First observation and Study of the \( K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \) decay with NA48/2 @ CERN

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on behalf of the NA48/2 Collaboration

KAON2019
11th International Conference on Kaon Physics
University of Perugia, Italy, September 10-13
Outline

- NA48/2 description of experimental setup & detector performances... any need to repeat it?
- ChPT and the $K^\pm \rightarrow \pi^\pm \pi^0 \, e^+ \, e^-$ decay mode
- Selection and backgrounds
- Branching Ratio
- ChPT contribution
- Asymmetries
- Summary/Prospects
The NA48/NA62 experiments at CERN-SPS

The NA48/2 collaboration:

- still analyzing > 15 years old valuable data!!
- ~100 physicists from 15 Institutes in 8 countries

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>(K_L + K_s)</td>
</tr>
<tr>
<td>1998</td>
<td>(K_L + K_s)</td>
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<tr>
<td>1999</td>
<td>(K_L + K_s)</td>
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<tr>
<td>2000</td>
<td>(K_L) only</td>
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<tr>
<td>2001</td>
<td>(K_L + K_s)</td>
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<tr>
<td>2002</td>
<td>(K_s/)hyperons</td>
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<tr>
<td>2003</td>
<td>(K^+ + K^-)</td>
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<tr>
<td>2004</td>
<td>Ag(CPV)</td>
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<tr>
<td>2007</td>
<td>(K^+ + K^-)</td>
</tr>
<tr>
<td>2008</td>
<td>(R_K + ) tests</td>
</tr>
<tr>
<td>2007</td>
<td>design &amp; construction</td>
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<tr>
<td>2012</td>
<td>technical run</td>
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<tr>
<td>2013</td>
<td>long shutdown</td>
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<tr>
<td>2014</td>
<td>commissioning</td>
</tr>
<tr>
<td>2018</td>
<td>data taking</td>
</tr>
</tbody>
</table>

September 10, 2019

KAON2019/B.Bloch-Devaux
The NA48/2 experimental setup; Kaon beam

2003 + 2004 run: ~ 6 months, ~ 2 $10^{11}$ K± decays in flight

Simultaneous $K^+$ and $K^-$ beams: large charge symmetrization of experimental conditions

Beams coincide within ~1mm all along the 114m decay volume flux ratio $K^+/K^-$ ~1.8
NA48/2 detector and performances

**LKr electromagnetic calorimeter:**
- quasi-homogenous and high granularity
- $\Delta E/E = (3.2/\sqrt{E} \pm 9.0/E \pm 0.42)/%$ (E in GeV)
  $\sigma_x = \sigma_y \approx 1.5 \text{ mm for } E=10 \text{ GeV}$
- Very good resolution for neutrals ($\pi^0 \rightarrow \gamma\gamma$)
  $\sigma (M_{\pi^0\pi^0}) = 1.4 \text{ MeV}/c^2$
- $E/p$ ratio can be used for $e/\pi$ separation

**Hodoscope for fast charged trigger**
precise time resolution $\sigma_t = 150 \text{ ps}$

**Magnetic spectrometer:**
- He tank to minimize multiple scattering
- 4 high-resolution DCH’s + dipole magnet
- $\Delta p/p = (1.02 \pm 0.044 \text{ p})/\%$ (p in GeV/c)
- Very good resolution for charged invariant masses: $\sigma (M_{3\pi^\pm}) = 1.7 \text{ MeV}/c^2$

Decay region expands over ~114m
Detector expands over ~50 m
Chiral Perturbation Theory and Kaon decays

• Kaon decays are a perfect laboratory to study ChPT (QCD at low energy)
  - see theory talks this week-
  $K^\pm \rightarrow \pi^\pm \pi^0 \gamma \gamma$, $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$, $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$, $K^\pm \rightarrow \pi^\pm \pi^0 \gamma \gamma \rightarrow \pi^\pm \pi^0 \gamma \gamma$ and many more.
  - see PLB 677 (2009), $\pi\mu\mu$ PLB 697 (2011), $\pi\gamma\gamma$ PLB730 (2014), $\pi\pi\gamma$ EPJC 68 (2010)

• What is so special about $\pi^\pm \pi^0 e^+ e^-$ decay?
  H. Pichl, EPJ C20 (2001) 371
  L. Cappiello, O. Catà, G. D’Ambrosio, EPJ C78 (2018) 265

$\frac{d^3\Gamma}{dE_\gamma^*dT_c dq^2} = \frac{d^3\Gamma_{IB}}{dE_\gamma^*dT_c dq^2} + \frac{d^3\Gamma_E}{dE_\gamma^*dT_c dq^2} + \frac{d^3\Gamma_M}{dE_\gamma^*dT_c dq^2} + \frac{d^3\Gamma_{int}}{dE_\gamma^*dT_c dq^2}$

• Never observed so far: can BR magnitude confirm ChPT predictions of DE contribution?

• If a fine analysis is possible:
  > sign of interference term (IB,E)
  > Magnetic term through (IB,M) interference
  > Charge asymmetry as direct CP violation
Event selection: signal and normalization

**Normalization:** \( \pi^\pm \pi^0_D = \pi^\pm e^+ e^- \gamma \)
- Final state: 3 charged tracks and 1 photon forming, with 2 opposite sign tracks, a \( \pi^0 \) pointing to the same decay vertex
- Closed kinematics: constraints on \( M_{\pi^0D}, M_K \)
- Very abundant: \( \text{BR}(\pi^\pi^0) \times \text{BR}(\pi^0D) \)
  \(20.67\% \times 1.174\% = 2.425 \times 10^{-3}\)

**Signal:** \( \pi^\pm \pi^0 e^+ e^- = \pi^\pm \gamma \gamma e^+ e^- \)
- Final state: 3 charged track and 2 photons forming a \( \pi^0 \) pointing to the same decay vertex. One more \( \gamma \) wrt norm mode
- Closed kinematics: constraints on \( M_{\pi^0}, M_K \)
- Subject to \( \text{BR}(\pi^0\gamma\gamma) = 98.823\% \)

**Same Trigger chain:**
L1: \( > 1 \) HOD quadrant (out of 16)
L2: DCH track based kinematics

**Photons:** \( E_{\text{LKr}} \) within \([3, 60 \text{ GeV}]\)

**Charged particles:** no PID, but use kinematic constraint to maximize geometrical acceptance
**Event selection: signal and normalization**

**Signal:** $\pi^\pm \gamma \gamma e^+ e^-$  
**Normalization:** $\pi^\pm e^+ e^- \gamma$

- Require 3 good quality tracks forming a vertex in the fiducial decay region
- + two good quality photon clusters
- + one good quality photon cluster

- Assign electron mass to the track with $Q$ opposite to vertex charge (K$^+$ or K$^-$)
- For both $(m_e, m_\pi)$ assignments to same-charge tracks, compute reconstructed $M_{\pi^0}$ and $M_K$ to be in a wide range and check kinematic correlation

\[
\begin{align*}
| M_{\pi^0} - M_{\text{PDG}} | &< 15 \text{ MeV/c}^2 \\
| M_K - M_{\text{PDG}} | &< 45 \text{ MeV/c}^2 \\
| M_{\pi^0} - 0.42 M_K + 73.2 \text{ MeV/c}^2 | &< 6 \text{ MeV/c}^2 \quad \text{(masses in MeV/c}^2) \\
\end{align*}
\]

> 99% in the band

96.5 % in the band
Backgrounds

Normalization:
• Semileptonic \( K_{l3D} = K_{e3D}, K_{\mu3D} \)
  \( \pi^0_D \) is correctly reconstructed \((e^+e^-\gamma)\)
  \( \pi \) mass assigned to the e or mu track

• Resulting fractions:
  \( N_{bn} \)/\( N_n = (0.106 \pm 0.001)\% \)
  \( K_{\mu3D} : 0.064\% \)
  \( K_{e3D} : 0.042\% \)

Signal:
• \( K_{\pi\pi^0\pi^0}D \) with one photon lost/merged: suppressed by \((M_{\pi\pi^0})^2 > 0.12\)
  \( \text{GeV}^2/c^4 \)
• \( K_{\pi\pi^0}D \) with an extra photon:
  suppressed by \(|M_{ee\gamma} - M_{\pi^0}| > 7 \text{ MeV}/c^2 \)

• Resulting fractions:
  \( N_{bs} \)/\( N_s = (4.9 \pm 0.4)\% \)
  \( K_{3\pi D} : 2.7\% \)
  \( K_{2\pi D} : 2.1\% \)
  \( K_{e3D} : 0.1\% \)

• Large simulated samples used to compute acceptances
• Contribution estimated from acceptances and BRs
Normalization : large very pure sample

Normalisation $K \pi \pi^0 D$ :
- $K \pi \pi^0$ generator code including 1 real photon emission - Gatti EPJ C 45 (2006)
- $\pi^0 D$ decays including 1 extra photon emission - Husek, Kampf, Novotny PRD 92 (2015)
- also $\pi^0 D$ decays including extra photon(s) emission - Photos Was et al CPC 79 (1994)

B/(S+B) = 0.106%
Include HKN ("Prague") rad cor.

Normalization candidates 16 316 690 (4 039)
Background 17 292 (159)
A (rad cor HKN) 3.981 (2) %
Signal : small clean sample

Signal $K \pi \pi^0 ee$: dominated by

- IB (99%), then DE (M) (1.39%) and INT(IB,E) (0.39% negative): independent generations (IB, M, INT(BE)) with different acceptances combined as $A_{eff}$ according to relative contributions
- Rad. cor. adding extra photon(s) emission using Photos

### \[ \text{rms} = 3.0 \text{ MeV/c}^2 \]

### \[ \text{rms} = 7.8 \text{ MeV/c}^2 \]

<table>
<thead>
<tr>
<th>Signal candidates</th>
<th>4919 (70)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>241 (20)</td>
</tr>
<tr>
<td>$A \ (\text{rad cor}) \ IB$</td>
<td>0.645(1) %</td>
</tr>
<tr>
<td>$A \ (\text{rad cor}) \ eff$</td>
<td>0.662(1) %</td>
</tr>
</tbody>
</table>

\[ \frac{B}{S+B} = 4.9\% \]

Include Photos rad cor
Branching ratio measurement ingredients

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta$BR/BR x $10^2$</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>Negl.</td>
</tr>
<tr>
<td>$A_s$ (MC stat)</td>
<td>0.171</td>
</tr>
<tr>
<td>$A_n$ (MC stat)</td>
<td>0.051</td>
</tr>
<tr>
<td>L1n x L2n (MC stat)</td>
<td>0.007</td>
</tr>
<tr>
<td>L1s x L2s (MC stat)</td>
<td>0.023</td>
</tr>
<tr>
<td>A (geometry control)</td>
<td>0.083</td>
</tr>
<tr>
<td>A (time variation)</td>
<td>0.064</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.400</td>
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<tr>
<td>Model dependence</td>
<td>0.285</td>
</tr>
<tr>
<td>Radiative effects</td>
<td>0.490</td>
</tr>
<tr>
<td>$BR_{\pi\pi}^0$</td>
<td>0.87</td>
</tr>
<tr>
<td>$BR_{\pi\pi^0D}/BR_{\pi\pi^0\gamma\gamma}$</td>
<td>2.946</td>
</tr>
</tbody>
</table>

Normalization candidates | 16 316 690 (4 039) |
Background                | 17 292 (159) |
A (rad cor HKN)           | 3.981 (2) % |
L1 efficiency             | 99.767(3) % |
L2 efficiency             | 98.495(6) % |

Signal candidates         | 4919 (70) |
Background                | 241 (20) |
A (rad cor) eff           | 0.662(1) % |
L1 efficiency             | 99.73(1) % |
L2 efficiency             | 98.60(2) % |

$\delta$BR/BR x $10^2$ stat 1.486
syst 0.777
external 2.971
Branching ratio measurement @ NA48/2

\[ BR = (4.237 \pm 0.063_{\text{stat}} \pm 0.033_{\text{syst}} \pm 0.126_{\text{ext}}) \times 10^{-6} = (4.237 \pm 0.145) \times 10^{-6} \]

Currently dominated by external error on BR(\(\pi^0D\))

In perfect agreement with ChPT calculations from EPJ C78 (2018), no Rad Cor, no Isospin breaking Cor

<table>
<thead>
<tr>
<th>IB only</th>
<th>IB +DE + INT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.183 \times 10^{-6}</td>
<td>4.229 \times 10^{-6}</td>
</tr>
</tbody>
</table>

Good data/MC agreement of the \(m_{ee}\) spectra over several orders of magnitude
Further studies

• Current BR measurement: \( \sim 3\% \) precision
• Expected relative contribution of DE(M) term : \( \sim 1\% \)
• Expected relative contribution of INT(BE) term : even smaller

No way to extract DE or INT contributions from the BR measurement BUT

• Cappiello et al suggested to look at \( m_{ee} \sim 50 \text{ MeV}/c^2 \) where IB,DE, INT contributions populate differently the \((E\gamma^*, T^*\pi)\) plane.
• Too few statistics, instead study the whole 3D-space \((q^2, E\gamma^*, T^*\pi)\) in a grid of 3D-boxes of equal data populations (N1 bands in \( q^2 \), then N2 bands in \( T^*\pi \), then N3 bands in \( E\gamma^* \))
• Distribute simulated events and background over the same grid as the data.
• Minimize a \( \chi^2 \) estimator to find \( a = \text{DE}/\text{IB}, b = \text{INT}/\text{IB} \) and \( N \) (overall norm)

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

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

In 3D-box \( i \):

\( N_i (\delta N_i) = \text{data events (error)} \)
\( M_i (\delta M_i) = \text{MC events (error)} \)
\( N_i^{\text{Bkg}} = \text{Bkg events} \)
3D-kinematic space study (N1=3, N2=5, N3=6)

Fit result: $\chi^2 = 98.2/87$, p-value = 19%

ChPT predictions

\[
\begin{align*}
M/IB & = 0.0114 \pm 0.0043_{\text{stat}} \\
BE/IB & = -0.0014 \pm 0.0036_{\text{stat}} \\
M/IB & = 0.0141 \pm 0.0014_{\text{ext}} \\
BE/IB & = -0.0039 \pm 0.0028_{\text{ext}}
\end{align*}
\]

Good agreement but limited precision!
What else? Asymmetries!

NA48/2 has accumulated $K^+$ and $K^-$ decays concurrently allowing asymmetry studies with reduced systematics. Measure BR($K^+$) and BR($K^-$) as independent quantities and evaluate:

\[
A_{CP} = \frac{\Gamma(\pi^+\pi^0e^+e^-) - \Gamma(\pi^-\pi^0e^+e^-)}{\Gamma(\pi^+\pi^0e^+e^-) + \Gamma(\pi^-\pi^0e^+e^-)}
\]

Statistics is even more limited as $K^+/K^- \sim 1.8$ at production target

\[
\begin{align*}
BR(K^+) &= (4.151 \pm 0.078_{\text{stat}}) \times 10^{-6} \\
BR(K^-) &= (4.394 \pm 0.108_{\text{stat}}) \times 10^{-6}
\end{align*}
\]

$A_{CP} = -0.0284 \pm 0.0155_{\text{stat}}$ or single-sided UL $|A_{CP}| < 1.98 \times 10^{-2}$ at 90% CL
Other CP Asymmetries

Partial integration in the angular space allows to build other asymmetries:

\[
\int_0^{2\pi} d\phi^* \equiv \left[ \int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{3\pi/2}^{2\pi} - \int_{3\pi/2}^{2\pi} \right] d\phi \text{ with } A_{CP}^{\phi^*} = \frac{\int_0^{2\pi} \frac{d\Gamma(K^-)}{d\phi} d\phi^*}{\int_0^{2\pi} \frac{d\Gamma(K^+K^-)}{d\phi} d\phi},
\]

\[
\int_0^{2\pi} d\tilde{\phi} \equiv \left[ \int_0^{\pi/2} + \int_{\pi/2}^{\pi} - \int_{3\pi/2}^{2\pi} - \int_{3\pi/2}^{2\pi} \right] d\phi \text{ with } A_{CP}^{\tilde{\phi}} = \frac{\int_0^{2\pi} \frac{d\Gamma(K^-)}{d\phi} d\tilde{\phi}}{\int_0^{2\pi} \frac{d\Gamma(K^+K^-)}{d\phi} d\phi}.
\]
Asymmetries

Computing BR for $K^+$ and $K^-$ in each $\Phi$ “sector” of the angular space:

$$A_{CP}^{(\Phi^*)} = -0.0119 \pm 0.0150_{\text{stat}} \quad A_{CP}^{(\Phi^\sim)} = 0.0058 \pm 0.0150_{\text{stat}}$$

Both are consistent with 0, giving single sided UL

$$|A_{CP}^{\phi}| < 1.9 \times 10^{-2} \text{ at } 90\% \text{ CL}$$

Another P-violating asymmetry can be defined for $K^+$, $K^-$ and combined if consistent

$$A_P^{(L)} = \frac{\int_0^{2\pi} d\Gamma \frac{d\phi^*}{d\phi}}{\int_0^{2\pi} d\Gamma \frac{d\phi}{d\phi}}$$

$K^+: A_P^{(L)} = 0.0059 \pm 0.0180$, $K^-: A_P^{(L)} = -0.0166 \pm 0.0237$, $K^\pm: A_P^{(L)} = -0.0023 \pm 0.0144$

$$|A_P^{(L)}| < 1.8 \times 10^{-2} \text{ at } 90\% \text{ CL.}$$
Summary and prospects

- NA48/2 has collected a clean sample of \( \sim 5000 \pi \pi^0 e^+ e^- \) decay candidates with less than 5% background: first observation leading to a 3% BR measurement in perfect agreement with ChPT predictions.
  - Small sample but rich source of information
- BR = \((4.24 \pm 0.07_{\text{exp}} \pm 0.13_{\text{ext}}) \times 10^{-6}\)
  - Total uncertainty dominated by external error
  - Experimental error dominated by signal statistics
  - Systematics could benefit from better consideration of radiative effects
- First evaluation of the M contribution \((1.1 \pm 0.4)\)%, in agreement with ChPT prediction
- Several asymmetries investigated with single-sided UL of \(\sim 2\% @ 90\% \text{ CL}\)

Discussion with theorists is most important for a correct and precise formulation of radiative and isospin breaking corrections

Prospects to collect more decays in the current NA62 run:
- Requiring 3 tracks + large electromagnetic energy incompatible with \(\pi \nu \nu\) trigger
- Parasitic 3-track trigger downscaled by a large factor: no way to collect more data than in 2003-2004 with this trigger \((1.74 \times 10^{11}\) charged kaon decays analyzed)
- Could be studied in Run 3 after LS2 (2021-2023) with a dedicated trigger and the caveat that geometrical acceptance is lower than @NA48/2
Spares
Background estimate

\[ N_{bn} = N_n \times A_{Kl3} / A_n \times BR(Kl3) / BR(K_{\pi\pi0}) \]

\[ A_{Kl3} \sim 10^{-4} , A_n \sim 4 \times 10^{-2} \]

\[ K_{3\pi D} : N_{bs} / N_n = 2 \times A_{K3\pi D} / A_n \times BR(K_{3\pi}) \times BR(\pi^0 \rightarrow \gamma\gamma) / BR(K_{\pi\pi0}), \]

\[ K_{2\pi D} : N_{bs} / N_n = A_{K2\pi D} / A_n. \]

\[ A_{K3\pi D} \sim 2 \times 10^{-6} , A_{K2\pi D} \sim 0.2 \times 10^{-6} \]
Acceptance

\[ A_{\text{eff}} = \frac{[A(\text{IB}) + 1/71 \ A(\text{DE}) - 1/253 \ A(\text{INT})]}{[1 + 1/71 - 1/253]} \]

INT(B-M) and INT(E-M) cancel in the angular integration
E term is order of magnitude smaller than M

\[ 1/71 = (M/IB) \quad \text{predicted using } N_{M}^{(0)} = +0.0285(14) \]
\[ -1/253 = (B-E/IB) \quad \text{predicted using } N_{E}^{(0)} = +0.0022(7) \text{ and "large" % } N_{E}^{(1,2) \text{ values}} \]
\[ N_{E}^{(1)} = -0.0167(13), N_{E}^{(2)} = +0.089(11), \quad L9 = 0.0069 \]

\( N_{M}^{(0)} \) comes from \( X_{M} = (254 \pm 6 \pm 6) \text{ GeV}^{-4} \)
\( N_{E}^{(0)} \) comes from \( X_{E} = ( -24 \pm 4 \pm 4) \text{ GeV}^{-4} \), both from EPJ C68

\[ A(\text{IB}) = (0.645 \pm 0.001)\% \]
\[ A(\text{DE}) = (1.723 \pm 0.003)\% \]
\[ A(\text{INT}>0) = (1.933 \pm 0.004)\% \]
\[ A(\text{INT}<0) = (1.805 \pm 0.005)\% \]
\[ A(\text{INT}) = (0.288 \pm 0.001)\% \quad (56\% \text{ INT}>0, 44\% \text{ INT}<0) \]

\[ A_{\text{eff}} = (0.662 \pm 0.001)\% \]
3D-space: IB, DE, INT populate differently the \((E_{\gamma*}, T^{*}\pi)\) plane

- BE contribution is <0 at low q^2 values.
- BE contribution changes sign with increasing q^2 values.
- BE contribution is >0 for large q^2 values.
Asymmetries

\[ A_{CP} \approx \sin \delta \sin \Phi_E \]
\[ A_{CP\Phi^*} \approx \cos \delta \sin \Phi_M \]
\[ A_{CP\Phi^*} \approx \cos \delta \sin \Phi \]
\[ A_P^{(L)} \approx N_M^{(0)} \sin \delta \]

\[ \delta = \delta_1^1 - \delta_0 \]

Strong phase of the $\pi\pi^0$ system
$\Phi_E$, $\Phi_M$, $\Phi$ CP violating phase