Model independent measurement of the leptonic kaon decay $K^{\pm} \rightarrow \mu^\pm \nu_\mu e^+ e^-$ with the NA48/2 at CERN

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on behalf of the NA48/2 Collaboration

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The NA48/NA62 experiments @ CERN

NA62 is the latest from a long tradition of fixed-target Kaon experiments in the CERN North Area

NA62: currently ~ 200 collaborators, 29 institutions from 12 countries
Experimental apparatus

Beam parameters

- **Narrow K± momentum spread:** $P_K = 60$ GeV/c, $\delta P_K / P_K \sim 1\%$ (rms)
- **Nominal K± decay rate:** $\sim 100$ kHz
- **Main triggers:** 3-track vertex, $K^\pm \rightarrow \pi^+\pi^0\pi^0$
- **Simultaneous K+/K− beams**

Principal sub-detectors

- **Spectrometer (4 DCHs)**
  $\sigma_p / P = 0.480\% \oplus 0.009\%p$ (GeV/c)
- **Scintillator Hodoscope**
  Fast trigger, time measurements $\sigma_t \sim 200$ ps
- **LKr EM Calorimeter**
  High granularity
  $\sigma_E / E = 3.2\% / \sqrt{E}$ (GeV) $\oplus 9\% / E$ (GeV) $\oplus 0.42\%$
  $\sigma_x = \sigma_y = 4.2\text{ mm} / \sqrt{E}$ (GeV) $\oplus 0.6\text{ mm}$ (1.5 mm @ 10 GeV)
The process $K^\pm \rightarrow \mu^\pm \nu_\mu e^+e^-$: Theory

- **Bijnens et. al. (1993) - Nucl.Phys., B396:81–118**

<table>
<thead>
<tr>
<th></th>
<th>Tree Level</th>
<th>CHPT Form Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full phase space</td>
<td>$2.49\times10^{-5}$</td>
<td>$2.49\times10^{-5}$</td>
</tr>
<tr>
<td>$z \geq \left(140\text{MeV}/M_K\right)^2$</td>
<td>$4.98\times10^{-8}$</td>
<td>$8.51\times10^{-8}$</td>
</tr>
</tbody>
</table>

$z = \left(M_{e^+e^-}/M_K\right)^2$

- Full phase space dominated by tree level processes
- At large $z$ CHPT FF have significant contribution to the branching fraction ($\sim 40\%$)
- The theoretical prediction does not include Radiative Corrections

**Previous measurements of the $K \rightarrow \mu \nu_\mu e^+e^-$ branching fraction**

- $\text{Br} (z \geq \left(140\text{MeV}/M_K\right)^2) = (12.3 \pm 3.2)\times10^{-8}$ (Diamant-Berger et.al. `76)
- $\text{Br} (z \geq \left(145\text{MeV}/M_K\right)^2) = (7.06 \pm 0.31)\times10^{-8}$ (Poblaguev et.al. `02)
The process $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$: MC generator

Decay properties

- Lower part of the spectrum at $z < 0.08$ ($M_{ee} < 140 \text{ MeV}/c^2$) is fully dominated by Inner Bremsstrahlung (IB)
- $z$ distribution is most sensitive to CHPT FF contributions

Experimentally clean signature

- High $z$ region chosen is clean of decays containing $\pi^0 \rightarrow e^+ e^- \gamma$ (Dalitz decay) in the final state ($M_{\pi^0} = 135 \text{ MeV}/c^2$)

<table>
<thead>
<tr>
<th>Decays suppressed by phase space</th>
<th>Total branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 (\pi^0 \rightarrow e^+ e^- \gamma)$</td>
<td>$3.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \mu^\pm \nu_\mu \pi^0 (\pi^0 \rightarrow e^+ e^- \gamma)$</td>
<td>$5.8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Distributions from MC simulation at generator level – no selection criteria applied
Backgrounds: Wrong Sign selection

Special selection can be used to estimate background contribution from $K_{3\pi}$, $K_{e4}$ and $K_{3\pi0}$

The same as signal selection but with picking up the wrong sign electrons (two electrons with same sign $\mu^-e^+e^+$ or $\mu^+e^-e^-$)

Signal experimental signature:
- 3 charged tracks
- Missing $p_t$
- No missing mass
- Vertex charge $|Q| = 1$

$K^\pm \rightarrow \mu^\pm\nu_\mu e^+e^-$ (Signal)

$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ ($K_{3\pi0}$ Bkg)

$K^\pm \rightarrow \pi^-\pi^+e^+\nu_e$ ($K_{e4}$ Bkg)

$K^\pm \rightarrow \pi^-\pi^+\pi^-$ ($K_{3\pi}$ Bkg)

1\pi misid as electron
1\pi misid as muon

$K^\pm \rightarrow \mu^\pm\nu_\mu \pi^0 \rightarrow \pi^0 \gamma$
Backgrounds: $K^\pm \rightarrow \pi^\pm e^+e^-$

\[ K^\pm \rightarrow \mu^\pm \nu_\mu e^+e^- \text{ (Signal)} \]

\[ K^\pm \rightarrow e^+e^- (K_{\pi e e} Bkg) \]

Strategy to remove muons coming from $K_{\pi e e}$ followed by pion decay

- Look in the invariant mass $M_{\mu\nu}$ of the muon and the neutrino where a peak at $M_{\pi\pm}$ (140 MeV/$c^2$) has to be observed

- Study the resolution of the $M_{\mu\nu}$ distribution at $M_{\pi\pm}$ using signal MC
  \[-\sigma(M_{\mu\nu}) = 10 \text{ MeV} / c^2 \text{ (at } M_{\pi\pm})\]

- Put a cut $M_{\mu\nu} > 170 \text{ MeV} / c^2$

Effect

- Reduces signal acceptance by 11%

- Removes all $K_{\pi e e}$ background
1663 data events observed

Background contamination of 3 % (factor of 6 improvement wrt previous result)

Z distribution very sensitive to non-IB contributions

Shape matches the MC with CHPT FF contribution
Normalization channel

- Similarities with the signal channel signature (three-track process)
- Allows cancelling of systematic effects
- Huge statistics \( \sim 10^9 \) \( K_{3\pi} \) decays
- \( M_{\pi^\pm \pi^+ \pi^-} = (493.65 \pm 0.01) \) MeV/c\(^2\)
- \( \sigma(M_{3\pi}) = 1.7 \) MeV/c\(^2\)
## Error budget

<table>
<thead>
<tr>
<th>Uncertainty type</th>
<th>$\delta$BR/BR[$\times 10^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>2.54</td>
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<tr>
<td>Normalization channel statistics</td>
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<tr>
<td><strong>Total statistical</strong></td>
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<tr>
<td>Rad. corr.</td>
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<tr>
<td>Background statistics</td>
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<tr>
<td>Trigger efficiency</td>
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<tr>
<td>Background systematic</td>
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<td>Muon ID efficiency</td>
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<td>Acc signal statistics</td>
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<td>Electron ID uncertainty</td>
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<tr>
<td>Acc normalization statistics</td>
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<tr>
<td><strong>Total systematic</strong></td>
<td>1.15</td>
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<tr>
<td>External uncertainty ($\text{Br }K_{3\pi}$)</td>
<td>0.72</td>
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<tr>
<td><strong>Total uncertainty</strong></td>
<td>2.88</td>
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</tbody>
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Results

\[ Br(K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^- | M_{ee} \geq 140 MeV/c^2) = (7.84 \pm 0.21(stat.) \pm 0.08(syst.) \pm 0.06(ext.) \times 10^{-8} \]

Measurement is statistically dominated
Conclusions

- New branching fraction measurement has been performed using NA48/2 data and presented for the first time:
  \[ \text{BR}(K \rightarrow \mu \nu_\mu e^+e^- | z \geq (145\text{MeV}/M_K)^2) = (7.84 \pm 0.23)x10^{-8} \]
- Background contamination of 3.2% - more than factor of 6 lower than previous measurements
- Factor of 3 improved systematic uncertainty
- Radiative corrections included using PHOTOS
- Measurement is in agreement with predictions of Chiral Perturbation Theory