Search for lepton number and flavour violation in $K^+$ and $\pi^0$ decays at NA62

Tom Bache (University of Birmingham, UK)

On behalf of the NA62 Collaboration
Conclusions and the future of NA62

Search for LFV/LNV in $K^+ \rightarrow \pi^+ \mu^+ e^+$ and $\pi^0 \rightarrow \mu^- e^+$

Opened signal regions

Search for LFV/LNV in $K^+ \rightarrow \pi^- l^+ l^+$

Background studies

Opened signal regions

Introduction to searches for LFV/LNV decays at NA62

Introduction to NA62 and kaon physics

History of kaon physics

NA62 beam and detector layout

NA62’s physics programme

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- History of kaon physics
- NA62 beam and detector layout
- NA62's physics programme

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Conclusions and the future of NA62
NA62 and kaon physics at CERN

~200 participants, 30 institutes, 14 countries

- **1980s**: NA31 - First evidence of direct CPV
- **1997-2001**: NA48 - Discovery of direct CPV
- **2002**: NA48/1 - Rare decay studies
- **2003-2004**: NA48/2 - Precision measurements
- **2007-2008**: NA62 - $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$
- **2015-2018**: NA62 Run 1 (2015-2018) - Main goal: $B(K^+ \to \pi^+ \nu \bar{\nu})$
- **2021-L53**: NA62 Run 2 (2021-L53) - Precision measurements

Run 1 searches in this talk!

$L_K/L_S$ beam

$K_S$/hyperon beam

$K^+/K^-$ beam

Main goal: $B(K^+ \to \pi^+ \nu \bar{\nu})$

LNV/LFV searches, HNL...

Precision measurements

27/08/2021

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Other NA62 talks

See the other ICNFP 2021 talks by NA62:

• 25th July -> P. Massarotti (Search for K+ decays to a lepton and invisible particles)

• 27th July (later this session) -> A. Bizzeti (Measurement of the very rare K+ to pi+ nu nubar decay)

• 30th July -> G. Lamanna (New measurement of radiative decays at the NA62 Experiment at CERN)
NA62 beam and detector layout

- **KTAG** (upstream Cherenkov detector) tags kaons in the beam ($\sigma_T \sim 70\text{ps}$)
- **GTK** (silicon pixel spectrometer) tracks the beam
- **STRAW** (magnetic spectrometer) tracks $K^+$ decay products
- **RICH** (downstream Cherenkov detector) provides PID ($\pi^+ / \mu^+ / e^+$) and timing ($\sigma_T \sim 70\text{ps}$)
- **LKr** (ECAL) provides PID and photon veto
- **LAV, IRC and SAC** provide additional photon veto to achieve hermetic acceptance (0-50 mrad) of photons
- Hadronic calorimetry provided by **MUV1/2**
- **MUV3** provides muon detection/veto
- **CHOD and NA48-CHOD** used for trigger and timing ($\sigma_T \sim 200\text{ps}$)

Protons from CERN SPS impinge on beryllium target.

Leads to an unseparated beam consisting of $K^+$, $\pi^+$ and protons entering NA62.

6% of the beam is $K^+$.

Beam rate $\sim 500$ MHz at decay region entrance $\Rightarrow K^+$ decay rate $\sim 5$ MHz in the decay region.

Beam momentum = 75 GeV/c ($\pm 1\%$)
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Key performance parameters:

➢ Very good timing resolution O(100 ps).
➢ Kinematic rejection O($10^4$) of $K^+ \rightarrow \pi^+ \pi^0$ and $K^+ \rightarrow \mu^+ \nu$.
➢ Particle ID to suppress muons from $K^+ \rightarrow \mu^+ \nu > 10^7$.
➢ Photon veto to suppress $\pi^0 \rightarrow \gamma \gamma$ from $K^+ \rightarrow \pi^+ \pi^0 > 10^7$. 

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NA62 beam and detector layout
NA62 data taking periods

Run 1 comprises of 3 years of data taking between 2016 and 2018.

- 408 days in total.
- $\sim 6 \times 10^{12} K^+$ decays.

Run 2 started in July 2021 and will continue until 2023.

- Expect to collect $O(10^{13}) K^+$ decays.
NA62’s varied physics programme

Main goal of NA62 is to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, a decay with branching ratio $\sim 10^{-10}$

- Aiming for O(10%) precision.
- 20 candidates observed in Run 1 ($6 \times 10^{12} K^+$ decays in flight, collected between 2016 and 2018), corresponding to a signal significance of 3.4$\sigma$ [JHEP 06 (2021) 093].
- Data taking in Run 2 restarted in July 2021!

Large variety of other measurements have been/are being conducted:

- Rare decay and precision measurements (e.g. $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ which has branching ratio $\sim 10^{-7}$ [ICHEP 2020 proceedings]).
- Exotic searches of e.g. HNL in $K^+ \rightarrow l^+ N$ [PLB 807 (2020) 135599, PLB 816 (2021) 136259].
- Searches for forbidden decays (e.g. LFV and LNV in $K^+ \rightarrow \pi^\pm \mu^\mp e^+$ and $K^+ \rightarrow \pi^- l^+ l^+$).
  ➢ This talk!
Conclusions and the future of NA62

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Conclusions and the future of NA62
Searches for forbidden LFV/LNV decays

Conservation of lepton flavour and lepton number is not required during construction of the standard model. Observation of LFV or LNV would suggest BSM physics was at play.

Five decays shown in this talk:

- $K^+ \to \pi^- \mu^+ e^+$ \(\rightarrow K_{\pi\mu e}\) \(\Delta L = 2\) if $\pi^-$ and $\Delta L_e = \Delta L_\mu = 1$

- $K^+ \to \pi^+ [\mu^- e^+]\pi^0$ \(\rightarrow K_{\pi\mu\pi}\) \(\Delta L_e = \Delta L_\mu = 1\) for $\pi^0 \to \mu^- e^+$

- $K^+ \to \pi^- \mu^+ \mu^+$ \(\rightarrow K_{\pi\mu\mu}\) \(\Delta L = 2\)

- $K^+ \to \pi^- e^+ e^+$ \(\rightarrow K_{\pi e e}\) \(\Delta L = 2\)

All analyses were blinded until the backgrounds were validated.
Searches for forbidden LFV/LNV decays

Four different triggers used to collect data for these analyses:

<table>
<thead>
<tr>
<th>Trigger</th>
<th>L0 definition</th>
<th>L1 definition</th>
<th>Downscaling (at L0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-track ((MT))</td>
<td>RICH + 2 CHOD signals</td>
<td>KTAG + STRAW</td>
<td>100</td>
</tr>
<tr>
<td>Muon multi-track ((\mu MT))</td>
<td>RICH + 2 CHOD signals + MUV3 signal</td>
<td>KTAG + STRAW</td>
<td>8</td>
</tr>
<tr>
<td>Dimuon multi-track ((2\mu MT))</td>
<td>RICH + 2 CHOD signals + 2 MUV3 signals</td>
<td>STRAW</td>
<td>2</td>
</tr>
<tr>
<td>Electron multi-track ((e MT))</td>
<td>RICH + 2 CHOD signals + 20 GeV energy in LKr</td>
<td>KTAG + STRAW</td>
<td>8</td>
</tr>
</tbody>
</table>

Triggers used for each mode:

\[
\begin{align*}
K^+ & \to \pi^- \mu^+ e^+ \\
K^+ & \to \pi^+ \mu^- e^+ \\
K^+ & \to \pi^+ [\mu^- e^+]_{\pi^0} - MT + \mu MT + e MT \\
K^+ & \to \pi^- \mu^+ \mu^+ - 2\mu MT \\
K^+ & \to \pi^- e^+ e^+ - MT + e MT
\end{align*}
\]

All analyses were blinded until the backgrounds were validated.

Use \(K^+ \to \pi^+ \pi^+ \pi^-\) as normalisation for \(K_{\pi\mu e}\) (collected with the \(MT\) trigger).

Use the SM equivalent decays for \(K_{\pi\ell\ell}\) normalisation (collected with the same triggers):

\[
\begin{align*}
K^+ & \to \pi^+ \mu^+ \mu^- \\
K^+ & \to \pi^+ e^+ e^-
\end{align*}
\]

All chosen as kinematically similar \(\Rightarrow\) systematics cancelation.
Conclusions and the future of NA62

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Outline
**$K_{\pi\mu e}$** background studies

Backgrounds arise from two mechanisms:
- **Mis-ID**
  - Selection uses the energy deposited in the LKr and the momentum measurement by STRAW for PID:
    \[
    \pi^{\pm} \rightarrow E/p < 0.9 \quad \text{and} \quad e^{\pm} \rightarrow 0.95 < E/p < 1.05
    \]
  - But...simulation constraints mean data-driven corrections are needed to account for mis-ID.
  - Mis-ID of $\pi/e$ as $\mu$ due to accidental activity in MUV3 also accounted for.
- **Decays in flight**
  - Charged pion decays: $\pi^+ \rightarrow \mu^+\nu$ and $\pi^+ \rightarrow e^+\nu$
  - Neutral pion decays: $\pi^0 \rightarrow e^+e^-\gamma$

Main background decays:
- $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^+ \rightarrow \pi^+e^+e^-$

Mis-ID accounted for by measuring probabilities using data (see plot) and reweighting MC.
Pion decay in flight well simulated but reduced by using dedicated cuts (photon veto, vertex quality, kinematic...) in the selection.
$K_{\pi\mu e}$ background studies

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

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

Backgrounds validated in control regions either side of signal region before unblinding (CR1 below and CR2 above).

After unblinding CRs:

<table>
<thead>
<tr>
<th>$K^+ \rightarrow \pi^- \mu^+ e^+$</th>
<th>CR1</th>
<th>Signal region</th>
<th>CR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>1.68 ± 0.20</td>
<td>1.06 ± 0.20</td>
<td>1.66 ± 0.26</td>
</tr>
<tr>
<td>Observed</td>
<td>2</td>
<td>BLIND</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$K^+ \rightarrow \pi^+ \mu^- e^+$</th>
<th>CR1</th>
<th>Signal region</th>
<th>CR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>3.41 ± 0.54</td>
<td>0.92 ± 0.34</td>
<td>1.27 ± 0.40</td>
</tr>
<tr>
<td>Observed</td>
<td>2</td>
<td>BLIND</td>
<td>0</td>
</tr>
</tbody>
</table>

Signal acceptances and SES:

\[ SES = \frac{1}{N_K \text{eff} A_s \epsilon_{\text{trigger}}} \]

<table>
<thead>
<tr>
<th>Acceptance, $A_s$</th>
<th>SES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^- \mu^+ e^+$</td>
<td>(4.90 ± 0.02)% × $10^{-11}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu^- e^+$</td>
<td>(6.21 ± 0.02)% × $10^{-11}$</td>
</tr>
</tbody>
</table>

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\[ K^+ \rightarrow \pi^\pm \mu^\mp e^+ \] - opening signal regions

Run 1 dataset used.

Results:
\[ B(K^+ \rightarrow \pi^- \mu^+ e^+) < 4.2 \times 10^{-11} @ 90\% CL \]
\[ B(K^+ \rightarrow \pi^+ \mu^- e^+) < 6.6 \times 10^{-11} @ 90\% CL \]

Both results are an order of magnitude improvement on the PDG. Accepted for publication in Phys. Rev. Lett.

Also altered the selection used for the \( K^+ \rightarrow \pi^+ \mu^- e^+ \) channel search to look for the LFV decay \( \pi^0 \rightarrow \mu^- e^+ \) from \( K^+ \rightarrow \pi^+ \pi^0 \).

Find \( N_{bkg} = 0.23 \pm 0.15 \) and \( N_{obs} = 0 \), leading to another result that is an order of magnitude improvement on the PDG:

\[ B(\pi^0 \rightarrow \mu^- e^+) < 3.2 \times 10^{-10} @ 90\% CL \]
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Conclusions and the future of NA62
$K^+ \rightarrow \pi^- l^+ l^+$

Two lepton number violating decays studied:

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

Main backgrounds present in the signal region differ in each case:

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

- $K^+ \rightarrow e^+ \nu [e^+ e^- \gamma] \pi^0$
- $K^+ \rightarrow e^+ \nu e^+ e^-$

$e^- \text{ mis-ID as } \pi^-$ (probability of $\sim 1\%$).

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

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

$\pi^+$ decay in flight and $\pi \leftrightarrow \mu \text{ mis-ID (probability of } 0.4 - 0.5\%)$.

- Normalisation done relative to $K^+ \rightarrow \pi^+ l^+ l^-$ (similar decay but under SM).
- Backgrounds validated in control regions (without the RICH in $K_{\pi ee}$ case to increase statistics).
$K^+ \rightarrow \pi^- l^+ l^+$ - opening signal regions

~30% of total Run 1 dataset used.

Final results:

$B(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ at 90% CL

$B(K^+ \rightarrow \pi^- \mu^+ \mu^-) < 4.2 \times 10^{-11}$ at 90% CL

Both results are a factor 2-3 improvement on the PDG.
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Conclusions

NA62 has collected $6 \times 10^{12}$ $K^+$ decays in flight during Run 1, with multiple world leading analyses taking place.

Only time to discuss searches for LNV/LFV during this talk:

- Order of magnitude improvement on upper limit of $B(K^+ \rightarrow \pi^+\mu^+\mu^-e^+) \text{ and } B(\pi^0 \rightarrow \mu^-e^+)$.
- Factor 2-3 improvement on upper limit of $B(K^+ \rightarrow \pi^-l^+l^+)$.

Other interesting analyses recently published/made public:

- $K^+ \rightarrow \pi^+\nu\bar{\nu}$ [JHEP 06 (2021) 093], $K^+ \rightarrow \pi^+\mu^+\mu^- \text{ [ICHEP 2020 proceedings], } K^+ \rightarrow l^+N \text{ [PLB 807 (2020) 135599, PLB 816 (2021) 136259], } K^+ \rightarrow \pi^+X$ [JHEP 03 (2021) 058].

NA62 Run 2 started in July 2021 and will continue until LS3. Improvements relative to Run 1:

- Higher intensity (70% -> 100%).
- 4th GTK station added.
- Three new veto counters placed upstream or downstream of decay region.
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