Search for Heavy Neutral Lepton production in $K^+$ decays at NA62

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on behalf of the NA62 Collaboration

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Kaon experiments at CERN

  - *Discovery of direct CPV*
- **NA48/1**: 2002, *beam*: $K_S$/hyperons
- **NA48/2**: 2003–2004, *beam*: $K^+/K^-$
  - $K^\pm \rightarrow \mu^\pm N_4$, $N_4 \rightarrow \mu \pi$
  - $K^+ \rightarrow \mu^+ N_4$
- **NA62**: since 2014, *beam*: $K^+$
  - 2014: pilot run
  - 2015: commissioning run
  - 2016-2018: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ runs

$\sim$ 200 participants, $\sim$ 30 institutes
Kaon experiments at CERN

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**This talk**

NA62: ~ 200 participants, ~ 30 institutes

NA62-R_K: K^+ \rightarrow \mu^+ N_4

K^+ \rightarrow \pi^+ \nu \bar{\nu}$ runs

Discovery of direct CPV

K^+ \rightarrow \mu^+ N_4

K^+ \rightarrow \pi^+ \nu \bar{\nu}$ runs

This talk
Heavy Neutral Leptons: Motivation

- **Neutrino oscillations** imply neutrinos are massive, not accommodated in SM
- **No SM Dark Matter** candidate and **Baryon Asymmetry** call for beyond SM physics
- Example of SM extension: **Neutrino Minimal SM (νMSM)** (*Asaka et al., PLB 620 (2005) 17*)
  - 3 right-handed sterile neutrinos $N_i$ are added to SM, $m_1 \sim 10$ keV, $m_{2,3} \sim 1$ GeV
  - $N_1$ serves as **Dark Matter candidate**
  - $N_{2,3}$ introduce extra CPV phases to account for **Baryon Asymmetry** and are responsible for SM neutrino masses (see-saw mechanism)

\[
\rho_\mu(m_N) \times R_K \approx 2.5 \times 10^{-5}
\]

\[
\rho_e(m_N) \times R_K
\]

R. Shrock PLB96 (1980) 159

- If $m_N < M_{K^\pm} - m_{l^\pm}$, heavy neutrinos are observable via production in processes

\[
\Gamma(K^\pm \rightarrow l^\pm N) = \Gamma(K^\pm \rightarrow l^\pm \nu_l) \rho_l(m_N) |U_{l4}|^2
\]

**Kinematic factor**

**Mixing matrix element**
Main goals

- \( R_K = \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu2})} \)


Beam parameters

- Narrow momentum bands:
  - \( P_K = 74 \text{ GeV/c}, \delta P_K / P_K \sim 1\% \text{ (rms)} \)
- Availability of \( K^+ \) and/or \( K^- \) beams

Main subdetectors

- Spectrometer (4 DCHs):
  - \( \sigma_p / p = 0.48\% \oplus 0.009\% \cdot p[\text{GeV}] \)
- Scintillator hodoscope: \( \sigma_t \sim 150 \text{ ps} \)
- LKr EM calorimeter
  - \( \sigma_E / E = 3.2\% / \sqrt{E[\text{GeV}]} \oplus 9\% / E[\text{GeV}] \oplus 0.42\% \)
  - \( \sigma_x = \sigma_y = 4.2 \text{ mm} / \sqrt{E[\text{GeV}]} \oplus 0.6 \text{ mm} (1.5 \text{ mm @ 10 GeV}) \)
- Muon veto system
Kaon decays in the fiducial volume

- \( N_K \sim 6 \times 10^7 \) (from reconstructed \( K^+ \rightarrow \mu^+ \nu \))

**Analysis outline**

- Analysis done on \( K^+ \) sample only
- Peak search performed in Missing Mass:
  \[ M_{\text{miss}} = \sqrt{(P_K - P_\mu)^2} \]
- Signal Region: \( M_{\text{miss}} \in (300, 375) \text{ MeV}/c^2 \)

**HNL MC simulation**

- Acceptance vs. HNL mass: \( A(m_{N_4}) \)
- \( M_{\text{miss}} \) resolution vs. HNL mass: \( \sigma(m_{N_4}) \)
Search for HNL at NA62-R\textsubscript{K}, ULs on $N_{\text{sig.}}$ and $\mathcal{B}(K^+ \rightarrow \mu^+ N_4)$

- Rolke-Lopez method used to determine UL on $N_{\text{sig.}}$.
- Heavy neutrino mass step: 1 MeV/c\textsuperscript{2}
- Search window determined according to $\sigma(m_{N_4})$
- Statistical significance never exceeds $3\sigma$: No signal observed
Main goal
- 10% precision measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

Beam parameters
- Beam momentum: 75 GeV/c (±1%)
- Positive beam: ~6% K+

Main subdetectors
- Trackers: beam (GTK), $\pi/\mu/e$ (STRAW)
- Hermetic veto detectors:
  - Photon vetoes (LAV, LKr, IRC, SAC)
  - Muon vetoes (MUV)
- Particle identification:
  - Beam kaons (KTAG)
  - $\pi/\mu/e$ (RICH, LKr, MUV)

Data taking conditions in 2015
- Minimum bias data: taken at 1% of design beam intensity
- Beam tracker not available: kaon momentum estimated as beam average
Search for HNL at NA62, single-track sample

Analysis outline

- Peak search performed in Missing Mass:
  \[ M_{\text{miss}} = \sqrt{(P_K - P_l)^2} \]

- Signal Regions:
  - \[ M_{\text{miss}}^e \in (170, 448) \text{ MeV/c}^2 \]
  - \[ M_{\text{miss}}^\mu \in (250, 373) \text{ MeV/c}^2 \]

Kaon decays in the fiducial volume\(^1\)

- \[ N_K^e = (3.00 \pm 0.11) \times 10^8 \]
- \[ N_K^\mu = (1.06 \pm 0.02) \times 10^8 \]

HNL MC simulation

- Acceptance vs. HNL mass:
  \[ A(m_{N_4}) \]

- \( M_{\text{miss}} \) resolution vs. HNL mass:
  \[ \sigma(m_{N_4}) \]

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\(^1\) Muon trigger chain was downsampled by a factor of \( \sim 3 \).

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Search for HNL at NA62, ULs on \( N_{\text{sig.}} \) and \( \mathcal{B}(K^+ \rightarrow l^+ N_4) \)

- Rolke-Lopez method used to determine UL on \( N_{\text{sig.}} \).
- Heavy neutrino mass step: 1 MeV/c\(^2\) in both cases
- Search window chosen to be \( \pm 1.5\sigma(m_{N_4}) \)
- Statistical significance never exceeds 3\(\sigma\): No signal observed
Summary and Outlook

NA62-\(R_K\) and NA62 HNL production searches in \(K^{\pm}\) decays were presented:

No HNL signal has been observed

- About 60 million \(K^+\) decays in the fiducial volume
- Improved limits on \(|U_{\mu 4}|^2\) for \(m_{N_4} \in (300, 375)\) MeV/c^2

- About 300 million \(K^+\) decays in the fiducial volume
- New limits on \(|U_{l 4}|^2\) reaching \(10^{-6} - 10^{-7}\)
  for \(m_{N_4} \in (170, 448)\) MeV/c^2 \((K^+ \rightarrow e^+ N_4)\) and
  for \(m_{N_4} \in (300, 373)\) MeV/c^2 \((K^+ \rightarrow \mu^+ N_4)\)

Future prospects
- Major analysis improvements with NA62 2016–2018 high intensity data (beam tracker fully commissioned)