Heavy neutral lepton, dark photon and LF/LN violation searches at NA62

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Outline:

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2) First published result: HNL production search in $K^+$ decays
3) Preliminary result: search for dark photon in $\pi^0$ decays
4) Status of LF/LN conservation tests in 3-track $K^+$ decays
5) Summary
Kaon programme at CERN

Main NA62 goal: an improved $K^+ \rightarrow \pi^+ \nu\nu$ measurement with a novel decay-in-flight technique.
Currently ~200 participants, ~30 institutions
Expected single event sensitivity for $K^+$ decays: $\text{BR} \sim 10^{-12}$.

Measured kinematic rejection factors (limited by beam pileup & MCS tails):
- $6 \times 10^{-4}$ for $K^+ \rightarrow \pi^+\pi^0$
- $3 \times 10^{-4}$ for $K \rightarrow \mu^+\nu$.

Hermetic photon veto: measured $\pi^0 \rightarrow \gamma\gamma$ decay suppression = $1.2 \times 10^{-7}$.

Particle ID (RICH+LKr+HAC+MUV): $\sim 10^{-7}$ muon suppression.
Commissioning run 2015: minimum bias (~1% of nominal beam intensity).

Physics run 2016 (40% intensity, limited by beam quality):
1.2\times10^{11} K^+ useful decays (1 month) for K^+\rightarrow\pi^+\nu\nu analysis; [talk by J.Pinzino]

Physics run 2017 (65% intensity): \sim 3\times10^{12} useful K^+ decays.

Physics run in April–November 2018: 218 days scheduled.
Searches for heavy neutral lepton production in $K^+$ decays

Result based on the 2015 data:
Heavy neutral leptons in $\nu$MSM

Neutrino minimal SM ($\nu$MSM) = SM + 3 right-handed neutral heavy leptons.

[Asaka et al., PLB631 (2005) 151]

Masses: $m_1 \sim 10$ keV [DM candidate]; $m_{2,3} \sim 1$ GeV.

HNLs observable via production and decay.

$$\Gamma(K^+ \rightarrow \ell^+ N) = \Gamma(K^+ \rightarrow \ell^+ \nu) \rho_{\ell}(m_N) |U_{\ell 4}|^2$$

Shaposhnikov, JHEP 0808 (2008) 008

Minimum bias data (1% intensity); 12k SPS spills (=5 days) in 2015.

Numbers of $K^+$ decays in fiducial volume:

- $N_K = (3.01 \pm 0.11) \times 10^8$ in positron case;
- $N_K = (1.06 \pm 0.12) \times 10^8$ in muon case.

Beam tracker not available: beam average kaon momentum is used.

HNL production signal: a spike above continuous missing mass spectrum.

- $K^+ \rightarrow \ell^+\nu$, $BR = 1.6 \times 10^{-5}$: 1.7k candidates

- $K^+ \rightarrow \mu^+\nu, \mu^+ \rightarrow e^+\nu\nu$, $BR = 64\%$: 24M candidates

**HNL search region**: low background due to photon veto and kaon ID
$K^+ \rightarrow \ell^+ N$: resolution & acceptance

- HNL mass resolution $\sigma_m$ vs mass
- Signal selection acceptance vs mass

- Selection for each HNL mass hypothesis ($m_{HNL}$) includes the “mass window” condition: $|m - m_{HNL}| < 1.5\sigma_m$: background is proportional to mass resolution.
- Also, resolution is crucial to resolve possible HNL mass splitting.

[Baryogenesis: 2 quasi-degenerate mass states; Canetti et al., PRD87(2013)093006]
Expected background (and stat.error) estimated from fits to the sidebands; numbers of observed and expected events converted into limits for the signal.

Background simulations used to certify the absence of peaking structures.

Full MC background estimate would allow searches for $K^+ \rightarrow \ell^+\nu\nu\nu$. 
HNL production search: results

Upper limits on BR(K⁺→ℓ⁺N)

| U_{ℓ4} |^2 limits from production searches

- Local signal significance never exceeds 2.2σ: no HNL signal is observed.
-Reached 10^{-6}–10^{-7} limits for |U_{ℓ4}|^2 in the 170–448 MeV/c^2 mass range.

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HNLs: prospects with full dataset

Data sample 2016–18 in comparison to data sample 2015:

- Beam tracker (GTK) in operation:
  - a factor \( \sim 2 \) improved HNL mass resolution \( \sigma_m \), therefore lower background and broader mass range accessible;
  - a factor \( \sim 3 \) lower background in the \( K^+ \rightarrow e^+N \) mode (\( K^+ \rightarrow \mu^+\nu, \mu^+ \rightarrow e^+\nu\nu \): muon decays in flight rejected geometrically);
  - lower background from upstream decays in the \( K^+ \rightarrow \mu^+N \) mode.

- Much larger datasets:
  - In the \( K^+ \rightarrow e^+N \) mode, the main \( K^+ \rightarrow \pi^+\nu\nu \) trigger is used (with reduced signal acceptance: max calorimetric energy = 30 GeV): expect at \( O(10^6) \) \( K^+ \rightarrow e^+\nu \) events, i.e. a factor \( \sim 1000 \) improvement.
  - In the \( K^+ \rightarrow \mu^+N \) mode, downscaled control trigger (\( D=400 \)): expect \( O(10^9) \) \( K^+ \rightarrow \mu^+\nu \) events, i.e. a factor \( \sim 100 \) improvement.

Expected sensitivities to \( |U_{\ell 4}|^2 \) with 2016–18 data:

- better than \( 10^{-8} \) for both \( |U_{e4}|^2 \) and \( |U_{\mu 4}|^2 \)

Large data sets already collected; analysis is in progress
Search for dark photon production in $\pi^0$ decays

(a preliminary result)
The simplest hidden sector model introduces an extra $U(1)$ gauge symmetry with its gauge boson: the dark photon ($A'$).

QED-like interaction with SM fermions:

$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

Considering SM decay modes only, DP lifetime below the di-muon threshold is

$$c \tau_{A'} \approx 0.8 \, \mu m \times \left( \frac{10^{-6}}{\varepsilon^2} \right) \times \left( \frac{100 \, \text{MeV}}{m_{A'}} \right)$$

- Multiple limits assuming decays into SM particles, including $(K^\pm \rightarrow \pi^\pm \pi^0, \pi^0 \rightarrow \gamma A', A' \rightarrow e^+e^-)$ from NA48/2 [Phys.Lett. B746 (2015) 178]
- DP decaying into SM fermions ruled out as explanation for the muon $g-2$ anomaly.
- At low $\varepsilon^2$, limits from beam dump experiments.
- The invisible DP is much less constrained.
**DP search at NA62**

**Decay chain:** $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow \text{invisible}$.  
**Data:** 4% of 2016 sample ($\sim 10^{10} K^+$ decays). Excellent photon veto: low background.

**Expected and observed ULs (90%CL)**

No DP signal observed

**Limit found**
1-s limit band
2-s limit band

**Further NA62 prospects for the invisible dark photon:**
Improved sensitivity to $K^+ \rightarrow \pi^+ A'$ over BNL E949, by-product of $K^+ \rightarrow \pi^+ \nu\nu$ analysis.
Searches lepton flavour and lepton number violation

(work in progress: status report)
Data sample 2003–04. $K^{\pm} \rightarrow \pi\mu\mu$ selection: 3-track vertex; no missing momentum; muon ID (LKr, muon detector).

- Blind analysis: selection optimized with dedicated MC samples.
- Main background: $K^{\pm} \rightarrow 3\pi^{\pm}$ with $\pi^{\pm} \rightarrow \mu^{\pm}\nu$ decays in flight.
- Muon identification optimized for background reduction.

- $K_{\pi\mu\mu}$ candidates
- FCNC decay studied earlier: 3.5k candidates
- $K^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}$
- (also used for normalization)

$N(\mu^{\pm}\mu^{\pm}) = 1$
$N_{\text{bkg}} = 1.16 \pm 0.87$

$BR(K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\mp}) < 8.6 \times 10^{-11}$ [90% CL]

Forbidden $K^+$ decays at NA62

Goal: improve over most existing limits (mainly from BNL E865, E777).

- Search for the LNV decay $K^+ \rightarrow \pi^- \mu^+ \mu^+$  [BR<8.6×10^{-11}, NA48/2@CERN]
- Search for the LNV decay $K^+ \rightarrow \pi^- e^+ e^+$  [BR<6.4×10^{-10}]
- Searches for LNV/LFV decays $K^+ \rightarrow \pi^- \mu e$, including $\pi^0 \rightarrow \mu e$.
  
  $[BR(\pi^- \mu^+ e^+)<5.0\times10^{-10}; BR(\pi^+ \mu^- e^+)<5.2\times10^{-10}; BR(\pi^+ \mu^+ e^-)<1.3\times10^{-11}]$
  $[BR(\pi^0 \rightarrow \mu^\pm e^\mp)<3.6\times10^{-10}, \text{kTeV@FNAL}]$
- Searches for $K^+ \rightarrow \mu^- \nu e^+ e^+$ and $K^+ \rightarrow e^- \nu \mu^+ \mu^+$ decays.
  $[BR(\mu^- \nu e^+ e^+)<1.9\times10^{-8}: \text{Geneva-Saclay, 1976}]$
- Searches for $\Delta S=\Delta Q$ violating decays $K^+ \rightarrow \pi^+ \pi^+ e^- \nu$ and $K^+ \rightarrow \pi^+ \pi^+ \mu^- \nu$.
  $[BR(\pi^+ \pi^+ e^- \nu)<1.3\times10^{-8}; BR(\pi^+ \pi^+ \mu^- \nu)<3.0\times10^{-6}: \sim 50 \text{ years old}]$

Approximate statistical reach with the 2016–17 data sample:

- Di-muon trigger stream:  $\sim 2\times10^{12}$ $K^+$ decays;  SES$\sim 10^{-11}$
- Decays to $\mu e$ and $ee$ pairs:  $\sim 5\times10^{11}$ $K^+$ decays;  SES$\sim 10^{-10}$
- Other 3-track decays:  $\sim 5\times10^{10}$ $K^+$ decays;  SES$\sim 10^{-9}$

NA62 is competitive for most of these decay modes
World’s largest $K^+\rightarrow\pi^+\mu^+\mu^-$ sample: 4.6k candidates in this partial data set; expect $\sim20k$ candidates in total.

Expect to make a competitive $K^+\rightarrow\pi^+\mu^+\mu^-$ measurement.

Search for new scalar: $K^+\rightarrow\pi^+S$, $S\rightarrow\mu^+\mu^-$: SES $\sim10^{-10}$, lifetimes up to $O(1\text{ ns})$.

Search for $K^+\rightarrow\pi^-\mu^+\mu^+$: background-free, reached SES $\sim10^{-11}$. 

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- A partial data set: background-free but not world’s largest $K^+\to\pi^+e^+e^-$ sample (1.1k events).
- First observation of $K^+\to\pi^+e^+e^-$ decay in the mass range $m_{ee}<140$ MeV/$c^2$.
- Observation of $\pi^0\to e^+e^-$ decay with an excellent $m_{ee}$ resolution.
- Search for $K^+\to\pi^+X$, $X\to e^+e^-$, $10<m_X<100$ MeV/$c^2$: SES~$10^{-9}$ for lifetime $\ll 1$ ns.
- Search for $K^+\to\pi^-e^+e^+$: background-free, SES~$10^{-10}$.
First NA62 physics run (2016–18) is in progress: a large $K^+$ decay data sample collected, data taking in progress.

Focused on $K_{\pi\nu\nu}$ measurement ($\text{SES} \sim 10^{-12}$); however a broad programme of rare decay measurements, hidden sector particles and LF/LN violation searches is pursued.

First published NA62 result: HNL production in $K^+ \to \ell^+ N$ decays. Sub-$10^{-6}$ limits on $|U_{\ell 4}|^2$; expect further $\sim 2$ orders of magnitude improvement. [*PLB778 (2018) 137*]

Improved $\varepsilon^2$ limit on invisible dark photon search from $\pi^0 \to \gamma A'$ decays. [*a preliminary result*]

Searches for LF/LN violation in 3-track decays: on track to reach sensitivities down to $10^{-11}$, improving over the world limits.
NA48/2: search for $K^\pm \rightarrow \pi^\pm X, \ X \rightarrow \mu^+\mu^-$

Background-limited search; $\text{UL} \sim 10^{-9}$. Leads to non-trivial limitations on the inflation ($\chi$) phase space: $\chi \rightarrow \mu^+\mu^-$ decay dominates at $m_\chi \sim 300$ MeV/c$^2$.