ cm to reject events with small $\theta_{ee}$
- $m_{ee} > .165$ GeV/c$^2$ (30 $\sigma_{m_{\pi_0}}$ above $m_{\pi_0}$)
Background from $K_S \rightarrow \pi^0\pi^0_D, \pi^0\pi^0_{DD}, \pi^0\pi^0(ee), \gamma$ conversions ...
\[ K_S \rightarrow \pi^0 e^+ e^- \]

Like-sign \( e^+ e^+ \) or \( e^- e^- \) pairs ...

No event observed in signal and control regions ...

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Background from $K_S \rightarrow \pi^0 \pi^0$ ...

Require $(m_{e\gamma}, m_{e\gamma}) > 0.165$ GeV/c$^2$ to reject low-energy $e^+, e^-$ escaping detection $\implies (m_{e\gamma}, m_{e\gamma}) \sim (m_{\pi^0}, m_{\pi^0})$ when $m_{ee\gamma} \sim m_K$

No event found in signal region from MC sample $\sim 30 \times 2002$ statistics (1 event in control region) ...
Background from $K_{L,S} \rightarrow e^+e^-\gamma\gamma$ ...

Estimated from $K_L \rightarrow e^+e^-\gamma\gamma$ decays with 2001 data
($\sim 10 \times 2002$ expected $e^+e^-\gamma\gamma$ statistics)

Background in the signal region: $0.08^{+0.03}_{-0.02}$ event ...
\[ K_S \rightarrow \pi^0 e^+ e^- \]

**Accidental activity ...**

Estimated from events in \((\Delta t = |t_{ee} - t_{\gamma\gamma}|)\) time sidebands

**Background in the signal region: \(0.07^{+0.07}_{-0.03}\) event ...**
Summary of the most significant background contributions ...

<table>
<thead>
<tr>
<th>Background source</th>
<th>Control region</th>
<th>Signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S \to \pi^0\pi^0_D$</td>
<td>0.03</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>$K_L \to ee\gamma\gamma$</td>
<td>0.11</td>
<td>0.08$^{+0.03}_{-0.02}$</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.19</td>
<td>0.07$^{+0.07}_{-0.03}$</td>
</tr>
<tr>
<td>Total</td>
<td>0.33</td>
<td>0.15$^{+0.10}_{-0.04}$</td>
</tr>
</tbody>
</table>

All other investigated sources of background were found to be negligible (e.g. $K_S \to \pi^0\pi^0_D$, $\Xi^0$ decays, $K_L \to \pi^+\pi^-\pi^0$, $\phi$ decays, etc.).

Control and signal regions remained masked until the study of the background was completed ...
Unmasking control and signal regions ...

7 events in signal region (bkg.=0.15) and 0 in control region (bkg.=0.33)

Probability that all 7 events are background is $\sim 10^{-10}$

$\Longrightarrow$ First observation of the decay $K_S \rightarrow \pi^0 e^+ e^-$
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$K_S \rightarrow \pi^0 e^+ e^-$

Decay amplitude from $\chi$PT model of AEIP (vector interaction + FF)

![Graph showing decay amplitude](Image)

$N_{\pi^0ee} = 6.85^{+3.8}_{-1.8}$ $K_S$ flux = $(3.51 \pm 0.17) \times 10^{10}$ (from $K_S \rightarrow \pi^0\pi^0_D$ decays)

Acceptance (no FF) = $(6.6 \pm 0.4)\%$

$\text{BR}(K_S \rightarrow \pi^0 e^+ e^-, m_{ee} > 0.165 \text{ GeV/c}^2) = (3.0^{+1.5}_{-1.2}\text{ stat} \pm 0.2\text{ syst}) \times 10^{-9}$

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

$\Rightarrow |a_S| = 1.06^{+0.26}_{-0.21}\text{ stat} \pm 0.07\text{ syst}$
Sensitivity of $BR(K_L \rightarrow \pi^0 e^+ e^-)$ to $\text{Im}(\lambda_t)$ ...

\[ BR(K_L \rightarrow \pi^0 e^+ e^-)_{\text{CPV}} \simeq (17.2_{\text{indirect}} \pm 9.4_{\text{interference}} + 4.7_{\text{direct}}) \times 10^{-12} \]

$\text{Im}(\lambda_t) = (1.30 \pm 0.12) \times 10^{-4}$  [S.H. Kettell, L.G. Landsberg and H. Nguyen, hep-ph/0212321]

If $a_S$ is negative then $BR(K_L \rightarrow \pi^0 e^+ e^-)$ retains some sensitivity to $\text{Im}(\lambda_t)$ through the interference term ...

\textit{A measurement of }$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-)$ \textit{by NA48/1 will come soon!}
$K_S \rightarrow \pi^0\pi^0\pi^0$
\[ K_S \rightarrow \pi^0 \pi^0 \pi^0 \]

\[ \eta_{000} = \frac{A(K_S \rightarrow \pi^0 \pi^0 \pi^0)}{A(K_L \rightarrow \pi^0 \pi^0 \pi^0)} \]

If CPT conserved: \[ \eta_{000} = \varepsilon + i \frac{\text{Im}(A_1)}{\text{Re}(A_1)} \]

- **2000 NEAR target data**
  - \( 5.9 \times 10^6 \) \( 3\pi^0 \) events

- **2000 FAR target data**
  - \( 1.3 \times 10^8 \) \( K_L \rightarrow 3\pi^0 \) decays
  - 1\textsuperscript{st} order accept. corr.

- **Monte Carlo**
  - 2\textsuperscript{nd} order accept. corr.

- **Analysis in energy bins**

\[ f(E, t) = \frac{I_{3\pi^0}^{\text{NEAR}}}{I_{3\pi^0}^{\text{FAR}}} = A(E)[1 + |\eta_{000}|^2 e^{(\Gamma_L - \Gamma_S) t} + 2D(E) (\text{Re}(\eta_{000}) \cos \Delta m t - \text{Im}(\eta_{000}) \sin \Delta m t) e^{\frac{1}{2} (\Gamma_L - \Gamma_S) t}] \]

Fit parameters \( A(E), \text{Re}(\eta_{000}), \text{Im}(\eta_{000}) \)

\( D(E): K^0 - \overline{K^0} \) dilution (from NA31)
\[ K_S \to \pi^0 \pi^0 \pi^0 \]

**Extract** Re(\(\eta_{000}\)) and Im(\(\eta_{000}\)) from a fit in energy bins:

\[(70 < E < 170 \text{ GeV})\]

\[
\text{Re}(\eta_{000}) = -0.026 \pm 0.010_{\text{stat}} \\
\text{Im}(\eta_{000}) = -0.034 \pm 0.010_{\text{stat}} \\
\rho = 0.78 \quad \chi^2/\text{ndf} = 415/405
\]

**Systematics:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Re((\eta_{000}))</th>
<th>Im((\eta_{000}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>± 0.003</td>
<td>± 0.003</td>
</tr>
<tr>
<td>Accid. activity</td>
<td>± 0.001</td>
<td>± 0.006</td>
</tr>
<tr>
<td>Energy scale</td>
<td>± 0.001</td>
<td>± 0.001</td>
</tr>
<tr>
<td>(K^0\bar{K}^0) dilution</td>
<td>± 0.003</td>
<td>± 0.004</td>
</tr>
<tr>
<td>Fit</td>
<td>± 0.001</td>
<td>± 0.002</td>
</tr>
<tr>
<td>Total</td>
<td>± 0.005</td>
<td>± 0.011</td>
</tr>
</tbody>
</table>

**NA48 Preliminary Result:**

\[
\text{Re}(\eta_{000}) = -0.026 \pm 0.010_{\text{stat}} \pm 0.005_{\text{syst}} \\
\text{Im}(\eta_{000}) = -0.034 \pm 0.010_{\text{stat}} \pm 0.011_{\text{syst}}
\]
$K_S \rightarrow \pi^0\pi^0\pi^0$

**NA48 Preliminary Results**

![Graph showing NA48 Preliminary Results](image_url)

- **CPLEAR (1998):**
  \[
  \text{Re}(\eta_{000}) = (18 \pm 14_{\text{stat}} \pm 6_{\text{syst}}) \times 10^{-2} \\
  \text{Im}(\eta_{000}) = (15 \pm 20_{\text{stat}} \pm 3_{\text{syst}}) \times 10^{-2} \\
  \text{Im}(\delta) = (2.4 \pm 5.0) \times 10^{-5}
  \]

- **SND (1999):**
  \[
  \text{BR}(K_S \rightarrow \pi^0\pi^0\pi^0) < 1.4 \times 10^{-5} \text{ 90\% CL}
  \]

- **CPT test (BS unitarity relation):**
  \[
  (1 + i \tan \phi_W) [\text{Re}(\varepsilon) - i \text{Im}(\delta)] = \sum_f \alpha_f
  \]

<table>
<thead>
<tr>
<th>$\alpha_f$</th>
<th>$10^3 \times \text{Re}(\alpha_f)$</th>
<th>$10^3 \times \text{Im}(\alpha_f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{+-}$</td>
<td>1.136±0.013</td>
<td>1.071±0.013</td>
</tr>
<tr>
<td>$\alpha_{00}$</td>
<td>0.517±0.010</td>
<td>0.486±0.010</td>
</tr>
<tr>
<td>$\alpha_{+-\gamma}$</td>
<td>0.003±0.001</td>
<td>0.003±0.000</td>
</tr>
<tr>
<td>$\alpha_{13}$</td>
<td>0.004±0.003</td>
<td>0.003±0.004</td>
</tr>
<tr>
<td>$\alpha_{+-\delta}$</td>
<td>0.000±0.002</td>
<td>0.000±0.004</td>
</tr>
<tr>
<td>$\alpha_{000}$</td>
<td>0.029±0.040</td>
<td>-0.026±0.058</td>
</tr>
</tbody>
</table>

- **NA48:**
  \[
  \text{Re}(\alpha_{000}) = (-0.009 \pm 0.004) \times 10^{-3} \\
  \text{Im}(\alpha_{000}) = (0.012 \pm 0.005) \times 10^{-3} \\
  \Longrightarrow \text{Im}(\delta) = (-1.2 \pm 3.0) \times 10^{-5}
  \]

- **If CPT is conserved in the decay:**
  \[
  m_{K^0} - m_{\bar{K}^0} = (-1.7 \pm 4.2) \times 10^{-19} \text{ GeV/c}^2
  \]
$K_S \rightarrow \pi^0 \gamma \gamma$
$K_S \rightarrow \pi^0 \gamma \gamma$

• $\chi PT$ predictions:
  - BR$(K_S \rightarrow \pi^0 \gamma \gamma)_{z>0.2} = 3.8 \times 10^{-8}$
  - total rate dominated by the $\pi^0$ pole
  - momentum dependent weak vertex

⇒ Chiral structure of the weak vertex can be tested from the shape of the $z = (m_{34}/m_K)^2$ distribution

• NA48/1:
  - 2000 NEAR target data
  - $K_S \rightarrow \pi^0 \pi^0$ decays as normalization

⇒ First observation of the $K_S \rightarrow \pi^0 \gamma \gamma$ decay
31 candidates observed in signal region

\[ |m_{12} - m_{\pi^0}| < 2 \text{ MeV}/c^2 \text{ and } z > 0.2 \]

### Background Events

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_L \rightarrow \pi^0\gamma\gamma )</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>( K_S \rightarrow \pi^0\pi_D^0 )</td>
<td>2.4 ± 1.2</td>
</tr>
<tr>
<td>Hadrons</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Accidentals</td>
<td>6.8 ± 2.9</td>
</tr>
<tr>
<td>( K_S \rightarrow \pi^0e^+e^- )</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13.7 ± 3.2</strong></td>
</tr>
</tbody>
</table>

**BR(\( K_S \rightarrow \pi^0\gamma\gamma \))_{z>0.2} = (4.9 \pm 1.6_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-8}**

**BR(\( K_S \rightarrow \pi^0\gamma\gamma \))_{z>0.2} = (4.9 \pm 1.8) \times 10^{-8}**

in agreement with \( \chi PT \) ... but more statistics needed to check the chiral structure of the weak vertex ...
\[ K_S \rightarrow \gamma\gamma \]
$K_S \rightarrow \gamma\gamma$

✧ $\chi$PT:

- Unambiguous and clean $O(p^4)$ prediction
- $\text{BR}(K_S \rightarrow \gamma\gamma) = 2.1 \times 10^{-6}$
  
  [G. D’Ambrosio and D. Espriu, PLB 175 (1986) 237]
  [J.L. Goity, ZPC 34 (1987) 341]

✧ NA48/1:

- 2000 NEAR target data (normalize to $K_S \rightarrow \pi^0\pi^0$ decays)
- Choose decays close to collimator exit to reject background from $K_S \rightarrow \pi^0\pi^0$ with only 2 showers in LKr calorimeter
  
  \[ \Rightarrow \text{Reconstructed vertex moves downstream due to missing energy} \]

- 2000 FAR target data to measure $\frac{\text{BR}(K_L \rightarrow \gamma\gamma)}{\text{BR}(K_L \rightarrow 3\pi^0)}$ and to estimate the irreducible $K_L \rightarrow \gamma\gamma$ background:

  \[
  \frac{\text{BR}(K_L \rightarrow \gamma\gamma)}{\text{BR}(K_L \rightarrow 3\pi^0)} = (2.81 \pm 0.01_{\text{stat}} \pm 0.02_{\text{syst}}) \times 10^{-3}
  \]
$K_S \rightarrow \gamma\gamma$

$$\text{BR}(K_S \rightarrow \gamma\gamma) = (2.78 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.02_{\text{norm}}) \times 10^{-6}$$

- **NA48/1 result:**
  $$\text{BR}(K_S \rightarrow \gamma\gamma) = (2.78 \pm 0.07) \times 10^{-6}$$

- **Much more precise than previous measurements:**
  - NA48 (1999): $(2.58 \pm 0.42) \times 10^{-6}$
  - NA31: $(2.4 \pm 0.9) \times 10^{-6}$

- **Decay rate larger by 30% w.r.t. $O(p^4)$ prediction of $\chi PT$**

$\Rightarrow$ **Indication of a large $O(p^6)$ contribution:**

$$\frac{8m_K^2}{p_\pi^2} \alpha_1 = 1.0 \pm 0.3 \ [\text{BDI}]$$

7461 ± 172 $K_S \rightarrow \gamma\gamma$ decays
\[ K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^- \]
\[ K_{L,S} \rightarrow \pi^+\pi^-e^+e^- \]

\[ \bullet \quad K_L \rightarrow \pi^+\pi^-e^+e^- \]

The interference between the dominant M1 (CP=-1) and IB (CP=+1) components gives rise to a large CP-violating asymmetry \( A_\phi \sim 14\% \) in the \( \phi \) distribution between the \( \pi^+\pi^- \) and \( e^+e^- \) planes in the kaon c.m.


\[ \bullet \quad K_S \rightarrow \pi^+\pi^-e^+e^- \]

Mainly due to IB ... no such asymmetry expected ...

1998+1999 NA48 data

\[ A_\phi = (14.2 \pm 3.0_{\text{stat}})\% \]

\[ \phi = \sin \psi \cos \varphi \]

\[ A_\phi = (0.5 \pm 4.0_{\text{stat}})\% \]

\[ \phi = \sin \psi \cos \varphi \]

\[ A_\phi \neq 0 \text{ is an unambiguous signature of CP violation} \]
$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$

**NA48 Final Results [EPJC 30 (2003) 33]**

- $K_S \rightarrow \pi^+ \pi^- e^+ e^-$ (1998+1999 data) 56+621 candidates

  \[ \text{BR}(K_S \rightarrow \pi^+ \pi^- e^+ e^-) = (4.69 \pm 0.30) \times 10^{-5} \]

  \[ \mathcal{A}_\phi^S = (-1.1 \pm 4.1) \% \]

  Measurements will be improved with the 2002 data: > 40k events

- $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ (1998+1999 data) 1162 candidates and S/B=31

  \[ \text{BR}(K_L \rightarrow \pi^+ \pi^- e^+ e^-) = (3.08 \pm 0.20) \times 10^{-7} \]

  \[ \mathcal{A}_\phi^L = (14.2 \pm 3.6) \% \]

  \[ \frac{\Gamma(K_L \rightarrow \pi^+ \pi^- e^+ e^-)^{\text{CPV}}}{\Gamma(K_L \rightarrow \pi^+ \pi^- e^+ e^-)^{\text{CP}}} = (0.833 \pm 0.066) \]

  Measurements in agreement with theoretical models based on a phenomenological description of radiative kaon decays

**M1 direct emission FF parameters:**

\[ \tilde{g}_{M1} = 0.99_{-0.27}^{+0.28} \text{ stat} \pm 0.07 \text{ syst} \]

\[ a_1/a_2 = (-0.81_{-0.13}^{+0.07} \text{ stat} \pm 0.02 \text{ syst}) \text{ GeV}^2 \]

**$K^0$ Charge Radius parameter:**

\[ g_P = 0.19 \pm 0.04 \text{ stat} \pm 0.02 \text{ syst} \]
Charged Kaon Decays
Charged Kaon Decays

Run 2003 (Jun-Sept): \( \sim 60 \) days of data-taking devoted to the study of \( K^\pm \) decays

- **Search for Direct CP violation through the asymmetry \( A_g \) in the Dalitz plot for \( K^\pm \to \pi^\pm \pi^+ \pi^- \)

\[
|M(u, v)|^2 \propto 1 + gu + hu^2 + kv^2
\]

\[
u = (s_3 - s_0) / m^2_{\pi} \quad v = (s_1 - s_2) / m^2_{\pi} \quad s_0 = (s_1 + s_2 + s_3) / 3
\]

\[
s_i = (P_K - P_i)^2 \quad (i=3 \text{ for the odd pion})
\]

\[
A_g = \frac{g^+ - g^-}{g^+ + g^-}
\]

If CP holds then \( g^+ = g^- \) and \( A_g = 0 \)

- **Current experimental value:** \( A_g = (-7 \pm 5) \times 10^{-3} \) \[Ford et al., 1970\]

Na48/2 aims at a precision of \( \sim 10^{-4} \) on \( A_g \)

- **Theoretical predictions for \( A_g \):** \( \mathcal{O}(10^{-6}) - \mathcal{O}(10^{-4}) \)

  e.g. NLO in \( \chi PT \): \( A_g = (-2.7 \pm 1.3) \times 10^{-5} \) \[E. Gámiz et al., hep-ph/0309172\]

  Some models beyond the SM can give \( A_g \sim \mathcal{O}(10^{-4}) \)

  \[G. D\'Ambrosio et al., PLB 480 (2000) 164\]

- **CP violation can also be investigated in \( K^\pm \to \pi^\pm \pi^0 \pi^0 \) or \( K^\pm \to \pi^\pm \pi^0 \gamma \) decays**
Charged Kaon Decays

✦ Measurement strategy
- use of simultaneous 60 GeV/c $K^+$ and $K^-$ beams ($\Delta P_{rms} : \pm 2.4 \text{ GeV/c}$)
- $7 \times 10^{11}$ p/spill on target $\Rightarrow$ 20 – 30 Mhz rate of $\pi^\pm , K^\pm , e^\pm , p$ ...
- focussed beams @ DCH1-DCH2 to minimize differential acceptance effects
- alternate magnet polarity of spectrometer (1/day)
- alternate $K^+/K^-$ beam positions in achromat (1/week)
  $\Rightarrow$ minimize sensitivity to beam and detector instabilities with time
- measure normalized ratio
  \[ R = \frac{N^+(u)}{N^-(u)} \approx 1 + A_g \cdot 2g u \]
- 80 Tbytes data volume and $\sim 1.25 \times 10^9$ reconstructed $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays
  $\Rightarrow \sigma(A_g) \sim 2.3 \times 10^{-4} \,(\text{stat})$

✦ Main systematics sources
- beam geometry ($K^+$ and $K^-$ beams coincide to better than 1 mm / 120 m)
- spectrometer mis-alignment (20-30 $\mu$m)
- drift chambers and trigger inefficiencies ($\sim 1 - 2\%$)
- backgrounds (small) and accidentals
- differential acceptance effects

  Systematic uncertainties must be kept $< 10^{-4}$
The $K^\pm$ beams

SIMULTANEOUS $K^+$ AND $K^-$ BEAMS

Target

0.36 mrad

$K^-$

$K^+$

TAX 17

TAX 18

Defining collimators

Protecitng collimator

KABES 1

KABES 2

KABES 3

Final collimator

Cleaning collimator

DF DF

Quadrupole Quadruplet

2nd ACHROMAT

Front-End Achromat

Edoardo Mazzucato
CEA-Saclay, DAPNIA/SPP

Recent results on Rare Kaon Decays
by the NA48 experiment at CERN (page 37)

October 6th - 11th, 2003
WIN'03 Workshop, Lake Geneva, WI, U.S.A.
Charged Kaon Decays

NA48/2 Trigger versatility and DAQ allows the study of many rare $K^\pm$ decays

✦ $K^{\pm}_{e4}$ ($K^{\pm}_{\mu4}$) decays
  - extract $\pi^+ \pi^-$ elastic scattering length $a_0^0$ with a precision of $< 0.01$
    \[ \Rightarrow \text{determine size of quark condensate} \langle 0|q\bar{q}|0 \rangle \sim F_\pi^2 \frac{m_q^2}{m_u + m_d} \]
  - expect $\sim 700 \text{k reconstructed } K^\pm_{e4} \text{ decays in 2003}$
  - electron id using E/P + NN technique (keep bkg $< 1\%$)
    BNL E865: $a_0^0 = 0.216 \pm 0.013_{\text{stat}} \pm 0.002_{\text{syst}} \pm 0.02_{\text{theor}}$ with 400 k events

✦ $K^\pm \rightarrow \pi^\pm e^+ e^-$ and $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$

- 4-5 k $K^\pm \rightarrow \pi^\pm e^+ e^-$ events
- BR and FF measurements
- Test of NLO $\chi PT$
Charged Kaon Decays

✦ Study of several other Kaon decays (test $\chi_{PT}$ predictions)

$$K^\pm \rightarrow \pi^\pm \pi^0 \gamma, \pi^\pm \pi^0 \gamma, \pi^\pm \pi^0 l^+l^-, l^\pm \nu l^+l^-, ...$$

✦ Beam Spectrometer (KABES)
- High-rate capability and high-resolution TPC based on micromegas-type chambers (50 $\mu$m amplification gap)
- provides accurate $P$, $t$ and $(X,Y)$ coordinates of incident beam particles
- tested up to 40 MHz
- gives useful kinematical constraints for decays with only 1 charged track
  or with neutrinos in the final state: e.g. $K_{e3}^\pm$, $K_{\mu3}^\pm$, $K_{\mu2}^\pm$, $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$, $...$ $K^\pm \rightarrow \pi^\pm \nu \bar{\nu}$!
- allows to recover $K^\pm \rightarrow \pi^\pm \pi^+\pi^-$ events when one pion escapes detection

✦ Dedicated $V_{us}$ run
- short run ($\sim 8$ hours) at reduced beam intensity (1/10)
- use highly efficient minimum bias 1 track trigger
- collect all important $K^\pm$ decay channels ($\sum BR_i \sim 1$):
  $$\mu\nu(\gamma), \pi^\pm \pi^0, \pi^\pm \pi^0 \pi^0, \pi^\pm \pi^+\pi^-, K_{e3}^\pm, K_{\mu3}^\pm, ...$$
- more than $100k$ $K_{e3}^\pm$ and $K_{\mu3}^\pm$ events

Aim to measure $BR(K_{e3}^\pm)$ and $BR(K_{\mu3}^\pm)$ to better than 1%
Micromegas Time Projection Chambers

- HT = -6 kV
- Ne/C2H6/CF4 (79%/11%/10%)
- .835 mm pitch
- ΔV = 1 kV in 1 cm
- Mesh Strip
- Mesh = -HT mesh
- 50 μm (60 to 70 kV/cm)

**Not to scale!**

Recent results on Rare Kaon Decays
by the NA48 experiment at CERN (page 40)
The KAon BEam Spectrometer
Tagging incident $K^\pm$ with $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays at 20 MHz

$$\sigma(X_{\text{BEAM}}) \approx \sigma(Y_{\text{BEAM}}) \sim 120 \mu m$$
KAon BEam Spectrometer

Tagging incident $K^\pm$ with $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays at 20 MHz

\[
\sigma(P_{\text{BEAM}})/P_{\text{BEAM}} < 1 \%
\]

效率: $\sim 100\%$

\[
\sigma(t_{\text{BEAM}}) < 1 \text{ ns}
\]

误标记概率: few\%
The use of high intensity $K_L$ and $K_S$ beams by the NA48 experiment has made possible the precise investigation of several rare kaon decays for tests of $CP$, $CPT$ asymmetries as well as $\chi PT$. The recent observation of 7 clean $K_S \rightarrow \pi^0 e^+e^-$ events allows to significantly improve the SM predictions for the golden $K_L \rightarrow \pi^0 e^+e^-$ mode. Additional information from the study of the $K_S \rightarrow \pi^0 \mu^+\mu^-$ channel will come very soon.

New results from the study of rare neutral kaon decays (e.g. $K_L \rightarrow e^+e^-\gamma$, $K_{e3}^0$, $K_{e4}^0$, $K_L \rightarrow \pi^0\pi^0\gamma$, etc.) and from the radiative and semileptonic $\Xi^0$ decays will also be available soon.

The 2003 run, dedicated to the high-precision investigation of charged kaon decays, has been successfully completed. More than $10^9 K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ decays have been collected for a measurement of the CP-violation $A_g$ asymmetry with a precision of a few $10^{-4}$. Several other rare charged kaon decays are also investigated. Additional beam time to run in 2004 at CERN is being requested.