Search for lepton number and flavour violation in $K^+$ and $\pi^0$ decays

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Kaon decay experiments @ CERN

Jura mountains

France

Switzerland

Geneva airport

NA62: ∼ 300 participants from 31 institutes

NA31
1987 - 1989: K_L/K_S

NA48
1997 - 2001: K_L/K_S

NA48/1
2002: K_S/hyperons

NA48/2
2003-04: K^+/K^-

NA62 - Rk
2007-08: K^+e^- / K^-e^+

NA62
2014: pilot run
2015: commissioning run
2016 - 18: Physics Run 1
2021 - : Physics Run 2
The NA62 apparatus

Physics Goal: Measuring $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% precision

Kaon decay in flight technique

Unseparated hadron beam: (70% $\pi^+$, 24% p, 6% $K^+$)

Primary beam: 400 GeV/c protons from SPS, 3.5 s spill

Secondary beam: 75 GeV/c ($dp/p \sim 1\%$), 750 MHz rate

Detector paper: 2017 JINST 12 P05025

1y of operation: $\sim 10^{18}$ POT, $4 \times 10^{12}$ $K^+$ decays

Single event sensitivity for $K^+$ decays: $\text{Br} \sim 10^{-12}$
Main goal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results:

2016 data (30 days, $2 \times 10^{11}$ $K^+$ decays): PBL 791 (2019) 156

2017 data (160 days, $2 \times 10^{12}$ $K^+$ decays): JHEP 11 (2020) 042

2018 data (217 days, $4 \times 10^{12}$ $K^+$ decays): JHEP 06 (2021) 093

Run #1 (2016-18) fully analyzed

More details in Michal’s talk
Recent results

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  [talk by Michal Zamkovsky]
- $K^+ \rightarrow l^+ + \text{inv}$  [talk by Roberta Volpe]
- LNV / LFV
  - $K^+ \rightarrow \pi^\pm \mu^\mp e^\mp$  PRL 127 (2021) 131802
  - $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \mu^\pm e^\mp$
  - $K^+ \rightarrow \pi^+ l^+ l^+$  PLB797 (2019) 134794
  - $K^+ \rightarrow \pi^-\pi^0 e^+e^+$

This talk

- Precise measurements:
  - $K^+ \rightarrow \pi^0 e^+\nu\gamma$ decay  [talk by Cristina Biino]
  - $K^+ \rightarrow \pi^+\mu^+\mu^-$  [to be published soon]
- HNL production:  PLB 807 (2020) 135599;  PLB 816 (2021) 136259.
- $\pi^0 \rightarrow \text{invisible}$:  JHEP 02 (2021) 201.
- $K^+ \rightarrow \pi^+ X$:  JHEP 06 (2021) 93;  JHEP 03 (2021) 58
LFV and LNV in Kaon decays

Lepton number (L) and Lepton flavour (L_e, L_μ, L_τ) are foreseen in some BSM theories.

\[ K^+ \rightarrow \pi^- l^+ l^+ \ (l = e, \mu) \]

Lepton number violation:
\[ \Delta L = 2 \] via Majoranna neutrinos \( U \)
(analogue to 0ν2β decays)

\[ K^+ \rightarrow \pi^\pm \mu^\pm e^+ \]
Lepton flavour violation: \( \Delta L_e = 1 \) and \( \Delta L_\mu = 1 \)
Mediated by a leptoquark

NPB 176 (1980) 135
JHEP 12 (2019) 089
JHEP 12 (2019) 089
PLB 491 (2000) 285
\[ K^+ \rightarrow \pi^\pm \mu^\mp e^+ \]

- 2017 + 2018 data sample
- Blind Analysis
- Triggers: L0(hardware) + L1 (software) run simultaneously to \( \pi\nu\bar{\nu} \) trigger with downscaling factor > 1
  - MultiTrack (RICH&QX) / 100
  - MultiTrack (RICH&QX) & LKr10 & MUV3 / 8
  - MultiTrack (RICH&QX) & LKr20 / 8

MultiTrack trigger efficiency \( \varepsilon = (93.2 \pm 0.5) \% \)

|                | \( K^+ \rightarrow \pi^- \mu^+ e^+ \) | \( K^+ \rightarrow \pi^+ \mu^- e^+ \) | \( \pi^0 \rightarrow \mu^- e^+ \) |
|----------------|--------------------------------------|--------------------------------------|-------------------------------|
| \( A_s \times 10^2 \) | 4.90 ± 0.02                          | 6.21 ± 0.02                          | 3.11 ± 0.02                   |
| \( \varepsilon_{\text{LKr10}} \times 10^2 \) | 97.5 ± 1.3                           | 97.5 ± 1.3                           | 92.9 ± 1.2                    |
| \( \varepsilon_{\text{LKr20}} \times 10^2 \) | 74.1 ± 1.6                           | 73.3 ± 1.6                           | 45.3 ± 1.0                    |
| \( B_{\text{SES}} \times 10^{11} \) | 1.82 ± 0.08                          | 1.44 ± 0.05                          | 13.9 ± 0.9                    |
SES (Single Event Sensitivity)

- Normalization channel: $K^+ \rightarrow \pi^+ \pi^+ \pi^-$, $Br = (5.583 \pm 0.024)\%$
- $N_K = (1.33 \pm 0.02) \times 10^{12}$ number of $K^+$ decays in Fiducial Volume ($105\text{ m} < Z_{\text{vtx}} < 180\text{ m}$)
- $N_{K^3\pi} = 2.73 \times 10^8$ number of $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays collected with MultiTrack trigger

\[
N_K = \sum_i N^i_K = \frac{1}{B(K_{3\pi}) A_n \varepsilon_n} \cdot \sum_i \left( N^i_{3\pi} D^i_{\text{MT}} \right) A_{n,s} \varepsilon_{n,s} \text{ acceptance} \]
\[
\varepsilon_{n,s} \text{ trigger efficiency} \]
\[
B^i_{\text{SES}} = \frac{1}{N^i_K A_s \varepsilon^i_s} = B(K_{3\pi}) \frac{A_n D^i_{\text{MT}}}{A_s N^i_{3\pi} D^i_{\text{MT}} \varepsilon_n} \varepsilon^i_s \text{ single event sensitivity} \]
\[
D^i_{n,s} \text{ trigger downscaling} \]

$SES \sim 10^{-10} \div 10^{-11}$
Background: particle misID

1. Particle misID:
   - $\pi^\pm \leftrightarrow e^\pm$ from $E/p$ measurements
     - $\pi^\pm$: $E/p < 0.9$
     - $e^\pm$: $0.95 < E/p < 1.05$
       - $P(\pi^\pm \Rightarrow e^\pm) = (4 \div 5) \times 10^{-3}$
       - $P(e^\pm \Rightarrow \pi^\pm) = (1 \div 3) \times 10^{-2}$
   - $\pi^\pm \leftrightarrow \mu^\pm$ from (accidental) matching to MUV3
     - $P(\pi^\pm \Rightarrow \mu^\pm) = (2 \div 3) \times 10^{-3}$
     - $P(\mu^\pm \Rightarrow \pi^\pm) = 1.5 \times 10^{-3}$
   - $e^\pm \leftrightarrow \mu^\pm$
     - $P(e^\pm \Rightarrow \mu^\pm) = 10^{-8}$
     - $e^\pm$ scattered & accidental activity in MUV3

2. Decay in flight
   - $\pi^\pm \rightarrow l^\pm \nu_l$ ($l = e, \mu$)
   - Dalitz $\pi^0$ decay: $\pi^0 \rightarrow e^+e^-\gamma$ ($e^\pm \Rightarrow \pi^\pm$ missID)
     - additional cut: $M(\pi^e^+) > 140$ MeV/c$^2$
**LFV $K \rightarrow \pi \mu e$: Background expectations**

$K^+ \rightarrow \pi^- \mu^+ e^+$

**Signal Region**

- **CR1**
  - Expected: $5.50 \pm 0.53$
  - Observed: 8

- **CR2**
  - Expected: $1.95 \pm 0.48$
  - Observed: 4

**Run 1 data**

$K^+ \rightarrow \pi^+ \mu^- e^+$

**Signal Region**

- **CR1**
  - Expected: $3.50 \pm 0.53$
  - Observed: 8

- **CR2**
  - Expected: $1.95 \pm 0.48$
  - Observed: 4

**Blinded**

- Data ($K^+ \rightarrow \pi^+ \mu^- e^+$ selection)
- $K^+ \rightarrow \pi^+ \mu^- e^+$
- $K^+ \rightarrow \pi^- \mu^+ e^+$
- $K^+ \rightarrow \pi^- \mu^- e^+$
- $K^+ \rightarrow \pi^+ \mu^- \mu^+$
- $K^+ \rightarrow \pi^- \mu^- \mu^+$
- $K^+ \rightarrow \pi^+ e^+ \mu^+$
- $K^+ \rightarrow \pi^- e^- \mu^+$

**Total uncertainty**
**LFV $K \rightarrow \pi\mu e$: signal regions open**

$K^+ \rightarrow \pi^- \mu^+ e^+$

**Signal Region**

- CR1
- CR2

**Observed in SR:** 0

$K^+ \rightarrow \pi^+ \mu^- e^+$

**Signal Region**

- CR1
- CR2

**Observed in SR:** 2

**Run 1 data**
# Results for $K^+ \rightarrow \pi^\pm \mu^\mp e^+$

|                      | $K^+ \rightarrow \pi^- \mu^+ e^+$                  | $K^+ \rightarrow \pi^+ \mu^- e^+$                  | $\pi^0 \rightarrow \mu^- e^+$                  |
|----------------------|---------------------------------------------------|---------------------------------------------------|--------------------------------------------------|
| Signal Acceptance    | $(4.90 \pm 0.02)$%                                 | $(6.21 \pm 0.02)$%                                 | $(3.11 \pm 0.02)$%                                 |
| SES                  | $(1.82 \pm 0.08) \times 10^{-11}$                  | $(1.44 \pm 0.05) \times 10^{-11}$                  | $(13.9 \pm 1.0) \times 10^{-11}$                   |
| Bkgd. expectation    | $1.07 \pm 0.20$                                    | $0.92 \pm 0.34$                                    | $0.23 \pm 0.15$                                    |
| Events observed      | 0                                                 | 2                                                 | 0                                                 |
| BR Upper limit @ 90%CL| $4.2 \times 10^{-11}$                             | $6.6 \times 10^{-11}$                             | $3.2 \times 10^{-10}$                             |
| Previous result      | $5.0 \times 10^{-10}$                             | $5.2 \times 10^{-10}$                             | $3.4 \times 10^{-9}$                              |

[PR 85 (2000) 2877]
2017 data: Search for $K^+ \rightarrow \pi^-\mu^+\mu^+$

**SM:** $M(\pi^+\mu^-\mu^+)$

- $K^+ \rightarrow \pi^+\pi^+\pi^-$  
  (misID: $\pi \Rightarrow \mu$)

- $K^+ \rightarrow \pi^+\pi^-\mu^+\nu$  
  (misID: $\pi \Rightarrow \mu$)

**LNV:** $M(\pi^-\mu^+\mu^+)$

- $K^+ \rightarrow \pi^+\pi^-\mu^+\nu$  

Candidates: 8357

$N_{K^+} = (7.94 \pm 0.23) \times 10^{11}$

$BR = (0.962 \pm 0.025) \times 10^{-7}$

Candidates: 1

Exp. background: $0.91 \pm 0.41$

$BR < 4.2 \times 10^{-11}$ @ 90% CL
Run1 data: Search for $K^+ \rightarrow \pi^- e^+ e^+$

**SM:** $M(\pi^+ e^- e^+)$

Candidates: 11041

$N_{K^+} = (1.015 \pm 0.0032) \times 10^{12}$

$BR = (3.00 \pm 0.09) \times 10^{-7}$

**Exp. background:** $0.43 \pm 0.09$

$BR < 5.3 \times 10^{-11} @ 90\%$ CL

**LNV:** $M(\pi^- e^+ e^+)$

Candidates: 0

**Signal region**

0 events in SR

$K^+ \rightarrow e^+ \nu \pi^0_D$
Run1 data: Search for $K^+ \rightarrow \pi^- \pi^0 e^+ e^-$

Normalization channel $K^+ \rightarrow \pi^+ e^+ e^-$

| Mode                        | Control region | Signal region |
|-----------------------------|----------------|---------------|
| $K^+ \rightarrow \pi^+ \pi^0 \pi^0_D$ | 0.16 ± 0.01    | 0.019         |
| $K^+ \rightarrow \pi^+ \pi^0_D \gamma$ | 0.06 ± 0.01    | 0.004         |
| $K^+ \rightarrow \pi^0_D e^+ \nu \gamma$ | 0.05 ± 0.02    | -             |
| $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$ | 0.01           | 0.001         |
| Pileup                      | 0.20 ± 0.20    | 0.020 ± 0.020 |
| Total                       | 0.48 ± 0.20    | 0.044 ± 0.020 |
| Data                        | 1              | 0             |

Candidates: 0
Expected background: 0.044 ± 0.020 evt
$\text{BR} < 8.5 \times 10^{-10}$ at 90% CL
## Summary

| Decay | Previous BR UL [pdg] | NA62 BR UL @ 90% CL | Comment |
|-------|----------------------|----------------------|---------|
| $K^+ \to \pi^+ \mu^+ \mu^+$ | $8.6 \times 10^{-11}$ | $4.2 \times 10^{-11}$ | Improved by factor of 2 [2017 data] |
| $K^+ \to \pi^- e^+ e^+$ | $6.4 \times 10^{-10}$ | Preliminary $5.3 \times 10^{-11}$ | Improved by factor of 12 |
| $K^+ \to \pi^- \mu^+ e^+$ | $5.0 \times 10^{-10}$ | $4.2 \times 10^{-11}$ | Improved by factor of 12 |
| $K^+ \to \pi^+ \mu^- e^+$ | $5.2 \times 10^{-10}$ | $6.6 \times 10^{-11}$ | Improved by factor of 8 |
| $K^+ \to \pi^+ \mu^+ e^-$ | $1.3 \times 10^{-11}$ | - | Not yet competitive |
| $\pi^0 \to \mu^- e^+$ | $3.4 \times 10^{-9}$ | $3.2 \times 10^{-10}$ | Improved by factor of 11 |
| $K^+ \to \pi^- \pi^0 e^+e^+$ | - | Preliminary $8.5 \times 10^{-10}$ | First search for this mode! |

The NA62 has started the new data taking and will run till LS3 (~ 2025).
Thank you