Latest results on rare kaon decays from the NA48/2 experiment @ CERN

Natalia Molokanova
Joint Institute for Nuclear Research, Dubna, Russia
on behalf of the NA48/2 Collaboration
NA48/2 experiment

Study of the $K^+\rightarrow\pi^+\pi^0e^+e^-$ decay

$K_{13}$ form factors precision measurement

Conclusion
The NA48/2 experiment was designed primarily to search for direct CP violation in $K^\pm \rightarrow 3\pi$ decay modes.

Simultaneous $K^+$ and $K^-$ beams:
- large charge symmetrization of experimental conditions
- Beams coincide within $\sim 1$ mm all along the 114 m decay volume

Flux ratio: $K^+/K^- \approx 1.8$

2003+2004 ~ 6 months, $\sim 2 \cdot 10^{11}$ $K^\pm$ decays

$P_K$ spectra, $60\pm 3$ GeV/c
Main detector components:

- Magnetic spectrometer (4 DCHs): 4 views/DCH inside a He tank
  $\Delta p/p = 1.02\% \oplus 0.044\% \times p$
  [$p$ in GeV/c].

- Hodoscope
  fast trigger;
  precise time measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogenous
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$
  $\sigma_x=\sigma_y=0.42/E^{1/2} \oplus 0.06$ cm
  [$E$ in GeV].
  (0.15 cm@ 10GeV)

- Hadron calorimeter, muon veto counters, photon vetoes

Detailed descriptions of the NA48/2 beam line and detector can be found in
**Motivation:**

The radiative decay with virtual photon exchange, converted to $e^+e^-$, **never observed so far**, brings information on the FF through the M, E and interference terms IB-M, IB-E, E-M

Confirmation of BR magnitude ChPT predictions:

Signal: $\pi^\pm (\pi^0 \rightarrow \gamma \gamma) e^+ e^-$

Normalization: $\pi^\pm (\pi^0_D \rightarrow \gamma e^+ e^-)$

- 3 tracks in both cases, but one photon less in the normalization channel. Cut for trigger efficiency: no 3 track in one HOD quadrant.

- No PID from LKr $\Rightarrow$ no LKr acceptance cuts for tracks

- Assign electron mass to the track with a charge opposite to kaon charge

- For both other tracks using both $M(e)$ and $M(\pi^-)$ reconstruct $M(\pi^0)$ and $M(K^\pm)$

- $|M(\pi^0) - M_{PDG}| < 15 \text{ MeV}/c^2$;

- $|M(K^\pm) - M_{PDG}| < 45 \text{ MeV}/c^2$;

- $|M(\pi^0) - 0.42 M(K^\pm) + 72.3 \text{ MeV}/c^2| < 6 \text{ MeV}/c^2$
Signal mode

\[ \sigma(\pi^0_{\gamma\gamma}) \approx 2.7 \text{ MeV}/c^2 \]

Normalization mode:

\[ \sigma(\pi^0_{\gamma\gamma} \text{ ee}) \approx 6.1 \text{ MeV}/c^2 \]

The mass resolutions (Gaussian rms) are measured from data and agree with MC.
## Selected statistics of events

<table>
<thead>
<tr>
<th></th>
<th>$N_N$</th>
<th>$16.3 \cdot 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Candidates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>$N_{BN}$</td>
<td>$17288 \pm 159$</td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td>$A_N$</td>
<td>$3.981%$</td>
</tr>
<tr>
<td><strong>L1 eff.</strong></td>
<td>$\varepsilon_{L1S}$</td>
<td>$(99.767\pm0.003)%$</td>
</tr>
<tr>
<td><strong>L2 eff.</strong></td>
<td>$\varepsilon_{L2S}$</td>
<td>$(98.495\pm0.006)%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$N_S$</th>
<th>4919</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Candidates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>$N_{BS}$</td>
<td>$241 \pm 21$</td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td>$A_S$</td>
<td>$0.662%$</td>
</tr>
<tr>
<td><strong>L1 eff.</strong></td>
<td>$\varepsilon_{L1S}$</td>
<td>$(99.729\pm0.009)%$</td>
</tr>
<tr>
<td><strong>L2 eff.</strong></td>
<td>$\varepsilon_{L2S}$</td>
<td>$(98.604\pm0.021)%$</td>
</tr>
</tbody>
</table>
All background contributions are estimated from simulation.

<table>
<thead>
<tr>
<th>Decay</th>
<th>N</th>
<th>R, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normalization mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{\mu 3D}$</td>
<td>10437 ± 119</td>
<td></td>
</tr>
<tr>
<td>$K_{e 3D}$</td>
<td>6851 ± 106</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.106</td>
</tr>
<tr>
<td><strong>Signal mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{3\pi 0D}$</td>
<td>132 ± 8</td>
<td></td>
</tr>
<tr>
<td>$K_{2\pi 0D\gamma}$</td>
<td>102 ± 19</td>
<td></td>
</tr>
<tr>
<td>$K_{e 3D}$</td>
<td>7 ± 3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4.9 ± 0.4</td>
</tr>
</tbody>
</table>

$R$ — background to signal ratio
In perfect agreement with ChPT \cite{ref1, ref2}:

\[ \text{BR} = \text{BR}(\pi^\pm \pi^0) \times \text{BR}(\pi^0_D) \times \frac{(N_S - N_{BS})}{(N_N - N_{BN})} \times \frac{(A_N/A_S) \times (\varepsilon_{L1N} \varepsilon_{L2N})}{(\varepsilon_{L1S} \varepsilon_{L2S})} \]

### Source

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta \text{BR}/\text{BR} \times 100 )</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>( A_S )</td>
<td>0.171</td>
</tr>
<tr>
<td>( A_N )</td>
<td>0.051</td>
</tr>
<tr>
<td>( \varepsilon_{L1N} \varepsilon_{L2N} )</td>
<td>0.007</td>
</tr>
<tr>
<td>( \varepsilon_{L1S} \varepsilon_{L2S} )</td>
<td>0.023</td>
</tr>
<tr>
<td>A(geom control)</td>
<td>0.083</td>
</tr>
<tr>
<td>A(time var. control)</td>
<td>0.064</td>
</tr>
<tr>
<td>Trig. efficiency</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>Background control</td>
<td>0.280</td>
</tr>
</tbody>
</table>

### Final Result:

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

Error is dominated by external error of \( \text{BR}(\pi^0_D) \)

In perfect agreement with ChPT \cite{ref1, ref2}:

For IB only

\[ \text{BR(IB)} = 4.183 \cdot 10^{-6} \]

including all DE and INT terms

\[ \text{BR(IB, DE, INT)} = 4.229 \cdot 10^{-6} \]
Predictions for IB and full BR differ only by 1%. The BR measurement is not precise enough to extract information on the contributions. But some information can be extracted from the kinematic space distribution.


The population of 3d-boxes in the kinematic space ($q^2, T^*_\pi, E^*_\gamma$) is used to determine the relative fraction of each component. The 3d-space is split into N1 slices along $q^2$, N2 slices along $T^*_\pi$ and then into N3 $E^*_\gamma$ slices, all boxes with equal populations.

To obtain the fractions (M)/IB and (IB-E)/IB reproducing the data, a $\chi^2$ estimator is minimized:

$$\chi^2 = \sum_{i=1}^{N_1 \times N_2 \times N_3} (N_i - M_i)^2 / (\delta N_i^2 + \delta M_i^2)$$

where $N_i (\delta N_i)$ - data population (error), $M_i (\delta M_i)$ – expected from MC population (error) in box $i$. The expected number of events in box $i$ is

$$M_i = N \times (N_i^{IB} + a \cdot N_i^M + b \cdot N_i^{IB-E}) + N_i^{kg}$$

where $N$ is normalization factor.

The obtained values of $a$ and $b$ are the relative contributions to (M)/IB and (IB-E)/IB:

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>M/IB</td>
<td>0.0114 ± 0.0043 stat</td>
<td>1/71 = 0.0141 ± 0.0014 ext</td>
</tr>
<tr>
<td>(IB-E)/IB</td>
<td>-0.0014 ± 0.0036 stat</td>
<td>-1/253 = -0.0039 ± 0.0028 ext</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>98.2/87</td>
<td></td>
</tr>
<tr>
<td>probability</td>
<td>19%</td>
<td></td>
</tr>
<tr>
<td>Correlation C(a, b)</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>
The simplest CP-violating asymmetry is the charge asymmetry between $K^+$ and $K^-$ partial rates integrated over the whole phase space:

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

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

Leads to $A_{CP} = -0.0284 \pm 0.0155_{\text{stat}}$ with statistical error only. This value is translated to a single-sided limit: $|A_{CP}| < 4.82 \times 10^{-2}$ at 90% CL.

The $A_{CP}^{\phi^*}$ and $A_{CP}^{\tilde{\phi}}$ angular asymmetries are defined in [Eur. Phys. J. C 72 (2012) 1872]:

$A_{CP}^{\phi^*} = 0.0119 \pm 0.0150_{\text{stat}}$ and $A_{CP}^{\tilde{\phi}} = 0.0058 \pm 0.0150_{\text{stat}}$

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

$|A_{CP}^{\phi^*}| < 3.11 \times 10^{-2}$, $|A_{CP}^{\tilde{\phi}}| < 2.50 \times 10^{-2}$ at 90% CL.


$A_{p}^{(L)}(K^+) = 0.0059 \pm 0.0180_{\text{stat}}$ and $A_{p}^{(L)}(K^-) = -0.0166 \pm 0.0237_{\text{stat}}$

The combined value is

$A_{p}^{(L)}(K^\pm) = -0.0023 \pm 0.0144_{\text{stat}}$

The value can be translated into a single-sided upper limit:

$A_{p}^{(L)} < 2.07 \times 10^{-2}$ at 90% CL.
In absence of electromagnetic effects, the differential $K_{l3}$ decay rate is described as

$$d^2\Gamma(K_{l3})/(dE_l^* dE_\pi^*) \sim A_1|f_+(t)|^2 + A_2 f_+(t) f_-(t) + A_3 |f_-(t)|^2,$$

where

$E_l^*$ is charged lepton energy, $E_\pi^*$ is $\pi^0$ energy (both in the kaon rest frame)

t = $$(P_K - P_\pi)^2 = M_K^2 + M_\pi^2 - 2 M_K E_\pi - 4$ momentum transfer to the leptonic system

and $f_-(t) = (f_+(t) - f_0(t))(m_K^2 - m_\pi^2)/t$ (another formulation: $f_0$ is «scalar» and $f_+$ is «vector» FF)

The kinematic factors are

$$A_1 = M_K^2 (2 E_l E_\nu - M_K (E_\pi^\text{max} - E_\pi)) + M_l^2 ((E_\pi^\text{max} - E_\pi)/4 - E_\nu)$$

$$A_2 = M_l^2 (E_\nu - (E_\pi^\text{max} - E_\nu)/2)$$

$$A_3 = M_l^2 (E_\pi^\text{max} - E_\nu)/4$$

negligible for Ke3

where $E_\pi^\text{max} = (M_K^2 + M_\pi^2 - M_l^2)/(2 M_K)$

<table>
<thead>
<tr>
<th>FF Parameterization</th>
<th>$f_+(t, \text{parameters})$</th>
<th>$f_0(t, \text{parameters})$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Taylor expansion</strong></td>
<td>$1 + \lambda_+ t/m_\pi^2 + \frac{1}{2} \lambda''<em>+ \left(\frac{t}{m</em>\pi^2}\right)^2$</td>
<td>$1 + \lambda_0 \frac{1}{m_\pi^2}$</td>
</tr>
<tr>
<td><strong>Pole</strong></td>
<td>$\frac{M_\nu^2}{M_\nu^2 - t}$</td>
<td>$\frac{M_S^2}{M_S^2 - t}$</td>
</tr>
<tr>
<td><strong>Dispersion</strong></td>
<td>$\exp\left(\frac{\Lambda_+ + H(t)}{m_\pi^2 t}\right)$</td>
<td>$\exp\left(\frac{\ln C - G(t)}{m_K^2 - m_\pi^2 t}\right)$</td>
</tr>
</tbody>
</table>

Data: 3 days from the NA48/2 data taken in 2004 (@low intensity)

Trigger: 1 charged track (2 hodoscope hits) and $E_{\text{LKr}} > 10$ GeV

Registration:
- **1 track** (> 0 candidates): $P_e \geq 5$ GeV, $P_\mu \geq 10$ GeV, $R_{\text{MUV}} > 30$ cm, $|X_{\text{MUV}}, Y_{\text{MUV}}| < 115$ cm.
- **2 LKr clusters** (> 1 candidates): $E > 3$ GeV, distance to closest track > 15 cm.

Kaon momentum reconstruction

Neutrino is missing, beam geometry and average momentum $P_b$ are measured from $K_{3\pi}^\pm$

Two solutions of the quadratic equation for $P_K$

- Best $P_K$ solution = closest $P_{1,2}$ to the average beam momentum $P_b$ (measured from $3\pi^\pm$ decays for each run).
- Select: $-7.5$ GeV/c $< (P_K - P_b) < 7.5$ GeV/c
- For each event, separately for $K_{e3}$ and $K_{\pi3}$ selections, the combination with a minimum $\Delta P = |P_K - P_b|$ is the best candidate.
Vertex definition:

\[ X_v, Y_v = \text{impact point of reconstructed charged track at } Z_v = Z_{\pi^0} \text{ decay plane} \]
**$\pi^0$ selection:**

- A pair of clusters in-time (within ±5 ns) without any in-time extra clusters (to suppress BG)
- Distance between the clusters in a pair > 20 cm
- $E(\pi^0) > 15$ GeV (for the trigger efficiency)
- $Z$ of decay: from $2\gamma$ assuming $\pi^0$ mass («neutral Z»); $Z > 200$ cm downstream the last collimator
- DCH1 inner flunge cut for the both $\pi$

**Track selection and identification:**

- A good track in-time with the $\pi^0$ within 10 ns
- No extra good track within 8 ns (against showers)
- If $0.9 < \frac{E_{\text{LKr}}}{P_{\text{DCH}}} < 2.0$ it is $K_{e3}$ electron
- If $\frac{E_{\text{LKr}}}{P_{\text{DCH}}} < 0.9$ (for true muons it cuts nothing) and there is an associated signal in MUV it is a $K_{\mu3}$ muon

Loose $\frac{E_{\text{LKr}}}{P_{\text{DCH}}}$ cuts $\Rightarrow$ negligible related systematics.
A cut against $\pi^\pm \pi^0 \pi^0$:

- $|P_2 - P_1| < 60 \text{ GeV}$
  $\Leftrightarrow$
  $D = (P_2 - P_1)^2 / 2 < 900 \text{ (GeV/c)}^2$

[D is large when one pion is missing]

Against

$K^\pm \rightarrow \pi^\pm \pi^0 \& \pi^\pm \text{misidentification as } \mu$

$m(\pi^0 \pi^0) < 0.475 \text{ GeV/c}^2$

Against $K^\pm \rightarrow \pi^\pm \pi^0 \& \pi^\pm \rightarrow \mu^\pm \nu$

$m(\pi^0 \pi^0) < 0.6 \text{ GeV/c}^2 - P_t(\pi^0) / c$

$m(\mu^\pm \nu) > 0.16 \text{ GeV/c}^2$

(to exclude $\pi^+$ mass region)

* $P_t(\pi^0)$ – the $\pi^0$ transverse momentum component with respect to the beam axis
Specific $K_{e3}$ selection cuts

- $\nu$ transverse momentum with respect to beam axis $P_t \geq 0.03$ GeV/c
- against $K^\pm \rightarrow \pi^\pm \pi^0$ with $\pi^\pm$ misidentified as $e$ (when $E/P > 0.9$)

Common cuts

- Beam (transverse elliptic) variable $B < 11$
- $P_L(\nu)^2 = (E^\nu)^2/c^2 - (P_t^\nu)^2 > 0.0014$ GeV$^2$/c$^2$
  negative and zero regions are difficult to simulate exactly: sensitive to beam shape.
- $Z > -1600$ cm
  (Final collimator is at $Z = -1800$ cm)

$$B = \sqrt{\left(\frac{X_n - X_n^0(Z_n)}{\sigma_{X_n}(Z_n)}\right)^2 + \left(\frac{Y_n - Y_n^0(Z_n)}{\sigma_{Y_n}(Z_n)}\right)^2}$$

$X_n, Y_n, Z_n$ are the reconstructed neutral vertex coordinates, $X_n^0, Y_n^0, \sigma_{X_n}, \sigma_{Y_n}$ are the reconstructed beam central positions and widths (1-0.6 cm).
In order to extract form factors, the background-corrected Dalitz plots were fitted by reweighting of each MC event using variable form factor parameters.
Reconstructed lepton and pion energy distributions of the Dalitz plots for data after background subtraction and simulated samples corresponding to the fit results using the Taylor expansion model, along with their ratios Data/MC. Other parameterizations look very similar.

The fit results and systematic uncertainties were obtained (see *JHEP 1810 (2018) 150*):

- for $K_{e3}$ and for $K_{\mu3}$ separately
- for the combined $K_{l3}$ sample:
  
  joint fit minimizing $\chi^2(K_{e3}) + \chi^2(K_{\mu3})$ with a common set of fit parameters
## Results for the joint $K_{l3}$ ($K_{e3}+K_{\mu3}$) analysis

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\lambda_+^\prime$</th>
<th>$\lambda_+''$</th>
<th>$\lambda_0$</th>
<th>$m_V$</th>
<th>$m_S$</th>
<th>$\Lambda_+$</th>
<th>$\ln C$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central values</strong></td>
<td>24.24</td>
<td>1.67</td>
<td>14.47</td>
<td>884.4</td>
<td>1208.3</td>
<td>24.99</td>
<td>183.65</td>
</tr>
<tr>
<td><strong>Statistical error</strong></td>
<td>0.75</td>
<td>0.29</td>
<td>0.63</td>
<td>3.1</td>
<td>21.2</td>
<td>0.20</td>
<td>5.92</td>
</tr>
<tr>
<td>Diverging beam component</td>
<td>0.97</td>
<td>0.35</td>
<td>0.55</td>
<td>1.1</td>
<td><strong>32.2</strong></td>
<td>0.08</td>
<td><strong>9.43</strong></td>
</tr>
<tr>
<td>Kaon momentum spectrum</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.1</td>
<td>0.7</td>
<td>0.00</td>
<td>0.19</td>
</tr>
<tr>
<td>Kaon mean momentum</td>
<td>0.04</td>
<td>0.01</td>
<td>0.04</td>
<td>0.2</td>
<td>1.7</td>
<td>0.01</td>
<td>0.47</td>
</tr>
<tr>
<td>LKr energy scale</td>
<td>0.66</td>
<td>0.12</td>
<td>0.61</td>
<td><strong>4.9</strong></td>
<td>17.4</td>
<td>0.32</td>
<td>5.16</td>
</tr>
<tr>
<td>LKr non-linearity</td>
<td>0.20</td>
<td>0.01</td>
<td>0.55</td>
<td>3.1</td>
<td>19.6</td>
<td>0.20</td>
<td>5.77</td>
</tr>
<tr>
<td>Residual background</td>
<td>0.08</td>
<td>0.03</td>
<td>0.04</td>
<td>0.1</td>
<td>0.7</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>Electron identification</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.2</td>
<td>0.2</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Event pileup</td>
<td>0.23</td>
<td>0.08</td>
<td>0.08</td>
<td>0.4</td>
<td>0.2</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.23</td>
<td>0.07</td>
<td>0.03</td>
<td>0.7</td>
<td>4.3</td>
<td>0.05</td>
<td>1.11</td>
</tr>
<tr>
<td>Neutrino momentum resolution</td>
<td>0.16</td>
<td>0.04</td>
<td>0.04</td>
<td>0.9</td>
<td>3.3</td>
<td>0.06</td>
<td>0.88</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.29</td>
<td>0.13</td>
<td>0.20</td>
<td>1.1</td>
<td>9.9</td>
<td>0.07</td>
<td>2.82</td>
</tr>
<tr>
<td>Dalitz plot binning</td>
<td>0.05</td>
<td>0.04</td>
<td>0.06</td>
<td>0.9</td>
<td>1.1</td>
<td>0.06</td>
<td>0.29</td>
</tr>
<tr>
<td>Dalitz plot resolution</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.0</td>
<td>1.3</td>
<td>0.00</td>
<td>0.39</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.17</td>
<td>0.01</td>
<td><strong>0.57</strong></td>
<td>2.5</td>
<td>20.1</td>
<td>0.16</td>
<td>5.92</td>
</tr>
<tr>
<td><strong>Systematic error</strong></td>
<td>1.30</td>
<td>0.41</td>
<td>1.17</td>
<td>6.7</td>
<td>47.5</td>
<td>0.62</td>
<td>14.25</td>
</tr>
<tr>
<td><strong>Total error</strong></td>
<td>1.50</td>
<td>0.50</td>
<td>1.32</td>
<td>7.4</td>
<td>52.1</td>
<td>0.65</td>
<td>15.43</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>$-0.934$ ($\lambda_+^\prime/\lambda_+''$)</td>
<td>$0.118$ ($\lambda_+^\prime/\lambda_0$)</td>
<td>$0.091$ ($\lambda_+''/\lambda_0$)</td>
<td>0.374</td>
<td>0.354</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi^2$/NDF</td>
<td>979.6/1070</td>
<td>979.3/1071</td>
<td>979.7/1071</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Joint $K_{l3}$ results comparison for quadratic parameterization

$1\sigma$ ellipses (39.4% CL) rather than 68% for better visibility
The 4919 $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$ rare decay candidates with a 5% background contamination are first observed in the NA48/2 experiment. Branching ratio measured to be $(4.24 \pm 0.15) \times 10^{-6}$ is in good agreement with ChPT-based theoretical predictions. The relative contributions of $(M)/IB$ and $(IB-E)/IB$ are also in agreement with the theory. Several CP-violating asymmetries and a long-distance P-violating asymmetry have been evaluated and found to be consistent with zero.


$K_{l3}$ form factors measurement is performed by NA48/2 on the basis of 2004 run selected $4.4 \cdot 10^6$ ($K_{e3}$) and $2.3 \cdot 10^6$ ($K_{\mu3}$) events. Result is competitive with the other ones in $K_{\mu3}$ mode, and a smallest error in $K_{e3}$ has been reached, that gives us also the most precise combined $K_{l3}$ result.

Published in JHEP 1810 (2018) 150.
THANK YOU
FOR YOUR ATTENTION!
**K^±→π^±π^0 e^+ e^- decay**

**Motivation:**

The radiative decay with virtual photon exchange, converted to e^+e^-, **never observed so far**, brings information on the FF through the M, E and interference terms IB-M, IB-E, E-M

Confirmation of BR magnitude ChPT predictions:


If a detailed analysis possible (**G.D'Ambrosio**):

- Sign of interference term (IB,E)
- Magnetic term from (IB,M) interference
- Charge asymmetry — direct CPV
- ChPT predicted bump in M(e^+e^-) spectrum

**Diagram:**

- **IB**
- **DE(M,E)**
- **Magnet field**
- **HOD LKr**
- L1: HOD > 1 quadrant
- L2: track based kinematics

**Trigger**
## Background

<table>
<thead>
<tr>
<th>Decay</th>
<th>$r_e, 10^{-3}$</th>
<th>$r_μ, 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm \to π^\pm (π^0 \to 2γ)$</td>
<td>0.272</td>
<td>0.392</td>
</tr>
<tr>
<td>$K^\pm \to π^\pm 2(π^0 \to 2γ)$</td>
<td>0.287</td>
<td>2.192</td>
</tr>
<tr>
<td>$K^\pm \to π^\pm (π^0 \to e^+e^-γ)$</td>
<td>0.049</td>
<td>0.000</td>
</tr>
<tr>
<td>$K^\pm \to π^\pm γ(π^0 \to 2γ)$</td>
<td>0.004</td>
<td>0.044</td>
</tr>
<tr>
<td>$K^\pm \to π^0 μ^±ν(μ \to eν)$</td>
<td>0.004</td>
<td>0.000</td>
</tr>
</tbody>
</table>

$r_e$ — background to signal ratio in $K_{e3}$ data  
$r_μ$ — background to signal ratio in $K_{μ3}$ data  

BG contamination from $2π$ and $3π$: very small, $O(10^{-4} - 10^{-3})$  
BG contamination from other channels: negligible
Angular asymmetries definition


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

\[ A_{CP}^{\bar{\phi}} = \frac{\int_0^{2\pi} d\Gamma_{(K^+K^-)} d\bar{\phi}}{\int_0^{2\pi} d\Gamma_{(K^+K^-)} d\phi} \], \quad \text{where} \quad \int_0^{2\pi} d\bar{\phi} \equiv \left[ \int_0^{\pi/2} d\phi + \int_{\pi/2}^{\pi} d\phi - \int_{3\pi/2}^{2\pi} d\phi - \int_{3\pi/2}^{2\pi} d\phi \right] d\phi.

Defining sectors of the \( \phi \) space between 0 and 2\( \pi \) as \( \Phi_1 (0, \pi/2) \), \( \Phi_2 (\pi/2, \pi) \), \( \Phi_3 (\pi, 3\pi/2) \), \( \Phi_4 (3\pi/2, 2\pi) \), and combining them as statistically independent sector sums (\( \Phi_{13} = \Phi_1 + \Phi_3 \), \( \Phi_{24} = \Phi_2 + \Phi_4 \)), one can define the long-distance asymmetry as:

\[ A_P^{(L)} = \frac{\int_0^{2\pi} d\Gamma d\phi^*}{\int_0^{2\pi} d\Gamma d\phi} \frac{\Gamma(\Phi_{13}) - \Gamma(\Phi_{24})}{\Gamma} \]
K_{l3} events-weighting fit procedure

We use MC radiative decay generator of C.Gatti [Eur.Phys.J. C45 (2006) 417–420] provided by KLOE collaboration. It includes $f^0_+ = 1 + \lambda' + t/m^2$. Generator for $K_{e3}$ is corrected by weighting to conform to the «universal» part of radiative effects ($K_{\mu3}$ is OK) [Cirigliano et al. Eur.Phys. J. C 23 (2002) 121]. So we measure «effective» FF-s that absorb interplay between QED and low-energy QCD.

For each fit iteration, the model Dalitz plot is filled in with an MC simulated reconstructed center-of-mass pion and lepton energies. Each event is weighted by

$$w = \rho_0(E_\pi^{true}, E_l^{true}, FF_{fit}) / \rho_0(E_\pi^{true}, E_l^{true}, FF_{MC \, eneator}),$$

where $\rho_0$ is the non-radiative Dalitz density formula (for $K_{e3}$ an additional factor is applied to conform the universal correction).

MINUIT package is searching for the FF_{fit} parameters minimizing the standard $\chi^2$ value:

$$\chi^2 = \sum_{i,j} \frac{(D_{i,j} - MC_{i,j})^2}{(\delta D_{i,j})^2 + (\delta MC_{i,j})^2},$$

where $i,j$ means the Dalitz plot cell indices, $D_{i,j}$ is the background-corrected experimental data content of the cell, $MC_{i,j}$ is the weighted MC bin content, and $\delta D_{i,j}$, $\delta MC_{i,j}$ are the corresponding statistical errors. Background correction contribution also has some dependence on FF due to the signal acceptance sensitivity.

At least 20 data events per cell are required in the fit area, so $\chi^2$ works well.