First measurement of the
$K^\pm \rightarrow \pi^0 \pi^0 \mu^\pm \nu (K^{00}_{\mu4})$ decay
with the NA48/2 experiment at CERN

R. Fantechi

CERN and INFN – Sezione di Pisa
on behalf of the NA48/2 Collaboration

The NA48/2 Collaboration
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Florence, Mainz,
Northwestern, Perugia, Pisa, Saclay, Siegen, Turin, Vienna

DIS 2022 – Santiago de Compostela
May 2\textsuperscript{nd}-6\textsuperscript{th}, 2022
Outline

• The NA48/2 beam and detector

• The measurement of $K^\pm \rightarrow \pi^0\pi^0\mu^\pm \nu$

• Prospects and conclusions
Kaons at CERN: NA48 and NA62

Kaon decay in flight experiments.
NA62: ~300 participants, ~30 institutes
\[ K^\pm \rightarrow \pi^0 \pi^0 \mu^\pm \nu \ (K^{00}_{\mu 4}) \]

The decay is characterized using the 5 Cabibbo-Maksymowicz variables:
\( S_\pi \) (dipion mass squared), \( S_l \) (dilepton mass squared) and the angles \( \theta_\pi \) (in the dipion frame), \( \theta_l \) (in the dilepton frame) and \( \phi \)

The amplitude depends on 4 form factors, named \( F, G, R, H \)

- With the two \( \pi^0 \) in s-wave, no dependence on \( \cos \theta_\pi, \phi \). Only \( F \) and \( R \) contribute
- Unlike \( K^{00}_{e 4} \), \( R \) plays some role due to the \( \mu \) mass
- Use the \( F(S_\pi, S_l) \) experimental parametrization from \( K^{00}_{e 4} \), according to lepton universality.
  - NA48/2 JHEP 08 (2014) 159
  - For \( R(S_\pi, S_l) \) use ChPT calculation
    - Bijnens, Colangelo, Gasser, Nucl.Phys.B 427(1194) 427
Current status

<table>
<thead>
<tr>
<th>$K_{l4}$ mode</th>
<th>BR $[10^{-5}]$</th>
<th>$N_{\text{cand}}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{e4}^{\pm}$</td>
<td>$4.26 \pm 0.04$</td>
<td>1108941</td>
<td>NA48/2 (2012)</td>
</tr>
<tr>
<td>$K_{e4}^{00}$</td>
<td>$2.55 \pm 0.04$</td>
<td>65210</td>
<td>NA48/2 (2014)</td>
</tr>
<tr>
<td>$K_{\mu4}^{\pm}$</td>
<td>$1.4 \pm 0.9$</td>
<td>7</td>
<td>Bisi et al. (1967)</td>
</tr>
<tr>
<td>$K_{\mu4}^{00}$</td>
<td>?</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

- **Goals:** first observation, ChPT test, check the presence of the R term, potential study of $\pi\pi$ rescattering effects in $F(S_{\pi})$.

- **Analysis challenge:** suppression of the huge background from $K^{\pm} \rightarrow \pi^{0}\pi^{0}\pi^{\pm} (\pi^{\pm} \rightarrow \mu^{\pm} \nu)$
The NA48/2 Beam

NA48/2 beam (2003-2004): simultaneous $K^+/K^-$

$N(K^+)/N(K^-) = 1.8$

$P_K = (60 \pm 3) \text{ GeV/c}$

$1.8 \times 10^{12}$ protons/spill

400 GeV/c

$114 \text{ m long decay volume}$

$2.5 \times 10^7 K/\text{spill}$

K decays in the vacuum tank: 22%

Beam size: 4x4 mm$^2$, 10x10 μm

R. Fantechi - DIS 2022 - May 3rd 2022
The NA48/2 Detector

**LKr Calorimeter:**
\[ \sigma(E)/E \approx 3.2%/\sqrt{E} \oplus 9%/E \oplus 0.42\% \]
\[ \sigma(x) = \sigma(y) \approx (4.2/\sqrt{E} \oplus 0.6) \text{mm} \approx 1.5\text{mm} @ 10 \text{ GeV} \]

**Spectrometer:**
\[ \sigma(P)/P \approx 1.02\% \oplus 0.044 \text{P[GeV/c]}\% \]

Scintillator hodoscope: fast trigger and good time resolution (150 ps)

Efficient trigger chain for 3-track vertices using the hodoscope multiplicity at L1 and drift chamber track reconstruction at L2
Event selection - Normalization

• The normalization channel is $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

• First set of common cuts for signal and normalization
  - First-order cancellations in BR computation
  - Triggered using HOD and LKr at L1, momentum calculation with DCH at L2
  - Event selection: 4 isolated photons consistent with $2\pi^0$ in time with a beam track and a DCH one

Normalization selection: ellipse cut
- Center: $M(K_{3\pi}) = M_K, \ P_t = 5 \text{ MeV/c}$
- Semi-axes: $\Delta M(K_{3\pi}) = 10 \text{ MeV/c}^2, \ \Delta P_t = 20 \text{ MeV/c}$
- Selection of $72.99 \times 10^6 \ K_{3\pi}$ events
Event selection - signal

- Events outside the $K_{3\pi}$ ellipse
- Association of the charged track with MUV response
- Define two invariant masses

\[
M_{\text{miss}}^2 = (P_K - P(\pi_1^0) - P(\pi_2^0) - P(\mu^\pm))^2
\]

\[
M_{\text{miss}}^2 (\pi^\pm) = (P_K - P(\pi_1^0) - P(\pi_2^0) - P(\pi^\pm))^2
\]

- Selection cut:  
  \[
  M_{\text{miss}}^2 (\pi^\pm) < 0.5 \cdot M_{\text{miss}}^2 - 0.0008 \frac{GeV^2}{c^4}
  \]
Event selection - signal

Cut on $\cos(\theta_l) < 0.6$
Event selection - signal

- Rejection of $\pi^+\rightarrow \mu^+\nu$ with a cut on $S_l = M(\mu^+\nu)^2$: $S_l > 0.03 \text{ GeV}^2/c^4$
- 3718 $K_{\mu4}$ candidates selected
- 2437 events in the $M_{\text{miss}}^2$ signal region $[-0.002,0.002] \text{ GeV}^2/c^4$
Acceptances

- $K^{00}_{\mu4}$ signal acceptance (full phase space)
  - $A_s = (0.651 \pm 0.001)\%$

- Restricted phase space ($S^\text{true}_l > 0.03 \text{ GeV}^2/\text{c}^4$)
  - $A_s = (3.453 \pm 0.007)\%$

- Normalization acceptance
  - $A_N = (4.477 \pm 0.002)\%$
Residual background

Coming from $K^\pm \rightarrow \pi^0\pi^0\pi^\pm$ with $\pi^\pm \rightarrow \mu^\pm\nu$ before the muon veto with a probability $\sim 10\%$ for $P(\pi^\pm) \sim 10$ GeV/c

Decay before the LKr calorimeter:

Estimation from MC

Late $\pi^\pm$ decay or muon emission in a late hadron shower:

Simulation not easy, use data with a background enhanced sample, selected with the ratio $E_{\text{LKr}}/P_{\text{DCH}}$
Signal extraction fit

2437 events in signal region

Background estimation with a fit for 
-0.003 < $M_{\text{miss}}^2$ < 0.006, ignoring the signal region

Fit with a combination of background and signal tails

354 $\pm$ 33_{stat} $\pm$ 62_{syst} background events

Systematics evaluated varying the way the background is estimated
Branching ratio evaluation

\[ BR(K^\pm \rightarrow \pi^0\pi^0\mu^\pm\nu) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{\text{trig}} \cdot BR(K^{00}_{3\pi}) \]

- \( N_S = \text{candidates-background: } 2437-(354\pm33_{\text{stat}}) = 2083\pm59_{\text{stat}} \)
- Normalization \( N_N = 72.99\times10^6 \)
- Normalization acceptance \( A_N = (4.477\pm0.002)\% \)
- Acceptance for the restricted phase space \( A_{rS} = (3.453\pm0.007)\% \)
- Acceptance for the full phase space \( A_S = (0.651\pm0.001)\% \)
- Trigger correction (from control triggers)
  - \( K_{\text{trig}} = K_{\text{CHT}} \times K_{\text{NUT}} = (0.998\pm0.002) \times (1.0007\pm0.0007) = 0.999\pm0.002 \)
- PDG \( BR(\pi^0\pi^0\pi^+) = (1.760\pm0.023)\% \)
Branching ratios and error budget

- Accidental obtained from side bands of time distribution
- MUV inefficiency uncertainty taken as full inefficiency effect
Comparison with theory

Bijnens, Colangelo, Gasser
Tree approximation
1-loop
Beyond 1-loop with measured
F from Rosselet et al.

Recalculated
F(K_{e4}) from NA48/2
R1 = R(1loop)
1-loop (F,R) phase
2020 PDG constants
Conclusions

- NA48/2 has observed for the first time the decay \( K^\pm \to \pi^0 \pi^0 \mu^\pm \nu \)

- 2437 signal candidates with a background of \( 354 \pm 33_{\text{stat}} \pm 62_{\text{syst}} \)

- The preliminary result for the restricted phase space \( (S_l > 0.03) \) is
  \[
  BR(K^\pm \to \pi^0 \pi^0 \mu^\pm \nu, S_l > 0.03) = (0.65 \pm 0.019_{\text{stat}} \pm 0.024_{\text{syst}}) \times 10^{-6} = (0.65 \pm 0.03) \times 10^{-6}
  \]

- The preliminary result for the full space is
  \[
  BR(K^\pm \to \pi^0 \pi^0 \mu^\pm \nu) = (3.4 \pm 0.10_{\text{stat}} \pm 0.13_{\text{syst}}) \times 10^{-6} = (3.4 \pm 0.2) \times 10^{-6}
  \]

- The results are consistent with a contribution of the \( R \) form factor, as from 1-loop ChPT computation