The $K^\pm \rightarrow \pi^\pm \pi^0e^+e^-$ decay: First observation and study with the NA48/2 experiment at CERN

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on behalf of the NA48/2 Collaboration
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- Kaon Physics at CERN
- The NA48/2 experiment at CERN
- The decay $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$
  - Motivation
  - Event selection and analysis
  - Branching ratio measurement
  - Kinematic space study
  - Asymmetry investigations
- Summary and perspectives
Kaon physics at CERN

**NA48**
- **Main goal**: Search for direct CPV
- Measurement of $\epsilon'/\epsilon$
- **Beams**: $K_L / K_S$

**NA48/1**
- **Main goal**: Rare $K_S$ decays and hyperon decays, CPV tests
- **Beam**: $K_S$

**NA48/2**
- **Main goal**: Search for direct CPV
- Charge asymmetry measurement
- **Beams**: $K^+ / K^-$

**NA62**
- **Main goal**: Rare kaon decays, measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- **Beam**: $K^+$

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The NA48/2 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of CP violation and rare decays in the kaon sector.

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

~ 120 participants, 15 institutions, 8 countries
NA48/2 – the Kaon beam

- 400 GeV proton beam on a beryllium target
- (60 ± 3) GeV Kaon momentum (~7x10^{11} ppp)
- Simultaneous, unseparated focused beams
- Similar acceptance for K^+ and K^- decays
- Flux ratio K^+/K^- = 1.8
- Data collected in 2003-2004, ~ 6 months
- ~ 2 x 10^{11} K^± decays in flight
NA48/2 – the detector

Main detector components

- Magnetic spectrometer (4 DCHs + dipole magnet)
  - 4 views: redundancy efficiency
  - $\frac{\sigma(p)}{p} = (1.02 \pm 0.044 \cdot p)\%$ (p in GeV/c)
- Hodoscope
  - fast trigger, precise time measurement (150 ps)
- Liquid Kryptron e.m. calorimeter
  - high granularity, quasi-homogeneous, 10 m$^3$ (~22 t), 1.27 m (27 $X_0$)
  - $\frac{\sigma(E)}{E} = (3.2/\sqrt{E} \pm 9.0/E \pm 0.42)\%$ (E in GeV)
- Hadron calorimeter, photon vetos, muon counters
First observation of the $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$ rare decay
Motivation

- Test of Chiral Perturbation Theory
- Long distance dominated decay, proceeds through virtual photon exchange $K^\pm \rightarrow \pi^\pm \pi^0 \gamma^* \rightarrow \pi^\pm \pi^0 e^+ e^-$
- The differential decay rate is described in terms of three components:
  - Inner Bremsstrahlung (IB), Direct Emission (DE (M,E)) and Interference
  - Never observed so far

H. Pichl, EPJ C20 (2001) 371
L. Cappiello, O. Catà, G. D’Ambrosio, EPJ C78 (2018) 265
Motivation

- Cappiello et al. predicted, on the basis of the NA48/2 measurement of the magnetic and electric terms involved in the $K^\pm \rightarrow \pi^\pm \pi^0\gamma$ decay, the BR of IB, DE and INT components of the $K^\pm \rightarrow \pi^\pm \pi^0 e^+e^-$ decay.

- A recent revised paper by the same authors re-evaluates the INT term, using more experimental results and fewer theoretical assumptions.

- The square amplitude of the decay, including the various contributions, can be written:
  \[ \sum_{\text{spins}} |M|^2 = \frac{2e^2}{q^4} \left[ \sum_{i=1}^{3} |F_i|^2 T_{ii} + 2Re \sum_{i<j} (F_i^* F_j) T_{ij} \right] \]

- Where $F_i$ are complex Form Factors and $T_{ij}$ are kinematic expressions which depend on the four-momenta of the decay products in the kaon rest frame.

- The FF’s that correspond to the electric part of DE make use of the ChPT counterterms $N_{E}^{(0,1,2)}$, whilst the one corresponding to the magnetic part of DE makes use of the counterterm $N_{M}^{(0)}$. 
Event signature: signal and normalization

**Signal:** $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \rightarrow \pi^\pm \gamma e^+ e^-$

- 3 charged tracks (2 “same sign” + 1 “opposite sign”), forming a vertex
- 2 photon clusters in LKr forming a $\pi^0$ pointing to the same decay vertex
- No PID from LKr, only kinematics $\rightarrow$ no LKr acceptance cuts on tracks

**Normalization:** $K^\pm \rightarrow \pi^\pm \pi^0_D \rightarrow \pi^\pm e^+ e^- \gamma$

- Very abundant: $\text{BR}(\pi^\pm \pi^0) = 22.66\%$ and $\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma}) = (1.188 \pm 0.035)\%$
- similar topology, only 1 photon
- similar cuts as for the signal
Event selection

- Assign electron mass to the «opposite-sign» track
- For both \((m_e, m_\pi)\) assignments to same-sign charged tracks, compute reconstructed masses \(M(\pi^0)\) and \(M(K^\pm)\) and apply cuts

\[
|M_{\pi^0} - M_{\pi^0}^{PDG}| < 15\ MeV/c^2
\]
\[
|M_{K^+} - M_{K^+}^{PDG}| < 45\ MeV/c^2
\]
\[
|M_{\pi^0} - 0.42\ M_{K^+} + 73.2\ MeV/c^2| < 6\ MeV/c^2
\]
Main backgrounds to signal: use specific cuts to suppress

\[ K_{3\pi D}(K^\pm \rightarrow \pi^\pm \pi^0 \pi_D^0) \quad 1 \gamma \text{ lost} \]

\[ K_{2\pi D}(K^\pm \rightarrow \pi^\pm \pi_D^0) \quad 1 \text{ extra } \gamma \]

\[ M^2(\pi^+\pi^0) > 0.12 \text{ GeV}^2 / c^4 \]

\[ M(e^+e^-\gamma) - M_{PDG}(\pi^0) > 7 \text{ MeV } / c^2 \]
$M_{ee}$ spectra

Data sample: $\sim 1.7 \times 10^{11}$ kaon decays ($K^+$ and $K^-$), collected in 2003-2004
Branching Ratio measurement

\[ BR(K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-) = \frac{N_S - N_{BS}}{N_N - N_{BN}} \cdot \frac{A_N}{A_S} \cdot \frac{\epsilon_N}{\epsilon_S} \cdot \frac{\Gamma(\pi^0)}{\Gamma(\pi^{0}_{\gamma\gamma})} \cdot BR(K^\pm \rightarrow \pi^\pm \pi^0) \]

<table>
<thead>
<tr>
<th>Signal</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidates (N_S)</td>
<td>4919</td>
</tr>
<tr>
<td>Background (N_{BS})</td>
<td>241 ± 21</td>
</tr>
<tr>
<td>Acceptance (A_S)</td>
<td>0.662 (1) %</td>
</tr>
<tr>
<td>L1 trigger eff. (S)</td>
<td>(99.729 ± 0.009)%</td>
</tr>
<tr>
<td>L2 trigger eff. (S)</td>
<td>(98.604 ± 0.021)%</td>
</tr>
<tr>
<td>Candidates (N_N)</td>
<td>16.3 x 10^6</td>
</tr>
<tr>
<td>Background (N_{BN})</td>
<td>17288 ± 159</td>
</tr>
<tr>
<td>Acceptance (A_N)</td>
<td>3.981(2) %</td>
</tr>
<tr>
<td>L1 trigger eff. (N)</td>
<td>(99.767 ± 0.003)%</td>
</tr>
<tr>
<td>L2 trigger eff. (N)</td>
<td>(98.495 ± 0.006)%</td>
</tr>
</tbody>
</table>

- \(A_S\) is the weighted average of IB, DE, INT acceptances using expected relative contributions to the total rate
- \(A_N\) is computed using the simulation of \(K^\pm \rightarrow \pi^\pm \pi^0\) (1) followed by the \(\pi^0\) decay according to (2)
- radiative correction to the signal taken into account using PHOTOS

### Uncertainties evaluation

Several sources of uncertainties have been considered:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta BR/BR \times 10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_s$</td>
<td>1.426</td>
</tr>
<tr>
<td>$N_{bs}$</td>
<td>0.416</td>
</tr>
<tr>
<td>$N_n$</td>
<td>0.025</td>
</tr>
<tr>
<td>$N_{bn}$</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>TOTAL STATISTICS</strong></td>
<td>1.486</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta BR/BR \times 10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_s$ (MC statistics)</td>
<td>0.171</td>
</tr>
<tr>
<td>$A_n$ (MC statistics)</td>
<td>0.051</td>
</tr>
<tr>
<td>$\varepsilon (L1_s \times L2_s)$ (MC statistics)</td>
<td>0.023</td>
</tr>
<tr>
<td>$\varepsilon (L1_n \times L2_n)$ (MC statistics)</td>
<td>0.007</td>
</tr>
<tr>
<td>Acceptance geometry control</td>
<td>0.083</td>
</tr>
<tr>
<td>Acceptance time variation control</td>
<td>0.064</td>
</tr>
<tr>
<td>Background control</td>
<td>0.280</td>
</tr>
<tr>
<td>Trigger efficiency (systematics)</td>
<td>0.400</td>
</tr>
<tr>
<td>Model dependence</td>
<td>0.285</td>
</tr>
<tr>
<td>Radiative effects</td>
<td>0.490</td>
</tr>
<tr>
<td><strong>TOTAL SYSTEMATICS</strong></td>
<td>0.777</td>
</tr>
</tbody>
</table>

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Branching ratio result

\[ BR(K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-) = (4.237 \pm 0.063_{\text{stat}} \pm 0.033_{\text{syst}} \pm 0.126_{\text{ext}}) \times 10^{-6} \]

✓ The statistical error is dominated by the signal statistics, the systematic error by the radiative effects and external error by the BR (\(\pi^0_D\)) uncertainty

✓ Result is in agreement with ChPT [EPJ C72 (2012), EPJ C 78 (2018) 265]

✓ Prediction for Inner Bremsstrahlung only
  ✓ BR(IB) = 4.183 \times 10^{-6}

✓ Prediction including Direct Emission and Interference
  ✓ BR(IB) = 4.229 \times 10^{-6}

First observation!

NEW

The contribution of the DE magnetic term (M) to the total decay rate cannot be quantified within the collected statistics.

In [Eur. Phys. J. C 72 (2012) 1872, Eur. Phys. J. C 78 (2018) 265] the authors pointed out that the contributions of IB, M, and IB-E terms have different distributions in the Dalitz plot \((T_{\pi}^*, E_{\gamma}^*)\) for different ranges of \(q^2\) values \((T_{\pi}^*, E_{\gamma}^*\) and \(q^2\) are the charged pion kinetic energy, the virtual photon energy in the kaon rest frame, and the e\(^+\)e\(^-\) mass squared, respectively).

A detailed study of the kinematic space has been performed.

- **3d-boxes in the kinematic space** \((q^2, T_{\pi}^*, E_{\gamma}^*)\) are used to determine the relative fraction of each component.
- The data 3d-space is split first into \(N_1\) slices along \(q^2\), then into \(N_2\) slices along \(T_{\pi}^*\), and finally, into \(N_3\) \(E_{\gamma}^*\) slices.
- \(N_1 \times N_2 \times N_3\) exclusive boxes of variable size, but equal population, are formed.
To obtain the fractions \((M)/IB\) and \((IB-E)/IB\) reproducing the data, a \(\chi^2\) estimator is minimized:

\[
\chi^2 = \sum_{i=1}^{N1 \times N2 \times N3} \frac{(N_i - M_i)/\delta N_i^2 + \delta M_i^2}{\delta N_i} \]

where \(N_i (\delta N_i)\) is the data population (error) and \(M_i (\delta M_i)\) is the expected population (error) in box \(i\).

The expected number of events in box \(i\) is computed as \((N\) is a global scale factor):

\[
M_i = N \times (N_i^{IB} + a \cdot N_i^M + b \cdot N_i^{IB-E}) + N_i^{Bkg}
\]

At the end of minimization, the obtained values of \(a\) and \(b\) can be related to the relative contributions \((M)/IB\) and \((IB-E)/IB\).
The obtained values for the two fractions \( \frac{M}{IB} \) and \( \frac{(IB-E)}{IB} \) are consistent with the predicted value obtained using the experimental measurement of \( N_M^{(0)} \) and agree with the predicted value obtained using the experimental measurement of \( N_E^{(0,1,2)} \).

<table>
<thead>
<tr>
<th></th>
<th>DATA</th>
<th>THEORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M/IB )</td>
<td>( 0.0114 \pm 0.0043 )(^{\text{stat}})</td>
<td>( 0.0141 \pm 0.0014 )(^{\text{ext}})</td>
</tr>
<tr>
<td>( (IB-E)/IB )</td>
<td>( -0.0014 \pm 0.0036 )(^{\text{stat}})</td>
<td>( 0.0039 \pm 0.0028 )(^{\text{ext}})</td>
</tr>
</tbody>
</table>

\( \chi^2 \) 98.2/87

Probability 19%

Correlation \( C(a,b) = 0.06 \)
The simplest CP-violating asymmetry is the charge asymmetry between $K^+$ and $K^-$ partial rates integrated over the whole phase space:

$$A_{CP} = \frac{\Gamma(K^+ \rightarrow \pi^+\pi^0e^+e^-) - \Gamma(K^- \rightarrow \pi^-\pi^0e^+e^-)}{\Gamma(K^+ \rightarrow \pi^+\pi^0e^+e^-) + \Gamma(K^- \rightarrow \pi^-\pi^0e^+e^-)}$$

The value of $A_{CP}$ can be related to the IB-E interference term.

The asymmetry is obtained from the statistically independent measurements of $K^+$ and $K^-$ Branching Ratios.

The value obtained, $A_{CP} = -0.0284 \pm 0.0155$ (the error is statistical only, as the systematic and external errors cancel in the ratio) is consistent with zero and is translated to a single-sided limit:

$$BR (K^+) = (4.151 \pm 0.078_{stat}) \times 10^{-6}$$
$$BR (K^-) = (4.394 \pm 0.108_{stat}) \times 10^{-6}$$

$$|A_{CP}| < 4.82 \times 10^{-2} \text{ at 90\% CL}$$
Other angular/charge asymmetries (defined in [EPJ C 72 (2012) 1872]) can be extracted selecting particular integration regions of the $\phi$ angular variable: $A_{CP}^{\phi^*}$ and $A_{CP}^{\bar{\phi}}$.

Both asymmetries are consistent with zero. The single-sided limits are

$$A_{CP}^{\phi^*} = 0.0119 \pm 0.0150_{\text{stat}}$$
$$|A_{CP}^{\phi^*}| < 3.11 \times 10^{-2} \text{ (90\% CL)}$$

$$A_{CP}^{\bar{\phi}} = 0.0058 \pm 0.0150_{\text{stat}}$$
$$|A_{CP}^{\bar{\phi}}| < 2.50 \times 10^{-2} \text{ (90\% CL)}$$

The long distance $P$-violating asymmetry $A_{p}^{(L)}$ also has been found to be consistent with zero.
Summary and perspectives

- The decay $K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-$ has been observed for the first time
- Using 4919 signal events, with 4.9% background, the Branching Ratio has been measured
  \[ BR(K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-) = (4.237 \pm 0.063_{\text{stat}} \pm 0.033_{\text{syst}} \pm 0.126_{\text{ext}}) \times 10^{-6} \]
- The result is in agreement with the ChPT prediction
- The relative contributions, $(M)/IB = (1.14 \pm 0.43_{\text{stat}}) \times 10^{-2}$ and $(IB-E)/IB = (-0.14 \pm 0.36_{\text{stat}}) \times 10^{-2}$, are also found consistent with the theoretical expectation
- Several CP-violating asymmetries and a long-distance P-violating asymmetry have been evaluated and found to be consistent with zero
- If larger data statistics becomes available (e.g. at the NA62 experiment), improved evaluation of DE term contribution can be achieved

NA48/2 still alive with new physics results!!
Thank you for your attention