SEARCH FOR $K^+$ DECAYS TO A LEPTON AND INVISIBLE PARTICLES

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Outline

- Heavy Neutral Leptons
- The NA62 Beam and Detector
- Search for HNLs in $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$.
- Search for $K^+ \rightarrow \mu^+\nu\bar{\nu}$ and $K^+ \rightarrow \mu^+\nu X$. 

**Search for HNLs in $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$.**

FV

**Search for $K^+ \rightarrow \mu^+\nu\bar{\nu}$ and $K^+ \rightarrow \mu^+\nu X$.**
Heavy Neutral Leptons (HNLs) and the vMSM

Standard Model very successful, but fails to explain:

- Neutrino masses
- Baryon asymmetry
- Dark matter

→ **vMSM extension** („*neutrino minimal SM extension“*, Asaka, Shaposhnikov, PLB 620 (2005) 17):

- Introduce **3 right-handed (sterile) neutrinos** $N_i$ which may mix with the classical, active neutrinos.

- **See-saw mechanism** with **lightest** $N_1$ mass of $\mathcal{O}(10 \text{ keV}) \rightarrow$ **dark matter candidate**.
  
  $N_2$ and $N_3$ masses of $\mathcal{O}(100 \text{ MeV} - 100 \text{ GeV})$.

- **Yukawa couplings** in the range $10^{-11}$ to $10^{-6}$. 

\[ \nu_\alpha = \sum_{i}^{3+k} U_{\alpha i} \nu_i \quad (\alpha = e, \mu, \tau); \quad k = 3 \]
HNL Production in $K^+$ Decays

If HNLs exist, they would be produced in processes containing active neutrinos with a rate proportional to the mixing parameters $|U_{\ell 4}|^2$ (only considering $k = 1$ here).

- Masses up to 0.5 GeV are observable in Kaon decays.
- **Master formula:** (Shrock, PLB 96 (1980) 159)

$$
\mathcal{B}(K^+ \rightarrow \ell^+ N) = \mathcal{B}(K^+ \rightarrow \ell^+ \nu) \cdot \rho\ell(m_N) \cdot |U_{\ell 4}|^2
$$

\[ \mathcal{O}(1) \]

- Kinematic factor effectively cancels helicity suppression in electron channel!
- **Branching fractions $K^+ \rightarrow \text{HNLs} = \mathcal{O}(\text{mixing parameter})$**

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**Figure:**

- Kinematic enhancement factor $\rho$ versus HNL mass.
- $\rho_{\mu}(m_N)$, $\rho_e(m_N)$, and $\Gamma(K-\text{ev})$ as a function of HNL mass.

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The NA62 Experiment

Fixed target Kaon experiment at the CERN SPS.

- About 200 participants
- Main goal: Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
The NA62 Beam and Detector

Beam

Magnet

Spectrometer

Target

RICH

The Apparatus
The NA62 Beam and Detector

1 m

$K^+$

CHANTI

Momentum selection & collimation

KTAG

Beam tracker

100 m

$X_{inv}$

1 m

100 m

150 m

E.M. calorimeters (large angles)

E.M. calorimeter (forward)

Hadron calorimeter

E.M. calorimeters (small angles)

Straw Spectrometer

~150 m

~100 m

1 m

CHANTI

vacuum

$\pi^+$

$\pi^-$

$\mu^+$

$\mu^-$

$\nu^+$

$\nu^-$

$\bar{\nu}^+$

$\bar{\nu}^-$

E.M. calorimeter (forward)

E.M. calorimeter (large angles)

RICH

EM calorimeters (forward)

EM calorimeters (small angles)

Hadron calorimeter

TARGET

Beam guard ring (CHANTI)

target

Detectors for decay products

Detectors for secondary beam

Beam guard ring (CHANTI)

Target
The NA62 Beam and Detector

SPS protons
400 GeV/c
$10^{12}$ protons/s
The NA62 Beam and Detector

**Detectors for Secondary Beam**
- Kaon ID (KTAG)
- Beam Tracker
- Beam guard ring (CHANTI)

**SPS protons**
- 400 GeV/c
- $10^{12}$ protons/s

**Secondary beam**
- 75 GeV/c, 750 MHz
- $K^+$ (6%), $\pi^+$ (70%), $p$ (23%)

**Momentum selection & collimation**

**KTAG**

**Beam tracker**

**CHANTI**

**E.M. calorimeters (large angles)**

**E.M. calorimeter (forward)**

**Hadron calorimeter**

**X_{inv}**

**~150 m**

**~100 m**

**1 m**

**target**

**Beam guard ring (CHANTI)**

**E.M. calorimeters (small angles)**

**Straw Spectrometer**

**Detectors for decay products**

**Detectors for Secondary Beam**

**~1 m**

**~150 m**

**~100 m**

**1 m**

**SPS protons**

**Secondary beam**

**RICH**

**E.M. calorimeters**

**E.M. calorimeter**

**CHANTI**

**vacuum**

**target**

**Beam guard ring (CHANTI)**

**E.M. calorimeters**

**E.M. calorimeter**

**Hadron calorimeter**

**Detectors for Secondary Beam**

**Kaon ID (KTAG)**

**Beam Tracker**

**Beam guard ring (CHANTI)**

**SPS protons**

**400 GeV/c**

**$10^{12}$ protons/s**

**Secondary beam**

**75 GeV/c, 750 MHz**

**$K^+$ (6%), $\pi^+$ (70%), $p$ (23%)**
The NA62 Beam and Detector

Detectors for Secondary Beam
- Kaon ID (KTAG)
- Beam Tracker
- Beam guard ring (CHANTI)

Detectors for Decay Products
- Charged Particle Tracking
- Photon Detection
- Particle ID

SPS protons
400 GeV/c
$10^{12}$ protons/s

Secondary beam
75 GeV/c, 750 MHz
$K^+ (6\%), \pi^+ (70\%), p (23\%)$

$K^+$ decay
60 m long
~ 5 MHz

Hadron calorimeter
E.M. calorimeter (forward)
E.M. calorimeters (small angles)
E.M. calorimeters (large angles)

KTAG
Beam tracker
Beam guard ring (CHANTI)
TARGET
Vacuum
Target

$K^+$
$X_{inv}$

1 m

100 m

150 m

1 m
Data Collection

Statistics, up to CERN Long Shutdown 2:

- **2016:** 30 days, 40% of nominal intensity, $2 \times 10^{11}$ useful kaon decays.
- **2017:** 161 days, 60% of nominal intensity, $2 \times 10^{12}$ useful kaon decays.
- **2018:** 217 days, 60% of nominal intensity, $4 \times 10^{12}$ useful kaon decays.

Trigger streams:

- **$K^+ \rightarrow \pi^+\nu\bar{\nu}$ trigger:** 1 track, $\gamma/\mu$ veto, used for $e^+$ channels. No downscaling.
- **Control trigger/400:** Single charged particle in the CHOD acceptance (*minimum bias*), used for $\mu^+$ channels. Downscaled by $D = 400$. 
Searches for HNLs in

\[ K^+ \rightarrow e^+N \text{ and } K^+ \rightarrow \mu^+N \text{ Decays} \]
Search for $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$

Measurement of squared missing mass from $K^+$ and lepton 4-momenta:

\[ m_{\text{miss}}^2 = (p_{K^+} - p_{\text{lepton}})^2 \]

= mass$^2$ of invisible particle

→ HNL signal: sharp peak in $m_{\text{miss}}^2$ spectra.

Selections & reconstruction fairly simple:

- $K^+$ and $l^+$ reconstruction & matching.
- Powerful particle ID (RICH, LKr, MUV).
- Vetoing of extra activity.
Search for $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$

Measurement of squared missing mass from $K^+$ and lepton 4-momenta:

$$m^2_{\text{miss}} = (p_{K^+} - p_{\text{lepton}})^2$$

= mass$^2$ of invisible particle

→ HNL signal: sharp peak in $m^2_{\text{miss}}$ spectra.

NA62 data:

<table>
<thead>
<tr>
<th></th>
<th>$K^+ \rightarrow e^+N$</th>
<th>$K^+ \rightarrow \mu^+N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>control (D=400)</td>
</tr>
<tr>
<td>$N_k$ in fiducial volume</td>
<td>$3.5 \times 10^{12}$</td>
<td>$1.1 \times 10^{10}$</td>
</tr>
<tr>
<td>Selected SM decays</td>
<td>$3.5 \times 10^6$</td>
<td>$2.2 \times 10^9$</td>
</tr>
</tbody>
</table>
Limits on $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$

Scan $m_{\text{miss}}^2$ spectra over possible HNL masses, based on the missing-mass resolution $\sigma(m_{\text{miss}}^2)$:

- The scan is performed in step sizes of $\mathcal{O}(1 \text{ MeV})$ (depending on the mass or mass resolution).

- At each scanned mass, a window of $\pm 1.5 \sigma$ is put around the scanned mass value and the expected (SM) events are obtained from a polynomial fit to the sidebands.

- Limits on $|U_{e4}|^2$ and $|U_{\mu4}|^2$:
  CL$_S$ comparison between observed and expected event numbers in each window.
Limits on $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$

**$K^+ \rightarrow e^+N$:**

(PLB 807 (2020) 135599)

- Less sensitivity close to the $\pi^+$ decay threshold (stricter selection).
- Maximum significance: $3.6\sigma$ for $m_N = 346$ MeV.
- Accounting for look-elsewhere effect:
  Global significance = $2.2\sigma$.

**$K^+ \rightarrow \mu^+N$:**

(PLB 816 (2021) 136259)

- Local significance never exceeds $3\sigma$.
  $\rightarrow$ no HNL production signals observed.
Results of HNL Searches

- No HNL signals observed in NA62.
- Limits on $|U_{e4}|^2$ of $\mathcal{O}(10^{-9})$, limits on $|U_{\mu4}|^2$ of $\mathcal{O}(10^{-8})$.
- $K^+ \rightarrow e^+N$:
  Values favored by Big Bang Nucleosynthesis (BBN) constraint (dashed red line) are excluded for HNL masses < 340 MeV.
- $K^+ \rightarrow \mu^+N$:
  Consistent with E949 and extending limits to higher HNL masses.
Searches for $K^+ \rightarrow \mu^+ \nu \nu \bar{\nu}$ and $K^+ \rightarrow \mu^+ \nu X$
Searches for $K^+ \rightarrow \mu^+\nu\bar{\nu}$ and $K^+ \rightarrow \mu^+\nu X$

$K^+ \rightarrow \mu^+\nu\bar{\nu}$:

- Very rare in the Standard Model: \( \text{Br} \approx 1.6 \times 10^{-16} \)
  (Gorbunov, Mitofanov, JHEP 10 (2016) 039).

- Current limit: \( \text{Br} < 2.4 \times 10^{-6} \)
  (E949, PRD 94 (2016) 032012).

$K^+ \rightarrow \mu^+\nu X$:

- $X$ is a scalar or vector particle
  (Krnjaic et al., PRD 124 (2020) 041802).
Searches for $K^+ \rightarrow \mu^+\nu\nu\bar{\nu}$ and $K^+ \rightarrow \mu^+\nu X$

$K^+ \rightarrow \mu^+\nu\nu\bar{\nu}$:
- Search region: $m^2_{\text{miss}} > 0.1 \text{ GeV}^2/c^4$ (optimized for strongest limit extraction).
- Observed events: 6894
  MC expectation: $7549 \pm 92$
  $\Rightarrow \text{Br}(K^+ \rightarrow \mu^+\nu\nu\bar{\nu}) < 1.0 \times 10^{-6}$ at 90% CL.

$K^+ \rightarrow \mu^+\nu X$:
- Limit extraction similar to $K^+ \rightarrow \mu^+ N$ in the mass range $10 - 370$ MeV.
- No signal observed.
- Upper limits of $\mathcal{O}(10^{-7} - 10^{-5})$. 

(PLB 816 (2021) 136259)
Conclusions & Outlook

- World-best limits on HNL mixing parameters with full NA62 data set before LS2:
  \[ \mathcal{O}(10^{-9}) \text{ limits on } |U_{e4}|^2, \quad \mathcal{O}(10^{-8}) \text{ limits on } |U_{\mu 4}|^2 \] (PLB 807 (2020) 135599, PLB 816 (2021) 136259).

- Searches for \( K^+ \rightarrow \mu^+ \nu \nu \bar{\nu} \) and \( K^+ \rightarrow \mu^+ \nu X \) performed:
  \[ \rightarrow \text{Again world-best limits of } \mathcal{O}(10^{-7}) - \mathcal{O}(10^{-9}) \] (PLB 816 (2021) 136259).

- In 2021 NA62 started new data-taking period covering the full time up to LS3.
  \[ \rightarrow \text{Running at 30\% higher beam intensity and collect } \mathcal{O}(10^{13}) K^+ \text{ decays.} \]
  \[ \rightarrow \text{Plan to collect } 10^{18} \text{ protons-on-target in “dump mode” } \rightarrow \text{ further HNL searches.} \]