Heavy Neutral Lepton Search at NA62

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Kaon Experiments at CERN

- **NA48** (1997-2001): Beam of $K_L/K_S$
  - Discovery of direct CPV
- **NA48/1** (2002): Beam of $K_S/\text{hyperons}$
- **NA48/2** (2003-2004): Beam of $K^+/K^-$
  - $K^\pm \rightarrow \mu^\pm N$, $N \rightarrow \mu \pi$
- **NA62-Rk** (2007-2008): Beam of $K^+/K^-$
  - $K^+ \rightarrow \mu^+ N$
- **NA62** (Since 2014): Beam of $K^+$
  - 2014: pilot run
  - 2015: Commissioning run
  - $K^+ \rightarrow \ell^+ N$
  - 2016-2018 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

NA62: ~ 200 participants, ~ 30 institutes
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- **NA48/2** (2003-2004): Beam of $K^+/K^-$
  - $K^\pm \rightarrow \mu^\pm N, N \rightarrow \mu \pi$
- **NA62-$R_k$** (2007-2008): Beam of $K^+/K^-$
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Why looking for heavy neutrinos

Open Theoretical questions:
1. Neutrino oscillations $\rightarrow$ non-zero neutrino masses
2. Why neutrinos are lighter than other leptons
3. Dark Matter $\rightarrow$ no SM particle satisfies DM properties
4. Baryon asymmetry
5. ...

SM extensions: **Neutrino Minimal SM** (\(\nu\)MSM) ([Asaka et al., PLB 620 (2005) 17](#))
- 3 right-handed steril neutrinos \(N_i\) are added to SM, \(m_1 \sim 10\ \text{keV}, \ m_{2,3} \sim 1\ \text{GeV}\),
- \(N_1\) is a 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)
If \( m_N < M_{K^\pm} - m_{\ell^\pm} \), heavy neutrinos are observable via production in K leptonic decay processes (\( K^\pm \rightarrow \ell^\pm N \)).

\[
\Gamma(K^\pm \rightarrow \ell^\pm N) = \Gamma(K^\pm \rightarrow \ell^\pm \nu_\ell) \rho(m_N) |U_{\ell 4}|^2
\]

Where:
- \( \rho(m_N) \rightarrow \) Kinematic factor, phase space and helicity suppression
- \( |U_{\ell 4}|^2 \rightarrow \) Mixing matrix element

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

R. Shrock PLB96 (1980) 159
**Main goal**
- 10% precision measurement of $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ see “J.Engelfried talk”

**Beam Parameters**
- Beam momentum: $75 \text{ GeV}/c(\pm 1\%)$
- Positive Beam: $\sim 6\%K^+$
- nominal intensity $750 \text{ MHz}$

**Main subdetectors**
- Trackers: Si pixel beam tracker(GTK), Straw tubes spectrometer (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 for 2015**
- Minimun bias data: taken at 1% of nominal beam intensity
- Beam tracker not available: kaon momentum estimated as beam average
**$K^+ \rightarrow \ell^+ N$: selection criteria**

**Event selection: $K^+ \rightarrow e^+ N \quad K^+ \rightarrow \mu^+ N$**

- single positive charged track in the spectrometer
- KTAG kaon signal
- no activity in photon-vetoes and CHANTI
- decay vertex in the fiducial decay region
- single cluster in LKr, no signal in muon detectors ($e^+$)
- signal in muon detectors ($\mu^+$)
- $E/p$ and RICH ($p<40$ GeV/c) to differentiate $e^+$ from $\mu^+$

**HNL production signal:** peaks in $m_{\text{miss}}^2 = (P_{K^+} - P_{\ell^+})^2$ distributions

**SM signal regions:**
- $e^+$: $|m_{\text{miss}}^2| < 0.014 \text{GeV}^2/c^4$
- $\mu^+$: $|m_{\text{miss}}^2| < 0.020 \text{GeV}^2/c^4$

**HNL signal regions:**
- $e^+$: $170 < m_{\text{miss}} < 448 \text{MeV}/c^2$
  
  \[
  (0.029 < |m_{\text{miss}}^2| < 0.2 \text{GeV}^2/c^4)
  \]
- $\mu^+$: $250 < m_{\text{miss}} < 373 \text{MeV}/c^2$
  
  \[
  (0.062 < |m_{\text{miss}}^2| < 0.14 \text{GeV}^2/c^4)
  \]
\( K^+ \rightarrow \ell^+ N \): measurement principle

- \( K^+ \rightarrow \ell^+ N \) decay rates measured with respect to the normalization SM \( K^+ \rightarrow \ell^+ \nu \)
- similar topologies and known branching fractions
- HNL signal events \( N^\ell_{\text{sig}} \) given by \( BR(K^+ \rightarrow \ell^+ N) \) assumptions and \( A^\ell_N \) acceptances of the \( K^+ \rightarrow \ell^+ N \) selections
  \[
  N^\ell_{\text{sig}} = N^\ell_K \cdot BR(K^+ \rightarrow \ell^+ N) \cdot A^\ell_N
  \]
- HNL search strategy: scan of \( m_{\text{miss}} = \sqrt{(P_K - P_{\ell^+})^2} \) distributions
  - 1\( \text{MeV}/c^2 \) step for mass scans in the HNL signal regions
  - search window size for each HNL mass hypothesis given by HNL mass resolution: \( |m - m_N| < 1.5\sigma_m \)
- statistical analysis
- HNL detailed MC simulation
  - HNL mass resolution \( \sigma_m \) vs HNL mass
  - selection acceptance vs HNL mass
**$K^+ \rightarrow \ell^+ N$ search results: limits**

Single event sensitivities of $O(10^{-8})$

- $N_{obs} \rightarrow$ Number of observed events in each HN mass hypothesis evaluated within $\pm 1.5\sigma_m$, with $1\,\text{MeV}/c^2$ mass scan step signal window
- $N_{exp} \rightarrow$ number of expected Background, evaluated using data for each HNL mass hypothesis with $m_{miss}$ distribution sidebands using polynomial fitting

Statistical significance never exceeds $2.2\sigma$:

- **No HNL signal observed**

$N_{obs}, N_{exp}$ and $\delta N_{exp}$ converted into confidence levels assuming Poissonian/Gaussian distributions for both distributions using Rolke-Lopez method to compute *90% CL*
$K^+ \rightarrow \ell^+ N$ search results: limits on $|U_{\ell 4}|$

$K^+ \rightarrow e^+ N$  \quad NA62-2015

Limit improved in a large mass range at the level of $10^{-7}$

- $K^+ \rightarrow \mu^+ N$  \quad $250 \leq m_N \leq 373 \text{ MeV}/c^2$
- $K^+ \rightarrow e^+ N$  \quad $170 \leq m_N \leq 448 \text{ MeV}/c^2$

HNL prospects with total data sample

2016 - 2018 data set

- Beam Tracker (GTK) in operation
  - Factor $\sim 2$ improvement in mass resolution
  - Factor $\sim 3$ lower background in $K^+ \rightarrow e^+ N$
  - Lower background from upstream decays in $K^+ \rightarrow \mu^+ N$
- Larger data set

Sensitivity better than $10^{-8}$ for $|U_{\mu 4}|^2$ and $|U_{e 4}|^2$

Larger data sets already collected. Analysis in progress
Beyond-Standard Model Model Particles

- **Dark Photon**
  - 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
  - **Forbidden \( K^+ \) decay searches**
    - **Goal:** Improve over most existing limits
    - Search for the LNV decay
      \[ K^+ \rightarrow \pi^- \mu^+ \mu^+ \]
    - Search for the LNV decay
      \[ K^+ \rightarrow \pi^- e^+ e^+ \]
    - Search for the LNV/LFV decay
      \[ K^+ \rightarrow \pi e \mu, \text{including } \pi^+ \pi^0 \text{ with } \pi^0 \rightarrow \mu e \]
    - Searches for \( K^+ \rightarrow \mu^- \nu e^+ e^+ \) and \( K^+ \rightarrow e^- \nu \mu^+ \mu^+ \)
    - Searches for \( \Delta S = \Delta Q \) violating decays
      \[ K^+ \rightarrow \pi^+ \pi^+ e^- \nu \] and
      \[ K^+ \rightarrow \pi^+ \pi^+ \mu^- \nu \]
**NA62 dump mode operation**

- TAXes (2 collimators): sliding copper and iron collimators, $2 \times 10.7 \lambda_I$ thick, higher Z than Be target, closer to the decay region → **DUMP**
- Easy to switch between $K^+$ beam and proton dump mode with TAXes
- Short dedicated runs in dump-mode with special low-bandwidth triggers
- Preliminary studies of background, rates and topologies have been performed: rejection power down to zero bkg at $\sim 4 \times 10^{15}$ POT for fully reconstructed di-muon final states
- **HNL** and Axion-like particles
Summary

- NA62 searches for HNL production in $K^+$ decays were presented:
  - No heavy neutrino signal observed

  - $N_K \sim 4 \times 10^8$ kaon decays in the fiducial volume
  - Set limits on $|U_{i4}|^2$

- NA62 physics run in progress up to 2018: a large sample of $K^+$ data in being collected

  - Main goal of measuring $BR(K^+ \to \pi^+ \nu \bar{\nu})$ with 10% accuracy
  - Broad program of rare decay measurements, hidden sector particles and LF/LN violation