Search for LNV and limits on Heavy Neutral Leptons by the CERN Kaon experiments

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* On behalf of the NA48/2 & NA62 Collaborations
Outlook

- Heavy Neutral Leptons (HNL) searches - Theoretical motivations
- Kaon physics at CERN: the NA48 & NA62 experiments
- Search for HNL in $K^+ \rightarrow \ell^+N (\ell=e,\mu)$ decays @ NA62 (2007 & 2015 data)
- Search for LNV and HNL decays in $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\pm$ decays @ NA48/2
- Conclusions

Also at this conference: more NA62 results by Bob Velghe on $K^+ \rightarrow \pi^+\nu\nu$ preliminary observation at CERN
Heavy Neutral Leptons

- Observation of neutrino oscillations
  → Neutrino masses need to be accommodated in the SM
- Heavy Neutrinos (HN): the neutrino minimal SM ($\nu$MSM)
  → adding to the SM 3 right-handed sterile neutrinos $N_i$

- $N_1$ is the lightest: $m_1 \sim O(10 \text{ KeV}/c^2)$ → Dark Matter candidate
- $N_2$ and $N_3$: mass $\sim O(\text{MeV}/c^2 \text{ to GeV}/c^2)$ introduce extra CPV-phases to account for Baryon Asymmetry of the Universe (BAU) and produce standard neutrino masses through See-Saw mechanism with a Yukawa coupling of $\sim 10^{-8}$

The model explains simultaneously:
- Neutrino oscillations and smallness of neutrino masses
- Cosmic Dark Matter (DM) candidate
- BAU: leptogenesis due to Majorana mass term

The branching fraction involving the HNL mass state

$$B(K^+ \rightarrow \ell^+ N) = B(K^+ \rightarrow \ell^+ \nu_\ell) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2$$

where $|U_{\ell 4}|$ are elements of the extended neutrino mixing matrix between the SM flavour and HNL mass state:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Active-sterile neutrino $N_i$ mixing with SM particles is described by the U-matrix

Effective vertices involving $N_i$, $W^\pm/Z$ bosons and SM leptons
Heavy Neutral Leptons

- HNL can be produced in the decay of beauty, charm and strange hadrons and by photons originated in the interaction of protons of a target.
- HNL coupling to SM particles are very suppressed → production rates of $10^{-10}$ or less.
- Since charm and beauty cross sections increase with the energy, a high intensity, high energy proton beam is required to improve over the current results.
- HNL are expected to be long-lived.

The decays of HNL to SM particles can be detected by experiments with long decay volumes followed by a spectrometer with particle id capability.

In this talk I present searches for HNL at the CERN SPS with the Kaon experiments NA48/2 and NA62.

**Production of HNL:**

$K, B, Bs, D, Ds \rightarrow \text{lepton} + \text{HN}$

$K, B, Bs, D, Ds \rightarrow \text{semi-leptonic modes}$

$\sigma(pp \rightarrow s\bar{s} \rightarrow X)/\sigma(pp \rightarrow X) \sim 0.15$

$\sigma(pp \rightarrow c\bar{c} \rightarrow X)/\sigma(pp \rightarrow X) \sim 2 \times 10^{-3}$

$\sigma(pp \rightarrow b\bar{b} \rightarrow X)/\sigma(pp \rightarrow X) \sim 1.6 \times 10^{-7}$
HNL searches with Kaons

• If $m_N < (m_K - m_\ell)$ the HNL can be observed in kaon decays.

**PRODUCTION:** search for peaks in $m_N^2 = m_{\text{miss}}^2 = (p_K - p_\ell)^2$

$$\text{BR}(K^+ \rightarrow \ell^+N) = \frac{\text{BR}(K^+ \rightarrow \ell^+\nu_\ell) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2}{\text{BR}(K^+ \rightarrow \ell^+\nu_\ell) \times \rho_\ell(m_N)}$$

**DECAY:** HNL decay only into *SM particles* $\Gamma(N \rightarrow SM \text{ part}) \sim |U_{\ell 4}|^2 \times m_N^3$

• If $m_N < 500 \text{ MeV}/c^2$ the main decays are:

  $N \rightarrow \pi^0\nu$, $N \rightarrow \pi^\pm\ell^\mp$ ($\ell = e, \mu$), $N \rightarrow \nu\nu\nu$

• Assuming $|U_{\ell 4}|^2 < 10^{-4}$

  – mean free path of $K^+ \rightarrow \mu^+N$ and $K^+ \rightarrow e^+N > 10 \text{ Km}$ in NA62

  – analysis possible in dump mode


**NA48/2:** HNL production + decay

• Model dependent (HNL decay modes and lifetime)

• Sensitive to short-lived (unstable) HNL

• Sensitive to the Majorana/Dirac nature of HNL ($|\Delta L|=2$ transitions)

• Search done on a sample of 3-track vertex events (LNC & LNV): $K^\pm \rightarrow \mu^\pm N$ and $N \rightarrow \mu\pi$

**NA62:** HNL production only

• Independent of HNL decay modes

• Sensitive to long-lived (or stable) HNLs

• Seeking peaks in the missing mass $m_{\text{miss}} = \sqrt{(p_K - p_\ell)^2}$ spectrum ($\ell^+ = e^+, \mu^+$)

• Search done on samples of minimum bias trigger events: $K^+ \rightarrow \mu^+ N (2007); K^+ \rightarrow e^+ N, \mu^+ N (2015)$
NA48 and NA62 experiments at CERN

A fixed target experiment at the CERN SPS dedicated to the study of CP violation and rare decays in the kaon sector….

Direct CP Viol. NA48 result: \( \varepsilon'/\varepsilon = (14.7 \pm 2.2) \times 10^{-4} \)

\[ \Gamma(K^\pm e_2) / \Gamma(K^\pm \mu_2) \] (LFU)

NA48 : \( K_L + K_S \)
Search for direct CPV : Measurement of \( \varepsilon'/\varepsilon \)

NA48/1 : \( K_S \)
Rare \( K_S / \) Hyperon decays, CPV tests

NA48/2 : \( K^+ + K^- \)
Search for direct CPV : Charge asymmetry measurement

NA62-2007 : \( K^+ + K^- \)
\[ R_K = \Gamma(K^\pm e_2) / \Gamma(K^\pm \mu_2) \] measurement (LFU)

NA62 : \( K^+ \)
Measurement of the decay \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

1997
1998
1999
2000
2001
2002
2003
2004
2007
2008
2015
2016
2018
2020?
Simultaneous, unseparated, focused charged hadron beam; \( K \approx 6\% \)
- Kaon decays in the vacuum tank: 22\%
- Flux ratio: \( K^+/K^- \approx 1.8 \)
- Similar acceptance for \( K^+ \) and \( K^- \) decays
- \( p_K = (60 \pm 3.0) \text{ GeV/c} \) (NA48/2)
- \( p_K = (74 \pm 1.4) \text{ GeV/c} \) (NA62-R\(_K\))

Decay region, in vacuum: 114 m

**Liquid Krypton em calorimeter (LKr)**

\[ \sigma_E / E = (3.2 / \sqrt{E} \oplus 9.0 / E \oplus 0.42)\% \quad (E \text{ in GeV/}) \]

\[ \sigma_x = \sigma_y = 4.2 / \sqrt{E} \oplus 0.6 \text{ mm} \quad (E \text{ in GeV/}) \]

**Magnetic spectrometer** (4 DCHs + dipole magnet)

\[ \sigma_p / p = (1.0 \oplus 0.044 \text{ p})\% \quad (p \text{ in GeV/c}) \quad \text{NA48/2} \]

\[ \sigma_p / p = (0.48 \oplus 0.009 \text{ p})\% \quad (p \text{ in GeV/c}) \quad \text{NA62-R}_K \]

**Charged scintillator Hodoscope** \( \sigma_t = 150 \text{ ps} \)

**Muon counter**
Primary beam: CERN SPS protons
- \(3 \times 10^{12}\) ppp, 3.4 s effective spill
- 750 MHz @GTK
- 400 GeV/c \((x3 \text{ NA48/2})\)

Secondary beam:
- unseparated positive beam \(\pi/K/p\)
- \(K^+ \sim 6\%\), \(p_K = 75\) GeV/c \((\Delta p/p \sim 1.1\%)\)
- \(K^+\) decays/year = \(4.5 \times 10^{12}\) \((\times 45 \text{ NA48/2})\)
- integrated average rate
- average \(K\) decay rate \(\approx 10\) MHz

Goal: measurement of \(\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) @ 10\%\) accuracy

Decay region
- Fiducial decay region 60 m
- Vacumm \(10^{-6}\) mbar
- \(K^+\) decay rate \(\sim 5\)MHz

Main detectors:
- Tracking: beam Si pixel tracker (GTK); Straw chambers in vacuum for decay products
- PID: beam Cherenkov for \(K^+\) (KTAG); RICH + MUVs for \(\pi/\mu/e\)
- Hermetic veto: calorimeters for \(\gamma/\mu\)
Heavy Neutral Leptons search @ NA62
(from 2007 and 2015 data samples)

The NA62 single muon sample

Only $K^+$ beam data (43% of NA62-2007 sample) $\rightarrow$ higher muon halo rejection

**Event selection**
- One well reconstructed $\mu^+$ track
- No extra clusters in LKr with $E > 2$ GeV
- Five-dimensional ($z_{vertex}$, $\theta$, $p$, CDA, $\phi$) kinematic suppression of muon halo

**Data driven study of:**
- Halo background
- Spectrometer resolution tails
- Trigger and $\mu$-ID efficiencies

**HNL detailed MC simulation for:**
- Acceptance vs HNL mass: $A(m_{N4})$
- $m_{miss}$ peak resolution vs HNL mass: $\sigma(m_{N4})$
- MC samples generated at 1 MeV/$c^2$ mass intervals

**Kaon decays in the fiducial volume**
- $N_K \sim 6 \times 10^7$ (from reconstructed $K^+ \rightarrow \mu^+\nu$)  
  (downscaling $D=150$ for the 1-track $\mu$ trigger)

$K^+ \rightarrow \mu^+N :$ Search for peaks in $m_{miss} = \sqrt{(p_K - p_\mu)^2}$

Signal region: $m_{miss}(\mu^+)$ in range [300 – 375] MeV/$c^2$

No HNL decay in the detector
Uncertainty on expected background:

-Muon halo background 5\%-20% 
-Statistical uncertainty on muon halo background dominates for HNL masses > 300 MeV/c^2 
-Kaon decays <1% (mainly K_{\mu3})

Upper Limit on \( K^+ \mu^+ N_4 \) signal events

-1 MeV/c^2 mass steps 
-Mass window size : ±(\sigma_{HN} = 12 \text{ MeV/c}^2 - 0.03 \times m_{HN}) 
-Rolke-Lopez method to get UL(\( N_{\text{sig}} \))

No HNL signal above 3\& observed
From $N_{\text{sig}}$ to BR:

$$\text{BR}_{UL}(K^+ \rightarrow \mu^+ N_4) = \frac{UL(N_{\text{sig}})}{N_k \times \text{Acceptance}}$$

From BR to $|U_{\mu 4}|^2$:

$$|U_{\mu 4}|^2 = \frac{1}{f(m_{HN})} \times \frac{\text{BR}(K^+ \rightarrow \mu^+ N_4)}{\text{BR}(K^+ \rightarrow \mu^+\nu_{\mu})}$$

**Graphs:**
- **Left Graph:**
  - X-axis: Heavy neutrino mass (MeV/c^2)
  - Y-axis: UL on $\text{BR}(K^+ \rightarrow \mu^+ N_4)$ at 90% CL
  - Expected limits and observed limits are shown.

- **Right Graph:**
  - X-axis: Heavy neutrino mass (MeV/c^2)
  - Y-axis: UL on $|U_{\mu 4}|^2$ at 90% CL
  - Expected limits and observed limits are shown.

**References:**
In 2015 NA62 collected 5 days of Min Bias data at 1% of nominal beam intensity
No beam tracker: $p_K$ given by beam average
Analysis of data shows: $\sim 24M K^+ \rightarrow \mu^+\nu_\mu$ ($1767 K^+ \rightarrow e^+\nu_e$) decays with a background level 100 times lower wrt NA62-2007 → Can set world most stringent limits on heavy neutrino production

Event selection for $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$
- one positive charged track
- positrons and muons identified by the $E/p$ ratio + MUV info and RICH up to 40 GeV
- one single electron clusters in the LKr calorimeter
- no photons in the photon-veto detector

HNL detailed MC for:
- Acceptance vs HNL mass: $A(m_{N4})$
- $m_{\text{miss}}$ peak resolution vs HNL mass: $\sigma(m_{N4})$

Search for peaks in $m_{\text{miss}} = \sqrt{(p_{K} - p_{l+})^2}$
Signal region: $m_{\text{miss}}$ in range [170 – 448] and [250-373] MeV/c²

\[ a \]
\[ b \]
Upper limit on signal events
- 1 MeV/c² mass scan steps
- search window size for each mass hypothesis: ±1.5 \( \sigma(m_N) \)
- Rolke-Lopez method to get UL\((N_{\text{sig}})\)

For each \( m_N \) hypothesis:
- numbers of expected \((N_{\text{exp}})\) and observed \((N_{\text{obs}})\) events, together with the uncertainty on \( N_{\text{exp}} \) (\( \delta N_{\text{exp}} \) as shown by the blue band)
- obtained expected and observed upper limits at 90% CL on the numbers of \( K^+ \rightarrow \ell^+N \) events

\[
B_{\text{SES}}(K^+ \rightarrow \ell^+N) = \frac{1}{[N_K \times A(K^+ \rightarrow \ell^+ N)]}
\]

\[
|U_{\ell4}|^2_{\text{SES}} = B_{\text{SES}}(K^+ \rightarrow \ell^+N)/[B(K^+ \rightarrow \ell^+\nu) \times \rho_{\ell}(m_N)]
\]

No HNL signal observed above 3\( \sigma \) significance
Current results on HNL searches: $|U_{\ell 4}|^2$

### Latest results on limits from production searches

<table>
<thead>
<tr>
<th>$U_{\ell 4}$ at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK (1984) $K^+ \rightarrow \mu^+ N, K^+ \rightarrow e^+ N$</td>
</tr>
<tr>
<td>TRIUMF (1992) $\pi^+ \rightarrow e^+ N$</td>
</tr>
<tr>
<td>NA62-2007 (2017) $K^+ \rightarrow \mu^+ N$</td>
</tr>
<tr>
<td>NA62-2015 $K^+ \rightarrow \mu^+ N, K^+ \rightarrow e^+ N$</td>
</tr>
<tr>
<td>PIENU (2017) $\pi^+ \rightarrow e^+ N$</td>
</tr>
<tr>
<td>E949 (2015) $K^+ \rightarrow \mu^+ N$</td>
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</tbody>
</table>

### $K^+ \rightarrow \mu^+ N$

**NA62 (2007) data**

About 60 billion $K^+$ decays

Improved limits in $300 \leq m_N \leq 375 \text{ MeV}/c^2$


### $K^+ \rightarrow e^+ N$

**NA62 (2015) data**

About 300 billion $K^+$ decays

New limits $O(10^{-6-7})$ in $170 \leq m_N \leq 448 \text{ MeV}/c^2$


### $K^+ \rightarrow \mu^+ N$

**NA62 (2015) data**

About 100 billion $K^+$ decays

New limits $O(10^{-6-7})$ in $250 \leq m_N \leq 373 \text{ MeV}/c^2$


**Prospects → NA62-2016 data:** $K^+ \rightarrow e^+ N$ analysis quite advanced, improvements due to higher beam intensity, commissioned beam tracker → higher sensitivity → $|U_{e4}|^2$ limit expected to decrease by 1-2 order of magnitude.
Search for LNV and resonances in $K^\pm \to \pi \mu \mu$ decays @ NA48/2

Two different samples:

• same-sign muons sample LNV decay
• opposite sign muons sample LNC decay

Kaon Physics

LNV in NA48/2

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Kaon decays in the fiducial volume

\[ N_K \sim 2 \times 10^{11} \text{ (from reconstructed } K^\pm \rightarrow \pi^\pm \pi^+ \pi^-) \]

Search for \( K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm \rightarrow |\Delta L| = 2 \) transitions mediated by Majorana neutrino exchange

**Blind analysis:**
- Selection based on MC simulation of \( K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm \) and \( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \)
- Additional \( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \) MC sample for background estimation
- Control region \( M(\pi^\mp \mu^\pm \mu^\pm) < 480 \text{ MeV/c}^2 \)

**Event selection:**
- One well reconstructed 3-track vertex
- 2 same-sign muons, 1 odd sign pion
- Total \( P_t \) consistent with zero
- Signal region \( |M(\pi^\mp \mu^\pm \mu^\pm) - M_K| < 5 \text{ MeV/c}^2 \)

Events in Signal Region observed after \( K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm \) selection:
- \( N_{\text{obs}} = 1 \)
- \( N_{\text{exp}} = 1.160 \pm 0.865 \)

Rolke-Lopez method to get \( \text{UL}(N_{\text{signal}}) \)

**World best limit**

\[ \text{BR}(K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} \text{ @ 90\% CL} \]
Event selection:
- Similar to same-sign muon sample
- One well reconstructed 3-track vertex
- 2 opposite-sign muons, 1 same-sign pion
- Total $P_t$ consistent with zero
- Signal region $|M(\pi^\pm \mu^+ \mu^-) - M_k| < 8$ MeV/$c^2$

- **3489 $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$** candidates in Signal Region
- **$K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$** Background: (0.32 ± 0.09)%
HN resonance search in LNV sample

Same-sign $\mu$ sample: search for $K^\pm \rightarrow \mu^\pm N_4 \left( N_4 \rightarrow \pi^\mp \mu^\pm \right)$

$$UL(N_{\text{sig}})$$

$$UL(BR(K^\pm \rightarrow \mu^\pm N_4) \times BR(N_4 \rightarrow \pi^\mp \mu^\pm)) = \frac{UL(N_{\text{sig}})}{N_k \cdot \text{Acceptance}}$$

Statistical significance never exceed $3\sigma$: no signal observed

$z = \frac{N_{ \text{obs}} - N_{ \text{exp}}}{\sqrt{\sigma(N_{ \text{obs}}) \oplus \sigma(N_{ \text{exp}})}}$
Opposite-sign $\mu$ sample: search for $K^\pm \rightarrow \mu^\pm N_4 (N_4 \rightarrow \pi^\pm \mu^\mp)$

\[ UL(N_{\text{sig}}) \]

\[ UL(\text{BR}(K^\pm \rightarrow \mu^\pm N_4) \cdot BR(N_4 \rightarrow \pi^\pm \mu^\mp)) = \frac{UL(N_{\text{sig}})}{N_K \times \text{Acceptance}} \]

Statistical significance never exceed 3$\sigma$: no signal observed
NA48/2 and NA62 are Kaon experiments at CERN with a broad physics program that includes studies of the neutrino sector.

**NA48/2: HNL Production + Decay**

- Search for LNV $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\pm$ decay:
  - $\text{BR}(K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} @ 90\% \text{ CL}$ (World Best Limit)
  - Factor 10 improvement wrt previous best limit ($1.1 \times 10^{-9} @ 90\% \text{ CL}$)

- Search for $K^\pm \rightarrow \mu^\pm N_4 (N_4 \rightarrow \pi^\pm \mu^\mp)$ (LNC Heavy neutrino)
  - Limits on BR products of the order of $10^{-9}$ for HNL lifetimes < 100 ps

- Search for $K^\pm \rightarrow \mu^\pm N_4 (N_4 \rightarrow \pi^\pm \mu^\mp)$ (LNV Majorana neutrino)
  - Limits on BR products of the order of $10^{-10}$ for HNL lifetimes < 100 ps

**NA62-2007: HNL Production in $K^+ \rightarrow \mu^+ N_4$ decays**

- Limits on $\text{BR}(K^+ \rightarrow \mu^+ N_4) \sim 10^{-5}$
- Limits on $|U_{\mu 4}|^2 \sim 10^{-5}$ for $m_{HN} > 300 \text{ MeV/c}^2$

**NA62-2015: HNL Production in $K^+ \rightarrow \ell^+ N_4 (\ell = e, \mu)$**

- Limits on $|U_{\ell 4}|^2 \sim 10^{-7} - 10^{-6}$ for $m_{HN} [170 ÷ 448]$ and $[250 ÷ 373] \text{ MeV/c}^2$ respectively

**NA62 perspectives:** 2016-2018 data set: $K^+ \rightarrow \ell^+ \ell^-$ event yield expected to be larger with improved mass resolution and much lower bkg

- Also improved results from $K^+ \rightarrow \pi \ell \ell$ expected in the coming years
2015 data

- 12000 SPS spills (collected over 5 days)
- Beam intensity typically 1% of the nominal
- Low-level trigger scheme based on minimum-bias signals in CHOD and MUV
- High-level trigger based on KTAG signals
- GTK under commissioning (not used)
The NA62 detector (*see next talk)

**Primary beam: CERN SPS protons**
- $3 \times 10^{12}$ ppp,
- 400 GeV/c ($\times 3$ NA48/2)

**Secondary beam:**
- unseparated positive beam $\pi/K/p$
- $K^+ \sim 6\%$, $p_K = 75$ GeV/c ($\Delta p/p \sim 1.1\%$)
- $K^+$ decays/year = $4.5 \times 10^{12}$ ($\times 45$ NA48/2)
- integrated average rate = 750 MHz
- average $K$ decay rate $\approx 10$ MHz

**Goal:** measurement of $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ @ 10% accuracy
- O(20) SM events/year
- 2014: detector commissioning
- 2015: Trigger and high intensity beam line commissioning, detector quality studies
- 2016: High level trigger and full beam tracker commissioning, physics analysis (ongoing)
- Data samples
  - 2015: Low intensity beam, minimum bias trigger
  - 2016-2018: Stable conditions up to 40% of nominal intensity
**The NA62 single muon sample**

Only $K^+$ beam data (43% of NA62-2007 sample) $\rightarrow$ higher muon halo rejection

**Event selection**
- One well reconstructed $\mu^+$ track
- No extra clusters in LKr with $E > 2$ GeV
- Five-dimensional ($z_{\text{vertex}}$, $\theta$, $p$, $CDA$, $\phi$) kinematic suppression of muon halo

**Data driven study of:**
- Halo background
- Spectrometer resolution tails
- Trigger and $\mu$-ID efficiencies

**HNL detailed MC simulation for:**
- Acceptance vs HN mass: $A(m_{N4})$
- $m_{\text{miss}}$ peak resolution vs HN mass: $\sigma(m_{N4})$
- 1 MeV/c$^2$ mass intervals

**Kaon decays in the fiducial volume**
- $N_K \sim 6 \times 10^7$ (from reconstructed $K^+ \rightarrow \mu^+\nu$) (downscaling $D=150$ for the 1-track $\mu$ trigger)

**Search for peaks in** $m_{\text{miss}} = \sqrt{(p_K - p_{\mu})^2}$

**Signal region:** $m_{\text{miss}}(\mu^+)$ in range [300 – 375] MeV/c$^2$

**Uncertainties on background**
- Strong limit exists below
- No acceptance above
• The limits on $n_{UL}$ are converted into limits on the branching fractions

$$B(K^+ \rightarrow e^+ N) \quad \text{and} \quad B(K^+ \rightarrow \mu^+ N) \quad \text{via} \quad B(K^+ \rightarrow \ell^+ N) = \frac{n_{UL}^\ell}{N_{K^+}^\ell A_N^\ell(m_N)}$$

which depends on the HNL acceptance $A_N^\ell(m_N)$
Comparison to existing peak search measurements

\[ |U_{\mu 4}|^2 = \frac{1}{f(m_{HN})} \cdot \frac{BR(K^+ \rightarrow \mu^+ N_4)}{BR(K^+ \rightarrow \mu^+ \nu_\mu)} \]

\( f(m_h) \) accounts for the phase space factor and the helicity suppression, and varies in the range 1.5–4.0 for \( m_{HN} \) in the region 300–375 MeV/c² considered in the present analysis.

- **NA62-2007 result extends the mass range for UL on \( |U_{\mu 4}|^2 \) in HN production search experiments**
  - Most stringent limit on HN production in the mass region \( 300 < m_{HN} < 375 \) MeV/c²

\[ \mathcal{B}_{\text{SES}}(K^+ \to \ell^+N) = \frac{1}{[N_K \times A(K^+ \to \ell^+ N)]} \]

\[ |U_{\ell4}|^2_{\text{SES}} = \frac{\mathcal{B}_{\text{SES}}(K^+ \to \ell^+N)}{[\mathcal{B}(K^+ \to \ell^+\nu) \times \rho_\ell (m_N)]} \]
Limit setting procedure

- Set limits on the number of HNL decays $n_{UL}$ using Rolke-Lopez method [4]
- The limit is computed based on number of observed $n_{obs}$ events, the number of expected events $n_{exp}$, and the uncertainty on $n_{exp}$

- Limit computed in steps of $1\text{MeV}/c^2$ across the HNL mass range
- $n_{obs}$ determined by counting events in a “search window” of $1.5\sigma_m$ at each HNL mass step
- $n_{exp}$ estimated by fitting data events outside of the search window
Limits on number of HNL decays

$K^+ \rightarrow e^+ N$

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

- Limits on the number of $K^+ \rightarrow e^+ N$ are set at the level of $O(30)$ events
- Limits on the number of $K^+ \rightarrow \mu^+ N$ are set at the level of $O(20)$ events
Fig. 2. Acceptances as functions of the assumed resonance mass and lifetime of: (a) the $K^{\text{LNV}}_{\pi\mu\mu}$ selection for $K^{\pm} \rightarrow \mu^{\pm} N_4$, $N_4 \rightarrow \pi^{\mp} \mu^\pm$ decays; (b) the $K^{\text{INC}}_{\pi\mu\mu}$ selection for $K^{\pm} \rightarrow \mu^{\pm} N_4$, $N_4 \rightarrow \pi^{\mp} \mu^\pm$ decays; (c) the $K^{\text{INC}}_{\pi\mu\mu}$ selection for $K^{\pm} \rightarrow \pi^{\pm} X$, $X \rightarrow \mu^{\pm} \mu^-$ decays. For resonance lifetimes $\tau > 1$ ns the acceptances scale as $1/\tau$ due to the required three-track vertex topology of the selected events. In the LNV selection, the tighter $M_{\pi\mu\mu}$ cut leads to a 5% smaller acceptance. The mass dependence in case (c) differs from the others due to the $p > 15$ GeV/c pion momentum cut, not applied to muons (Sec. 2).
Search for $K^\pm \rightarrow \pi^\pm X \ (X \rightarrow \mu^+\mu^-)$ decay

UL ($BR(K^\pm \rightarrow \pi^\pm X) \times BR(X \rightarrow \mu^+\mu^-)$) = \frac{UL(N_{\text{sig}})}{N_{K} \times \text{Acceptance}}

Acceptance $\sim 1/\tau$ for $\tau > 1\text{ ns}$

Statistical significance never exceeds $+3\sigma$

No signal observed!

Warsaw, 29/11/16

DISCRETE 2016
From UL on BR to UL on $|U_{\mu 4}|^2$:

$$|U_{\mu 4}|^2 = \frac{8\sqrt{2\pi}\hbar}{G_F\sqrt{M_K}\tau_K f_K f_\pi |V_{us}V_{ud}|} \sqrt{\frac{\mathcal{B}(K^\pm \to \mu^\pm N_4)\mathcal{B}(N_4 \to \pi \mu)}{\tau_{N_4} M_{N_4}^5 \lambda^2 (1, r_{\mu}^2, r_{N_4}^2) \lambda^2 (1, \rho_{\pi}^2, \rho_{\mu}^2) \chi_{\mu\mu}}}$$

**Same sign $\mu$ sample (LNV)**

**Opposite-sign $\mu$ sample (LNC)**

- **UL on $|U_{\mu 4}|^2$ at 90% CL**

- **UL on $|U_{\mu 4}|^2$ at 90% CL**

- **NA48/2 limits on $|U_{\mu 4}|^2$ only applies to short lived HN ($\tau < 100$ ps)**
Limits on $|U_{\mu 4}|^2$
NA62 in dump mode

A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:

NA62: **Muon halo & neutrino halo**

- **Muons** produce inelastic interactions and combinatorial background
  - In beam mode about $\sim 5$ MHz of $\mu^+$ and 150 kHz $\mu^-$ present due to early decays in flight of $K$ and $\pi$ in the beam
  - In dump mode the muon halo is reduced by 2 orders of magnitudes (2016 data)
- **Neutrinos** produce inelastic interactions in the material surrounding the Fiducial Volume
  - In dump mode about $\sim 10$ GHz of active neutrinos are expected at nominal condition
Assume to detect all 2-track final states, including open channels, and zero background.

Zero background for charged particle final states has been proven at $\sim 4 \times 10^{15}$ POT and fully reconstructed final states

The current NA62 run will be exploited to evaluate background rejection up to $\sim 10^{16} – 10^{17}$ POT’s

- optimise the detector design for future beam-dump mode: improvements in the setup are under study
- potentially achieve first results on the dark sector searches

- Possible running in dump-mode after LS2 to collect $10^{18}$ PoT (80 days @ full intensity) to search for hidden particles from charm/beauty decays