Precision Measurements of Kaon Radiative Decays at NA48

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*On behalf of the NA48 collaboration
• NA48/2 experiment @ CERN SPS

• Study of the $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay
  – Measurement of DE and INT term fractions
  – Measurement of DE assuming INT=0
  – Limit on CPV parameters ($A_N, A_W$)

• Measurement of the $K^\pm \rightarrow \pi^\pm \gamma \gamma$ (preliminary)

• Measurement of the $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$

• Conclusions
The NA48/NA62 experiment

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

**Final NA48 result:**
\[ \varepsilon'/\varepsilon = (14.7 \pm 2.2) \times 10^{-4} \]

**NA62 phase II measurement of the decay**
\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

(2008-2010 R&D & construction, 2011 start of data taking)
NA48/2 simultaneous $K^\pm$ beam

NA48-2 beams: simultaneous $K^+/K^-$, focused, high momentum, narrow band designed to precisely measure $K^\pm \rightarrow \pi^+\pi^\pm (\pi^0 \pi^0 \pi^\pm)$ Dalitz-plot density to search for direct CPV and tuned for $K_{e2}$ measurement.

- Simultaneous, unseparated, focused beams
- Flux ratio: $K^+/K^- \sim 1.8$
- Similar acceptance for $K^+$ and $K^-$ decays
- Large charge symmetrization of experimental conditions
**NA48 detector**

- **Magnetic spectrometer (4 DCHs)**
  - 4 views: redundancy ⇒ high efficiency;
  - \( \sigma_p/p = (1.0 \pm 0.044 \, p\% \) (\( p \) in GeV/c).

- **Hodoscope**
  - Fast trigger;
  - Precise time measurement \( (\sigma_t = 150 \, \text{ps}) \).

- **Liquid Krypton EM calorimeter (LKr)**
  - Quasi-homogeneous ionization chamber
  - 27 electromagnetic radiation lengths long active volume
  - Segmented transversally 13248 cells, 2x2 cm²
  - Energy resolution \( (E \) in GeV): 
    \[ \frac{\sigma_E}{E} = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\% \ (E \text{ in GeV/}) \]
  - \( \sigma_x = \sigma_y = 0.42/E^{\frac{1}{2}} + 0.6 \, \text{mm} \)

The NA48/NA62 experiment

Vacuum beam pipe:
non-decayed kaons

Resolution
0.9 MeV/c²

π⁺π⁰π⁰ inv. mass, GeV/c²

He filled tank, atmospheric pressure

Drift chamber 1

Vacuum volume upstream

Drift chamber 4
Anti counter 7

Helium tank

Drift chamber 3

Magnet

Drift chamber 2
Anti counter 6

Hadron calorimeter
Liquid krypton calorimeter

Muon veto system

Kaon Radiative Decays

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Unprecedented statistics in many channels

Two years of data taking (2003 and 2004)

Main purpose was to measure direct CP violation in charged kaon decays, through asymmetry in Dalitz plot distribution

New limits on CP violation in charged kaon decays

\[ A_g^{ch} = (-1.5 \pm 2.1) \times 10^{-4} \]
\[ A_g^0 = (1.8 \pm 1.8) \times 10^{-4} \]
$K^\pm \rightarrow \pi^\pm \pi^0\gamma$ rare decay

Theoretical framework and motivation

Differential rate

\[ \frac{\partial \Gamma \pm}{\partial W} = \frac{\partial \Gamma_{IB} \pm}{\partial W} \left[ 1 + 2 \cos(\pm \phi + \delta_1^\mp - \delta_0^\pm) m^2 \pi m_K^2 \right] \left| X_E \right| W^2 + m^4 \pi m_K^4 \left( \left| X_E \right|^2 + \left| X_M \right|^2 \right) W^4 \]

Lorentz invariant

\[ W^2 = \frac{(P_K^* \cdot P_\gamma^*) (P_\pi^* \cdot P_\gamma^*)}{(m_K m_\pi)^2} \]

DE can occur via electric and magnetic dipole transitions \( X_E \) and \( X_M \)

Inner Bremsstrahlung (IB)
- BR = \( (2.75 \pm 0.15) \times 10^{-4} \) PDG (55<T\( _\pi^* \)<90 MeV)

Direct Emission (DE)
- BR = \( (4.3 \pm 0.7) \times 10^{-6} \) PDG (55<T\( _\pi^* \)<90 MeV)

Interference (INT)
- not yet measured

Very different distributions!
Event reconstruction and signal region

- **NA48/2 measurement of** \( K^\pm \rightarrow \pi^\pm \pi^0 \gamma \) decay

  - Fit performed with both polynomial and likelihood techniques

  - **Simultaneous** \( K^+ \) and \( K^- \) beams: possibility to study CP violating effects

  - Background contribution <1% wrt DE, mainly from \( K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \)

  - Larger \( T^*_\pi \) region in the low energy part \( (0 < T^*_\pi < 80 \text{ MeV}) \) wrt previous experiments

  - W resolution better than \( 1 \times 10^{-2} \)

  - Order \( \% \) \( \gamma \) mistagging prob. for IB, DE and INT

\[ T^*_\pi : \text{kinetic energy of the Pion in the kaon cms} \]
Event reconstruction and signal region

- **NA48/2 measurement of** $K^\pm \to \pi^\pm \pi^0 \gamma$ **decay**

- **High statistics:**
  - more than 1 M reconstructed events (the full number is used for the CPV measurements)
  - after a cut on $W$ [0.2, 0.9] and on $E_\gamma$ (> 5GeV), still 600 k events left in the region $M_{K^\pm}$ ± 10 MeV for the measurement of DE and INT fraction
Fitting techniques and fit results

- **Extended Maximum Likelihood Fit**
  - *(main method)*
  - An algorithm assigns weights to MC **W** distributions of the 3 components to reproduce data
  
  \[ Data(i) = (1 - \alpha - \beta) \cdot IB(i) + \alpha \cdot DE(i) + \beta \cdot INT(i) \]

- This algorithm relies on the very different **W** distributions

---

**Final result (2003+2004 data):**

\[
\begin{align*}
\text{Frac}(DE)_{T^*\pi(0-80)\text{MeV}} &= \frac{BR(DE)}{BR(IB)} = (3.32 \pm 0.15_{\text{stat}} \pm 0.14_{\text{sys}}) \times 10^{-2} \\
\text{Frac}(INT)_{T^*\pi(0-80)\text{MeV}} &= \frac{BR(INT)}{BR(IB)} = (-2.35 \pm 0.35_{\text{stat}} \pm 0.39_{\text{sys}}) \times 10^{-2}
\end{align*}
\]

**Systematics**

<table>
<thead>
<tr>
<th></th>
<th>DE x $10^{-2}$</th>
<th>INT x $10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>&lt;0.10</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>L1 trigger</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>L2 trigger</td>
<td>--</td>
<td>0.30</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.09</td>
<td>0.21</td>
</tr>
<tr>
<td>Total</td>
<td>0.14</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Fitting techniques and fit results

- **Polynomial Fit**
  
  *(used as cross-check)*

  - Assumes same acceptance as a function of $W$ for IB, DE and INT
  - The ratio $W(\text{Data})/W(\text{MC}_{IB})$ is fitted with polynomial function:

    \[
    F = c \cdot (1 + aW^2 + bW^4)
    \]

**Final result (2003+2004 data):** *(cross-check)*

\[
\text{Frac(DE)}_{T^*\pi(0-80)\text{MeV}} = \frac{\text{BR(DE)}}{\text{BR(IB)}} = (3.19 \pm 0.16_{\text{stat}}) \times 10^{-2}
\]

\[
\text{Frac(INT)}_{T^*\pi(0-80)\text{MeV}} = \frac{\text{BR(INT)}}{\text{BR(IB)}} = (-2.21 \pm 0.41_{\text{stat}}) \times 10^{-2}
\]
Fit results

Final result (2003+2004): extended ML fit

\[
\text{Frac(}\text{DE})_{T^*\pi(0-80)\text{MeV}} = \frac{\text{BR(}\text{DE})}{\text{BR(}\text{IB})} = (3.32 \pm 0.15_{\text{stat}} \pm 0.14_{\text{sys}}) \times 10^{-2}
\]

\[
\text{Frac(}\text{INT})_{T^*\pi(0-80)\text{MeV}} = \frac{\text{BR(}\text{INT})}{\text{BR(}\text{IB})} = (-2.35 \pm 0.35_{\text{stat}} \pm 0.39_{\text{sys}}) \times 10^{-2}
\]

Final result (2003+2004): polynomial fit

\[
\text{Frac(}\text{DE})_{T^*\pi(0-80)\text{MeV}} = \frac{\text{BR(}\text{DE})}{\text{BR(}\text{IB})} = (3.19 \pm 0.16_{\text{stat}}) \times 10^{-2}
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\]

**K^+\rightarrow\pi^+\pi^0\gamma** – first extraction of X_E X_M

Under the following approximations:

\[\phi = 0 \text{ and } \cos(\delta_1 - \delta_0) = \cos(6.5^\circ) \sim 1\]

X_E and X_M can be extracted using the formulae:

\[
X_E = \frac{\text{Frac(}\text{INT})}{2 \cdot (0.105 \cdot m_K^2 m_\pi^2)}
\]

\[
X_M = \sqrt{\frac{\text{Frac(}\text{DE}) - m_K^4 m_\pi^4 | X_E |^2 2.27 \cdot 10^{-2}}{2.27 \cdot 10^{-2} \cdot m_K^4 m_\pi^4}}
\]

WZW reducible anomaly prediction for X_M \sim 270 \text{ GeV}^{-4}

**Magnetic and electric components**

\[X_E = (-24 \pm 4_{\text{stat}} \pm 4_{\text{sys}}) \text{ GeV}^{-4}\]

\[X_M = (254 \pm 11_{\text{stat}} \pm 11_{\text{sys}}) \text{ GeV}^{-4}\]

INT has never been observed before!
Fit to data with INT=0

In order to compare the NA48/2 results with those from previous measurements, the ML fit of the selected sample has been redone setting the interference term to zero, and the result for DE extrapolated to

$$55 < T < 90 \text{ MeV}.$$ 

In the figure you can see the ML fit residuals.

The $\chi^2$ demonstrates that the data distribution cannot be properly described without an interference term and that the DE-only fit is not appropriate for this data.
Comparison with previous experiments

The BR(DE) assuming INT=0 (T^* π^* = 55-90) MeV using polynomial fit technique

\[ \text{BR(DE)}_{T^*\pi(55-90)\text{MeV}} = (2.32 \pm 0.05_{\text{stat}} \pm 0.077_{\text{sys}}) \cdot 10^{-6} \]

\[ \text{PDG08}_{\text{avg}} = (4.3 \pm 0.7) \cdot 10^{-6} \]

Remember that the bad \( \chi^2 \) probab. of the polynomial fit: indicates that INT=0 is a wrong assumption.
Asymmetry in the total rate:

\[ A_N = \frac{N_+ - RN_-}{N_+ + RN_-} = (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{sys}}) \times 10^{-3} \]

where \( R = \frac{N_{\text{beam}}(K^+)/N_{\text{beam}}(K^-)}{K^+ \rightarrow \pi^+ \pi^0 \pi^0} \) from \( K^\pm \to \pi^\pm \pi^0 \pi^0 \) decay used as normalization.

\[ |A_N| < 1.5 \times 10^{-3} \ @ 90\% CL \]

First limit on \( \sin \Phi = -0.01 \pm 0.43 \); \( |\sin \Phi| < 0.56 @ 90\% CL \)

Asymmetry in the Dalitz plot:

\[ d\Gamma^\pm /dW = d\Gamma^\pm_{IB}/dW (1 + (a \pm e)W^2 + b W^4) \]

\[ A_W = e \int I_{\text{INT}} / I_{\text{IB}} = (-0.6 \pm 1.0_{\text{stat}}) \times 10^{-3} \]
$K^\pm \rightarrow \pi^\pm \gamma \gamma$  rare decays
In the Chiral Perturbation Theory framework the differential rate of the $K^\pm(p) \to \pi^\pm(p_3) \gamma(q_1) \gamma(q_2)$ process (no $\mathcal{O}(p^2)$ contribution) is:

$$\frac{\partial^2 \Gamma}{\partial y \partial z} = \frac{m_{K^\pm}}{(8\pi)^3} \cdot \left[ z^2 \cdot (|A + B|^2 + |C|^2) + \left( y^2 - \frac{1}{4} \lambda(1, z, r_\pi^2) \right)^2 \cdot (|B|^2 + |D|^2) \right]$$

$$y = \frac{p \cdot (q_1 - q_2)}{m_{K^\pm}^2} \quad z = \frac{(q_1 + q_2)^2}{m_{K^\pm}^2} = \frac{m_{\gamma\gamma}^2}{m_{K^\pm}^2}$$

- The leading contribution at $\mathcal{O}(p^4)$ is given by $A(z, \hat{c})$ (loops) which is responsible for a cusp at $m_{\gamma\gamma} = m_{2\pi}$
- $C$ (WZW) corresponds to $\sim 10\%$ of $A$ at $\mathcal{O}(p^4)$
- $B, D = 0$ at $\mathcal{O}(p^4)$


$\mathcal{O}(p^6)$ unitarity corrections can increase the BR by $30\div40\%$

$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ Decay: Theory

Both decay spectrum and rate strongly depend on the single $\hat{c}$ parameter ($\mathcal{O}(p)$)

$$\text{BR}(K^+ \rightarrow \pi^+\gamma\gamma) = (5.26 + 1.64 \cdot \hat{c} + 0.32 \cdot \hat{c}^2 + 0.49) \cdot 10^{-7} \geq 4 \cdot 10^{-7}$$

$m_{\gamma\gamma}$ spectrum

**cusp-like behaviour at $2\pi$ threshold**

unitarity corrections

NA48 Kaon Physics Rare Kaon Decays $K^{\pm} \rightarrow \pi^{\pm} \gamma\gamma$ C. Biino – BEACH 2010
1164 events found in 20% of NA48/2 data (~40 times previous world sample)

Main background: $K^\pm \to \pi^\pm \pi^0 \gamma$ (3.3%)

Main systematics from trigger efficiency determination

Data shape ($m_{\gamma\gamma}$) follows ChPT description ($MC \mathcal{O}(p^6)$ and $\hat{c}=2$ shown for qualitative comparison)

Our model dependent BR determination is:

$$BR(K^+ \to \pi^+ \gamma \gamma) = (1.07 \pm 0.04_{\text{stat}} \pm 0.08_{\text{syst}}) \cdot 10^{-6}$$

assuming $\mathcal{O}(p^6)$ and $\hat{c}=2$

Overtaken the previous result from E787 with 31 events candidates:

$$BR(K^+ \to \pi^+ \pi \gamma \gamma) = (1.10 \pm 0.32) \cdot 10^{-6}$$
\[ K^\pm \rightarrow \pi^\pm e^+e^- \gamma \] rare decays
K$^\pm \rightarrow \pi^\pm e^+e^- \gamma$ Decay Results

• 120 events candidates
• Background from $K^+ \rightarrow \pi^+ \pi_0^D \gamma$ (6.1%)
• BR computed in bins of $m_{ee\gamma}$
• no assumption on $m_{ee\gamma}$ (model independent measurement)
• Cut on $m_{ee\gamma} > 260$ MeV/c$^2$

\[ \sigma(p^6) \text{ ChPT prediction } \text{BR}(\pi^\pm e^+e^- \gamma) = (0.9 \pm 1.6) \cdot 10^{-8} \]

\[ [\text{Gabbiani, PRL D59, 094022}] \]

\[ \text{BR}(K^\pm \rightarrow \pi^\pm e^+e^- \gamma) = (1.19 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}) \cdot 10^{-8} \]
\[ K^\pm \rightarrow \pi^\pm e^+e^-\gamma \text{ shape analysis} \]

- Assuming ChPT $\mathcal{O}(p^4)$, the $\hat{c}$ value is

\[ \hat{c} = (0.90 \pm 0.45) \quad \chi^2/\text{ndf}=8.1/17; \text{prob}=96.4\% \]

extracted from $m_{ee\gamma}$ distribution

(1.2 $\sigma$ away from BNL E787 value in $K^+ \rightarrow \pi^+\gamma\gamma$ : $\hat{c} = 1.8 \pm 0.6$)

- From this, the model dependent ChPT BR is:

\[
\text{BR}(K^\pm \rightarrow \pi^\pm e^+e^-\gamma) = (1.29 \pm 0.13_{\exp} \pm 0.03_{\hat{c}}) \cdot 10^{-8}
\]


\[ [\text{Phys. Lett. B659 (2008), 493}] \]
Conclusions

**NA48-2 exp: $K^\pm \to \pi^\pm \pi^0 \gamma$**
- First measurement of DE and INT fraction for $K^\pm \to \pi^\pm \pi^0 \gamma$ decay
- Incompatibility of data with INT=0 hypothesis has been established
- Non vanishing interference has been observed for the first time
- Magnetic and electric part of DE have been separated:
  - $X_E = -24\pm4_{\text{stat}}\pm4_{\text{sys}}$ GeV$^{-4}$
  - $X_M = 254\pm6_{\text{stat}}\pm6_{\text{sys}}$ GeV$^{-4}$
- CPV parameter $A_N < 1.5 \cdot 10^{-3}$ in both rates and Dalitz plot

**NA48-2 exp: $K^\pm \to \pi^\pm \gamma \gamma$**
- First possibility for shape study
- Preliminary BR measurement at $O(p^6)$ and $\hat{c} = 2$:
  \[
  \text{BR}(K^\pm \to \pi^\pm \pi^0 \gamma \gamma) = (1.07 \pm 0.04_{\text{stat}} \pm 0.08_{\text{syst}}) \cdot 10^{-6}
  \]
- Model independent measurement and $\hat{c}$ extraction in preparation

**NA48-2 exp: $K^\pm \to \pi^\pm e^+ e^- \gamma$**
- First observation and measurement of BR and shape
  \[
  \text{BR}(K^\pm \to \pi^\pm e^+ e^- \gamma) = (1.19 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}) \cdot 10^{-8}
  \]
  \[
  \hat{c} = (0.90 \pm 0.45)
  \]
Spares
Mistagging self background to DE

Reconstructed IB events using a $\gamma$ from the $\pi^0$ look like DE!!!
Mistagging lead to overestimated DE

**NA48/2 mistag**

\[
\text{Mistag(IB)} = (0.52 \pm 0.06) \cdot 10^{-3}
\]
\[
\text{Mistag(DE)} = (0.48 \pm 0.23) \cdot 10^{-3}
\]
\[
\text{Mistag(INT)} = (0.49 \pm 0.24) \cdot 10^{-3}
\]
Previous results

Assumption INT=0 in all the DE measurement (55-90)MeV

No Interference and no CPV observed

• INT(E787) = (-0.4 ± 1.6)%

$T_{\pi}^*$ (55-90) MeV

### Results for BR(DE)$_{(55-90)\text{MeV}}$

<table>
<thead>
<tr>
<th></th>
<th>DE±err</th>
<th>stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>E787</td>
<td>(4.7±0.9)$\cdot 10^{-6}$</td>
<td>20K</td>
</tr>
<tr>
<td>E470</td>
<td>(3.8 ± 1)$\cdot 10^{-6}$</td>
<td>10K</td>
</tr>
<tr>
<td>ISTRA$^+$</td>
<td>(3.7 ± 4)$\cdot 10^{-6}$</td>
<td>930</td>
</tr>
<tr>
<td>PDG 08</td>
<td>(4.3±0.7)$\cdot 10^{-6}$</td>
<td>//</td>
</tr>
</tbody>
</table>
The NA48/NA62 experiment

Kaon Physics

LFV in Kl2 decays

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