Search for heavy neutral lepton production in kaon decays

Chris Parkinson, on behalf of the NA62 collaboration

Moriond EW 2018

Outline

1. Introduction to heavy neutral leptons
2. Introduction to the NA62 experiment
3. Improved limits on heavy neutral lepton production
4. Summary

Heavy Neutral Leptons

- **Neutrinos are massless in the Standard Model (SM), which is contrary to the experimental observation of neutrino oscillations**
- **Extensions of the SM often predict heavy neutrino mass states that mix with the SM flavour states, typically referred to as "sterile neutrinos" or "heavy neutral leptons", which can mix with the SM flavour states**
- **One model, known as the νMSM [1,2], predicts two O(GeV/c^2) mass states and one DM candidate at O(KeV/c^2)**
- **The heavy mass state N can be produced in leptonic kaon decays:**

$$K^+ \to \ell^+ N \ (\ell = e, \mu)$$

making these decays a sensitive probe of the neutrino sector!

Heavy Neutral Leptons

- **The branching fraction involving the HNL mass state**

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

- **Where $|U_{\ell 4}|^2$ are elements of the extended neutrino mixing matrix between the SM flavour states and the HNL mass state**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix} \bullet \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Heavy Neutral Leptons

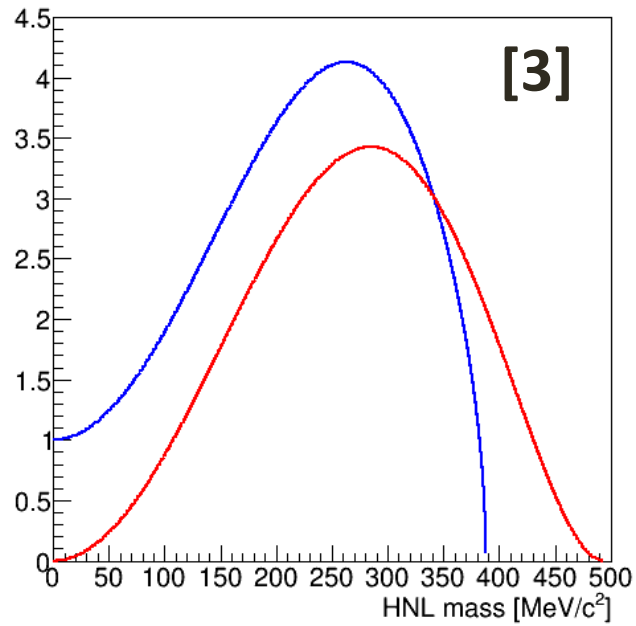
- **The branching fraction involving the HNL mass state**

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

- **Where $\rho_\ell(m_N)$ is a kinematic factor accounting for phase-space and helicity suppression**

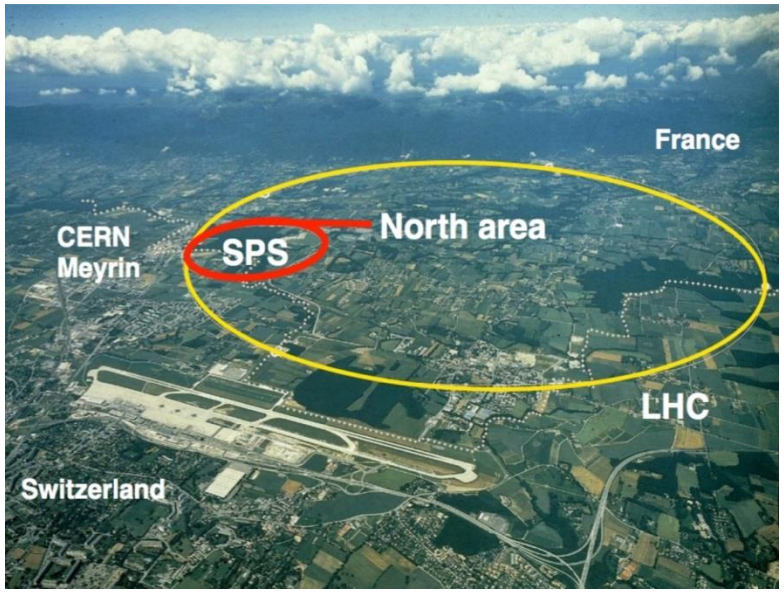
- **For the muon channel: $\rho_\mu(m_N)$**
- **For the electron channel: $\rho_e(m_N) \bullet R_K$**

with $R_K = \frac{B(K^+ \to e^+ \nu)}{B(K^+ \to \mu^+ \nu)} \sim 10^{-5}$



The NA62 experiment

NA62 at CERN



The NA62 collaboration

About 200 participants
from 28 institutes

Running periods in **2007-2008**
and **2015-2018**

The NA62 physics programme

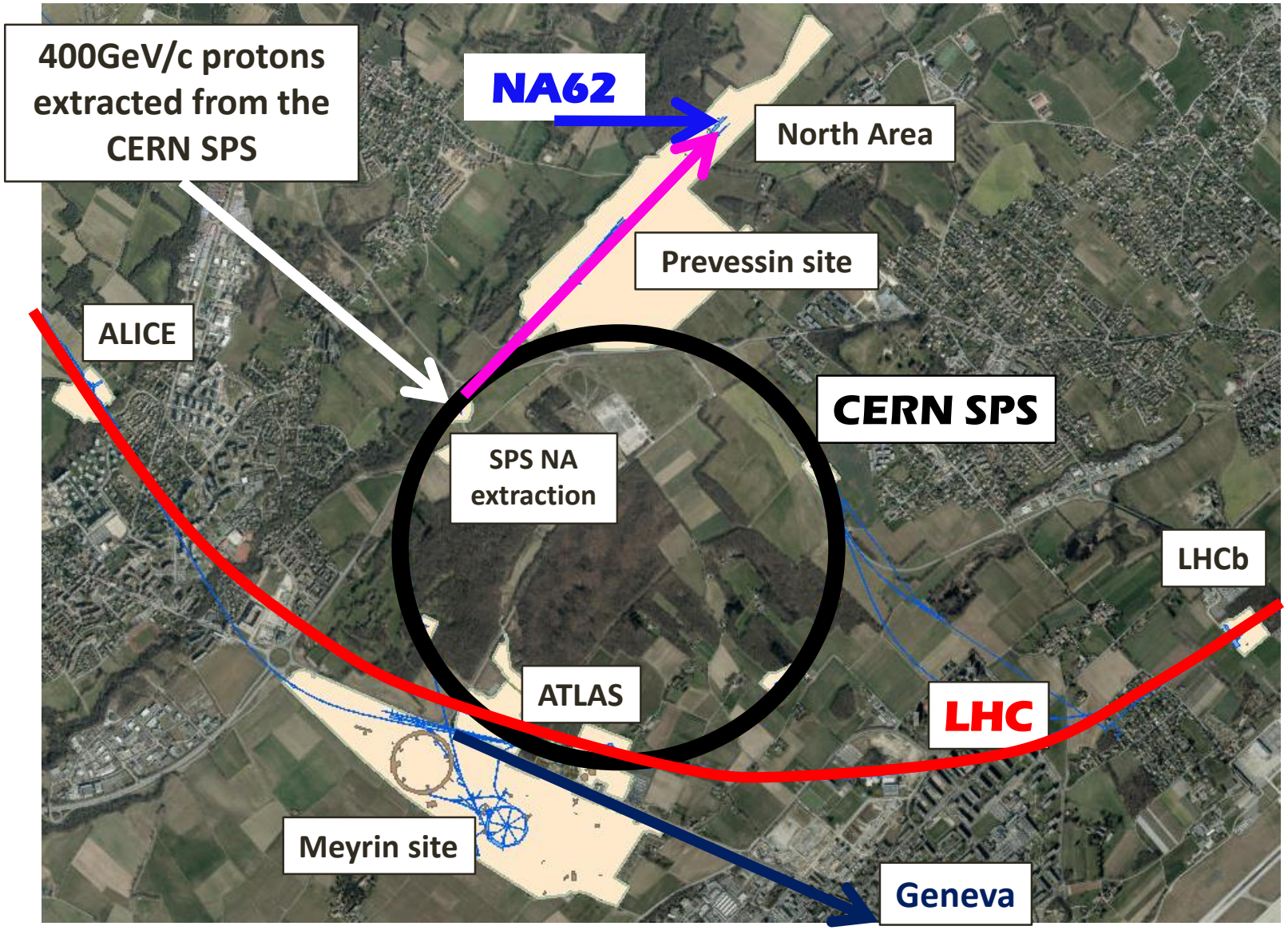
R_K (2007)
[Phys.Lett. B719 (2013) 326]

$K^+ \to \pi^+ \nu\nu$
[New results: R. Marchevski]

★ **Rare/forbidden Kaon decays** ★

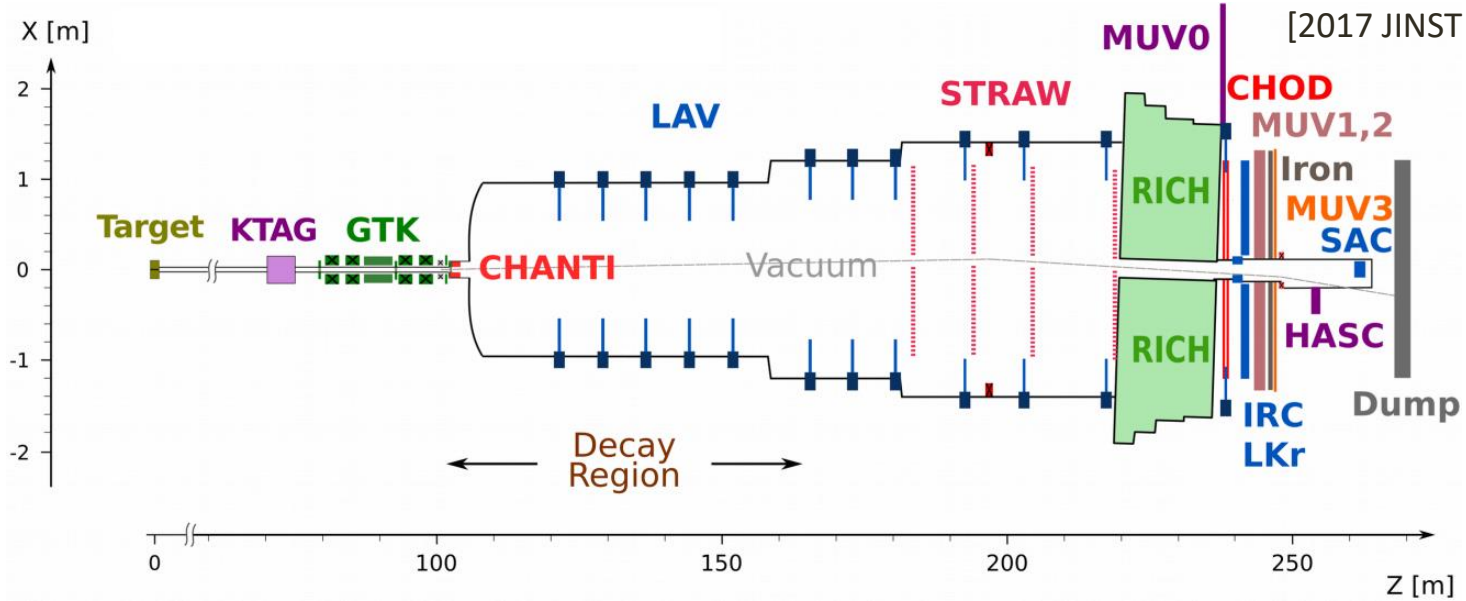
Exotic processes
[Talk by M. Drewes]

The NA62 experiment



The NA62 beamline

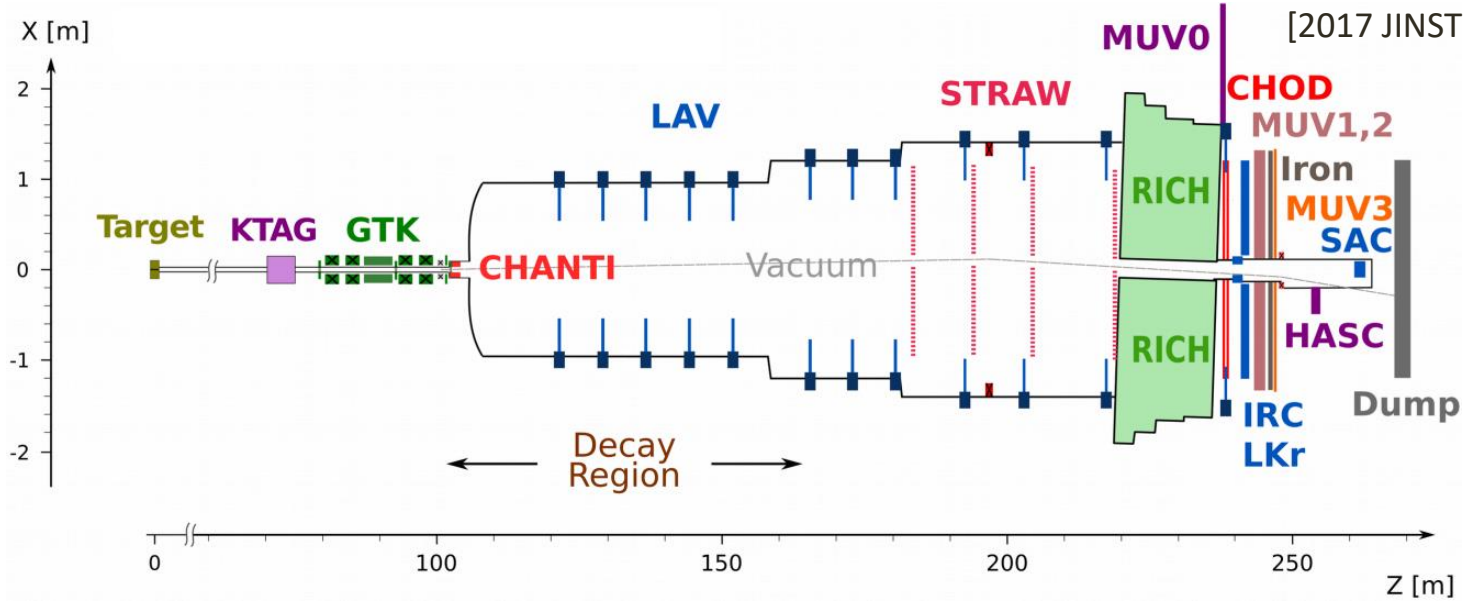
NA62 detector paper
[2017 JINST 12 P05025]



- Protons with momenta of **400 GeV/c** from the CERN SPS are extracted to the North Area in **spills of 5 seconds duration**
- Interactions with the **target** produce a secondary beam of hadrons
- **Positive hadrons** are momentum-selected to **within 1% of 75GeV/c**
  - **750 MHz** of particles in the beam
  - 70% pions, 24% protons, **6% kaons**

The NA62 beamline

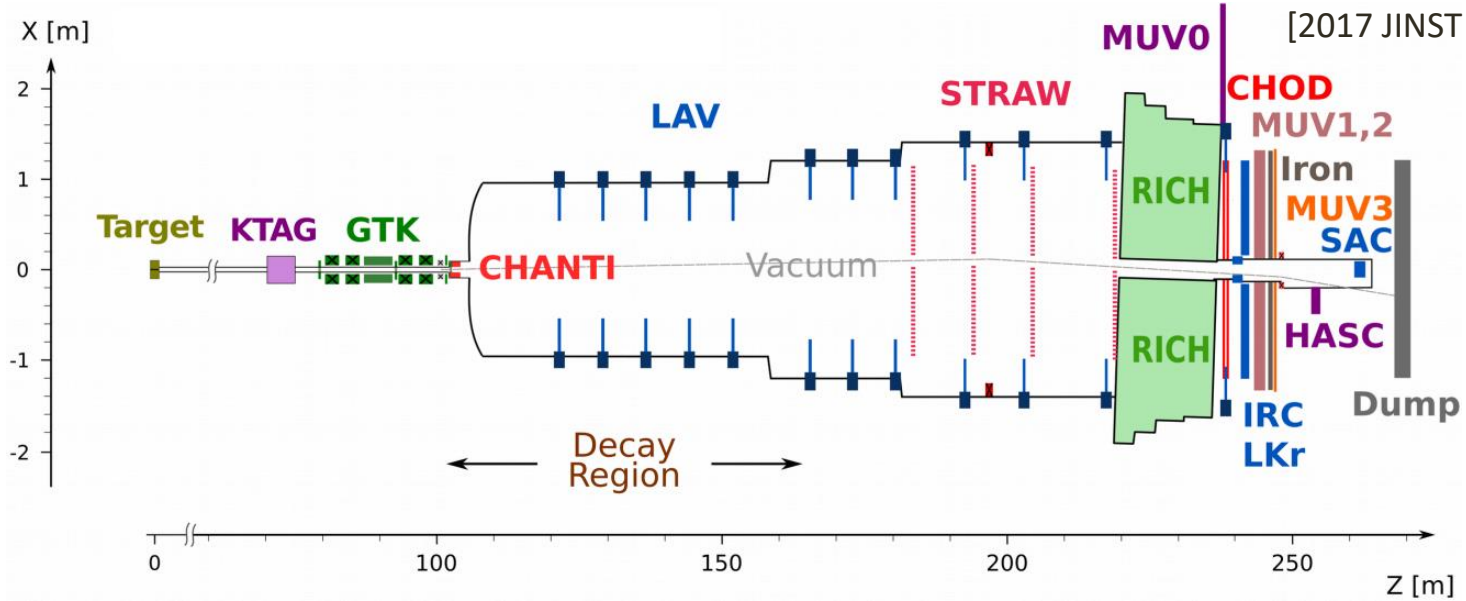
NA62 detector paper
[2017 JINST 12 P05025]



- Positive hadrons are transported from the **target** to the ~75m long **vacuum decay region** (105 to 180m), passing through the upstream detectors: **KTAG**, **GTK**
- About **20%** of Kaons decay within the vacuum decay region
- The Kaon decay products traverse the downstream detectors for particle measurement (**STRAW**, **CHOD**), particle identification (**RICH**, **LKr**, **MUV**) and photon rejection (**LAV, IRC, SAC**)

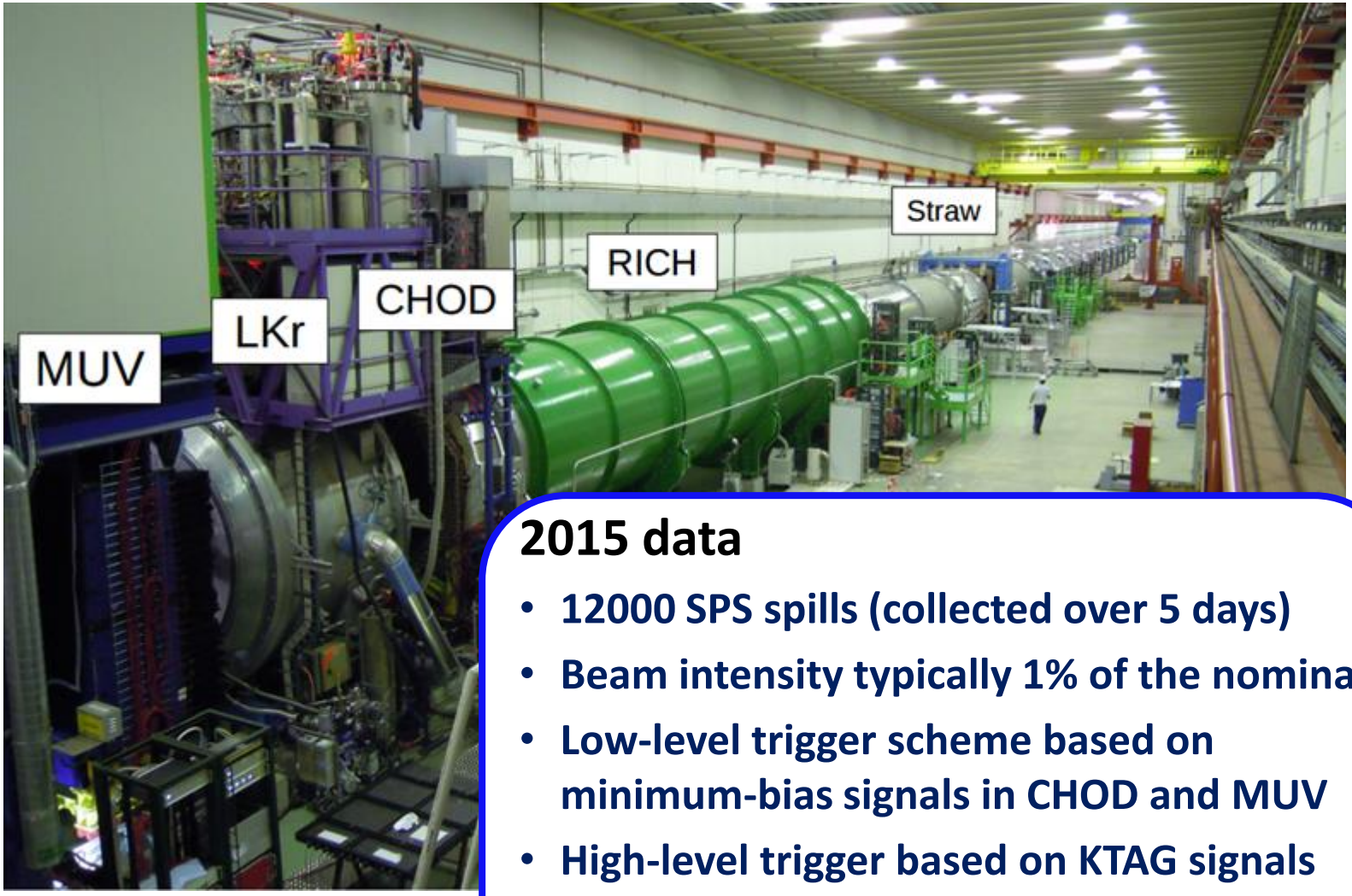
The NA62 beamline

NA62 detector paper
[2017 JINST 12 P05025]



- $K^+ \to \ell^+ N$ decays can be identified in the experiment as they peak sharply in the missing-mass-squared spectrum, m^2_{miss}, where
$$m^2_{\text{miss}} = (P_K - P_\ell)^2 = m^2_N$$
- Access to the missing mass allows NA62 searches for HNL **production** in $K^+ \to \ell^+ N$ decays, using a decay-in-flight technique
- Limits on $|U_{\ell 4}|^2$ from production searches scale **linearly** with the number of kaons (protons on target)

NA62 data sample

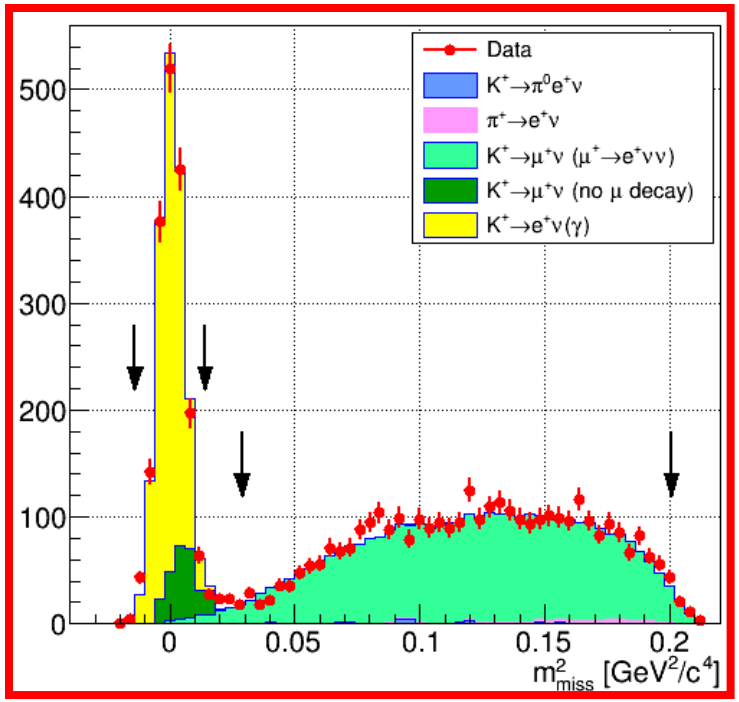


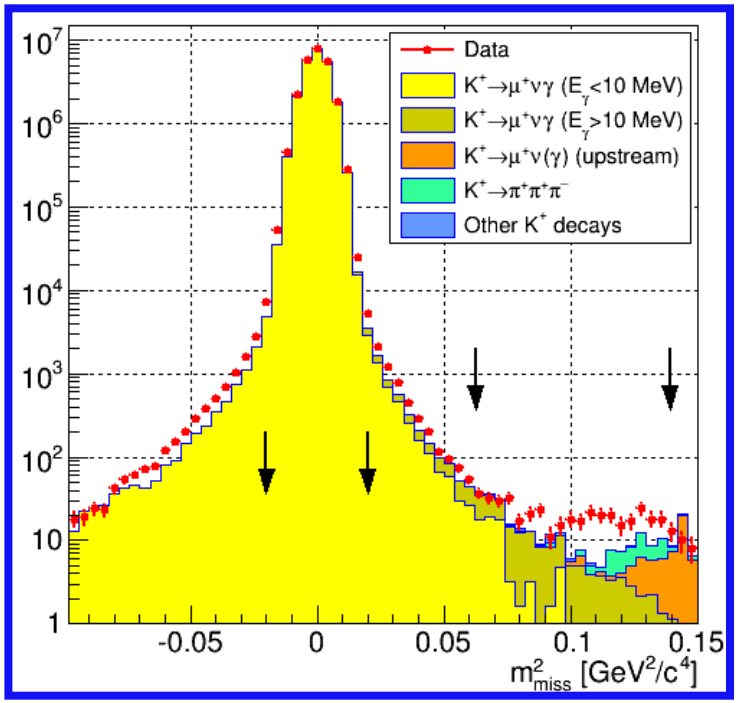
2015 data

- **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)**

Selected event samples

- With a cut based "single track" selection, NA62 has isolated samples of **1767 $K^+ \to e^+\nu$ (red)** and **24M $K^+ \to \mu^+\nu$ (blue)** decays
- SM decays appear as peaks at $\mathbf{m^2_{miss} = 0}$, with missing mass resolution of **4.7x10^{-3} GeV^2/c^4** and **4.9x10^{-3} GeV^2/c^4** respectively
- Search for peaks of $K^+ \to \ell^+ N$ decays above background in HNL signal regions: **170 < m_N < 448 MeV/c^2** and **250 < m_N < 373 MeV^2/c^4**

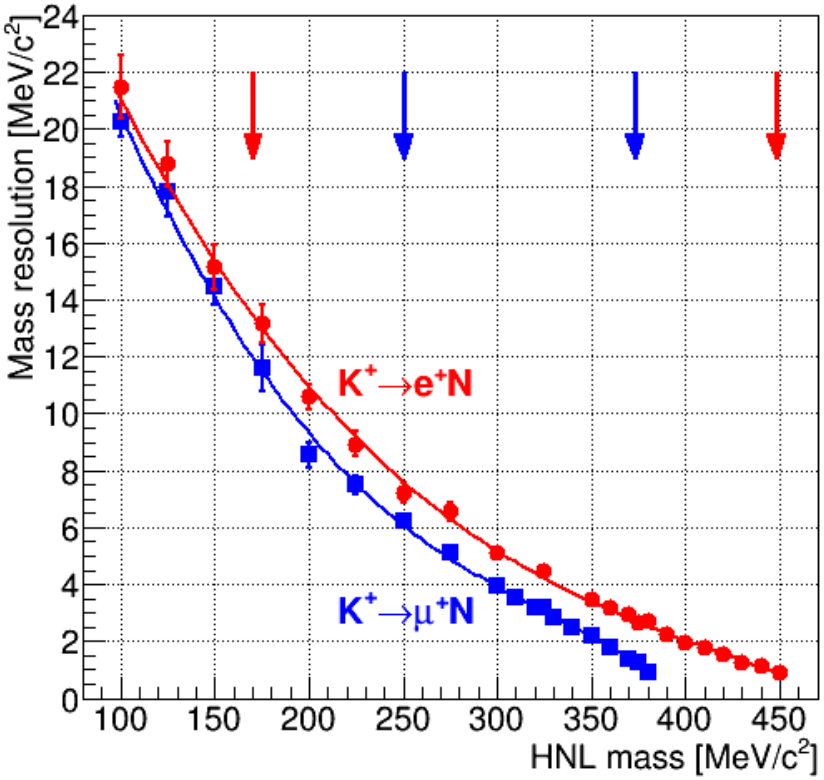




Limit setting procedure

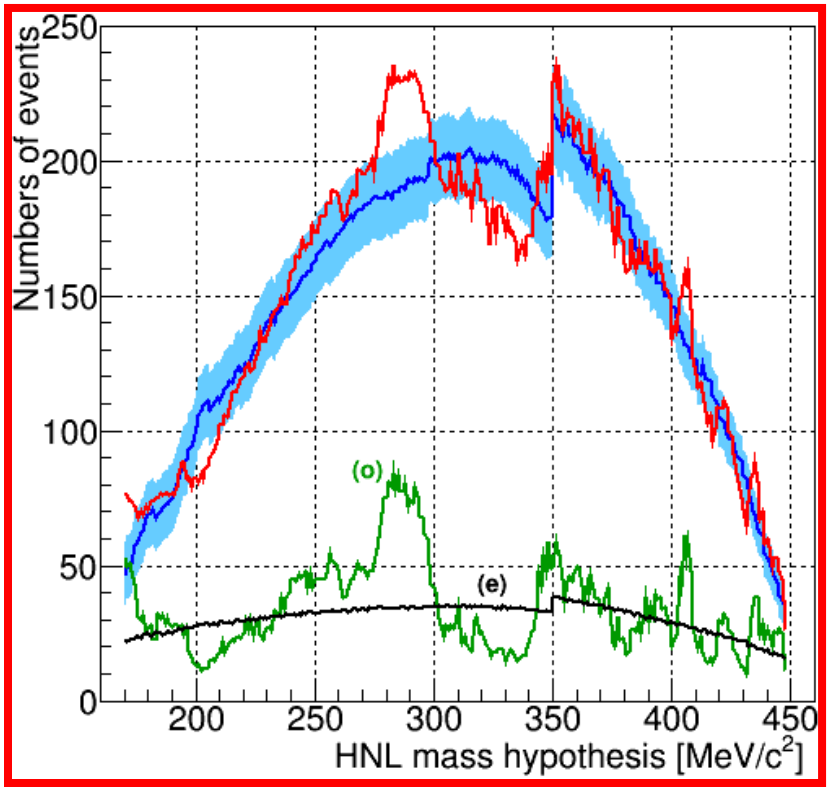
- Set limits on the number of HNL decays $\mathbf{n_{UL}}$ using **Rolke-Lopez** method [4]
- The limit is computed based on number of observed $\mathbf{n_{obs}}$ events, the number of expected events $\mathbf{n_{exp}}$, and the uncertainty on $\mathbf{n_{exp}}$

- Limit computed in steps of **1MeV/c²** across the **HNL mass** range
- $\mathbf{n_{obs}}$ determined by counting events in a "search window" of $\mathbf{1.5\sigma_m}$ at each HNL mass step
- $\mathbf{n_{exp}}$ estimated by fitting data events outside of the search window

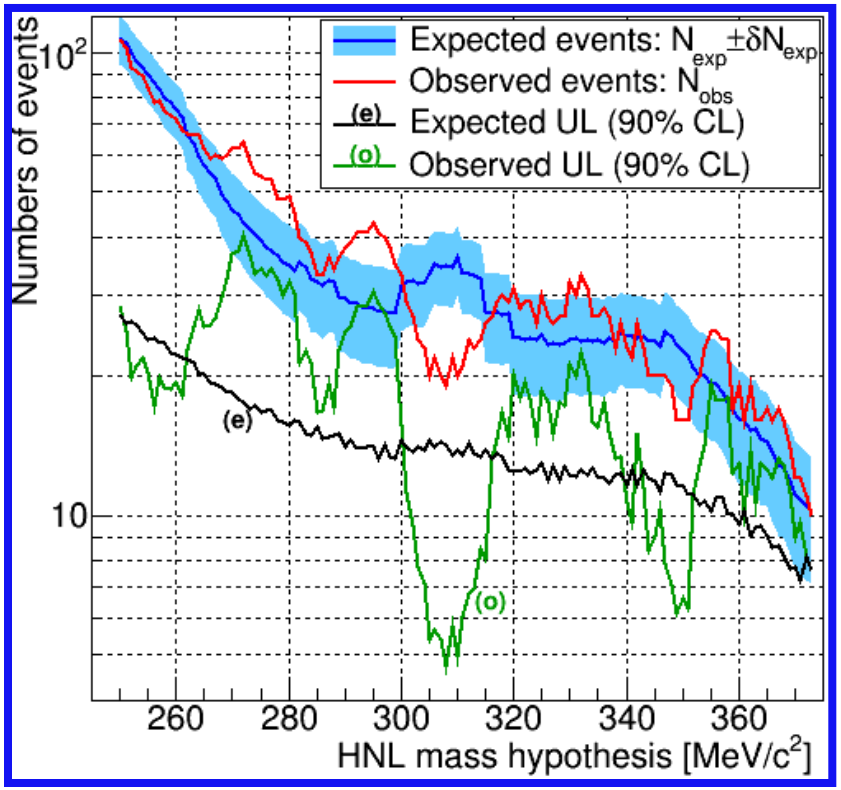


Limits on number of HNL decays

$K^+ \to e^+ N$



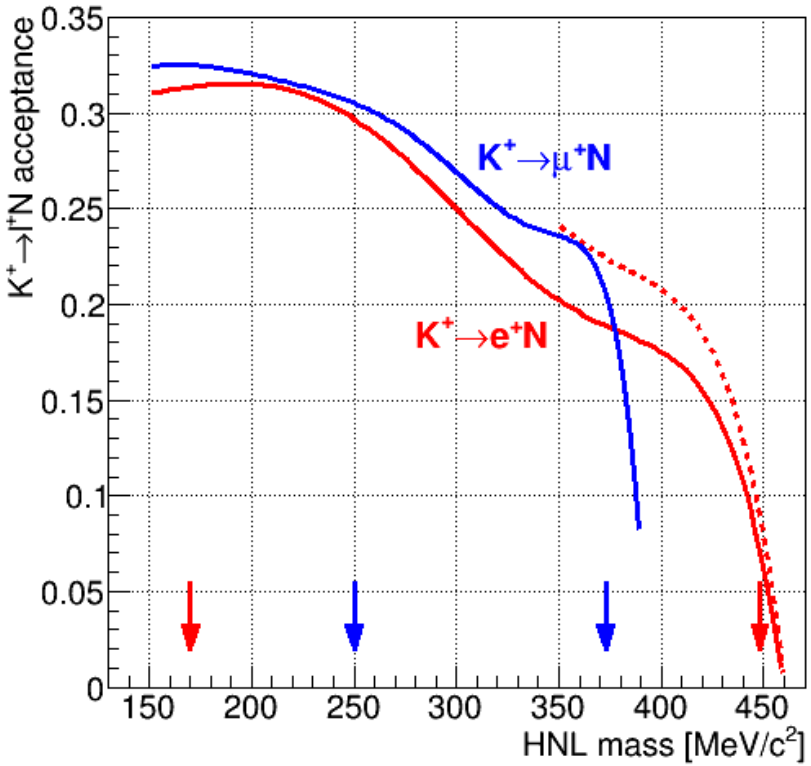
$K^+ \to \mu^+ N$

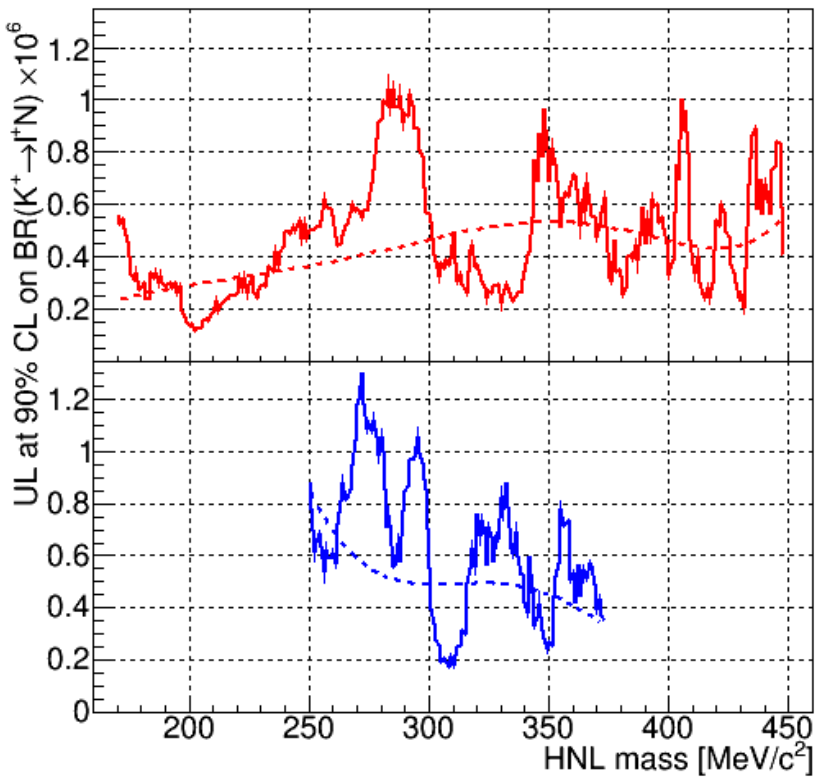


- Limits on the number of $K^+ \to e^+ N$ are set at the level of **O(30)** events
- Limits on the number of $K^+ \to \mu^+ N$ are set at the level of **O(20)** events

Limits on HNL branching fraction

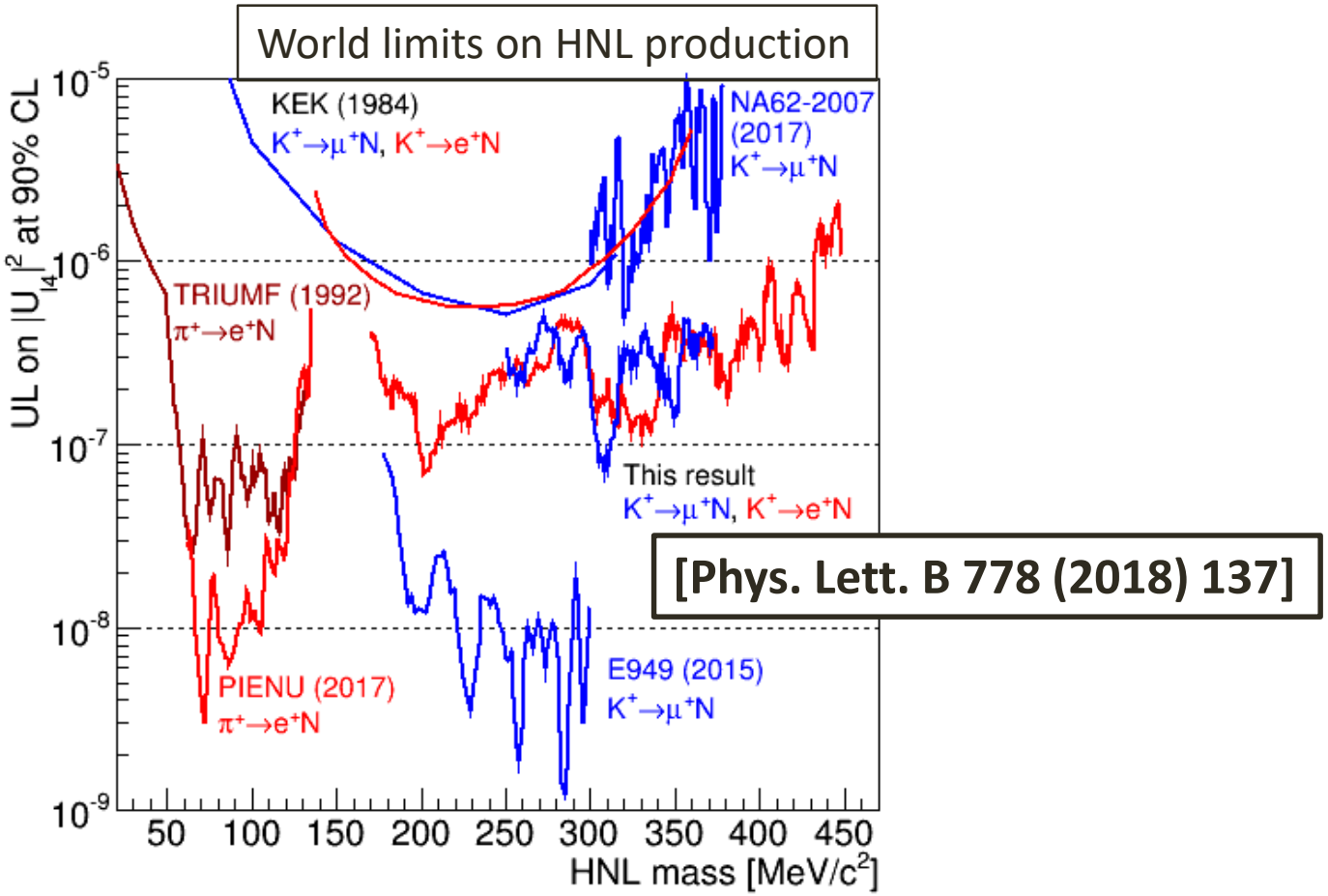
- The limits on $\mathbf{n_{UL}}$ are converted into limits on the branching fractions $B(K^+ \to e^+N)$ and $B(K^+ \to \mu^+N)$ via $B(K^+ \to \ell^+N) = \frac{n_{UL}^{\ell}}{N_K^{\ell} \bullet A_N^{\ell}(m_N)}$ which depends on the HNL acceptance $A_N^{\ell}(m_N)$





Limits on HNL mixing strength

- The limits on $\mathbf{n_{UL}}$ are converted into a limit on the mixing elements $|U_{e4}|^2$ **(red)** and $|U_{\mu 4}|^2$ **(blue)** via $|U_{\ell 4}|^2 = \frac{B(K^+ \to \ell^+ N)}{B(K^+ \to \ell^+ \nu)} \times \frac{1}{\rho(m_N)}$



[Phys. Lett. B 778 (2018) 137]

Outlook

- NA62 has already collected large data sets during 2016 and 2017, with more data taking during 2018 anticipated

In the 2016-2017 (and 2018) data:

- **The GTK is in operation**, providing:
  - Approx. factor two improved HNL mass resolution, reducing backgrounds and extending accessible mass range
  - Lower backgrounds in both the $K^+ \to e^+ N$ and $K^+ \to \mu^+ N$ channels

- **The data sets are much larger**, providing:
  - About 2.6×10^6 $K^+ \to e^+ \nu$ decays: **limits ~10^{-9} on $|U_{e4}|^2$**
  - About $\sim 10^9$ $K^+ \to \mu^+ \nu$ decays: **limits ~10^{-8} on $|U_{\mu 4}|^2$**

Summary

- **NA62 is a Kaon physics experiment at CERN**, with a broad physics programme that includes **studies of the neutrino sector**

- I presented a search for heavy neutral lepton production in **K^+** decays, using a data sample collected with a **minimum bias trigger in 2015**

- Upper limits were set at the level of $\mathbf{10^{-7}}$ **to** $\mathbf{10^{-6}}$ on the elements of the extended neutrino mixing matrix $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ for heavy neutral lepton mass in the ranges **$170 < m^2_{miss} < 448$ MeV/c²** and **$250 < m^2_{miss} < 373$ MeV/c²** respectively

- **NA62 sets the world's best limits on heavy neutrino production** over the whole mass range considered for $|U_{e4}|^2$, and above 300 MeV/c² for $|U_{\mu 4}|^2$.

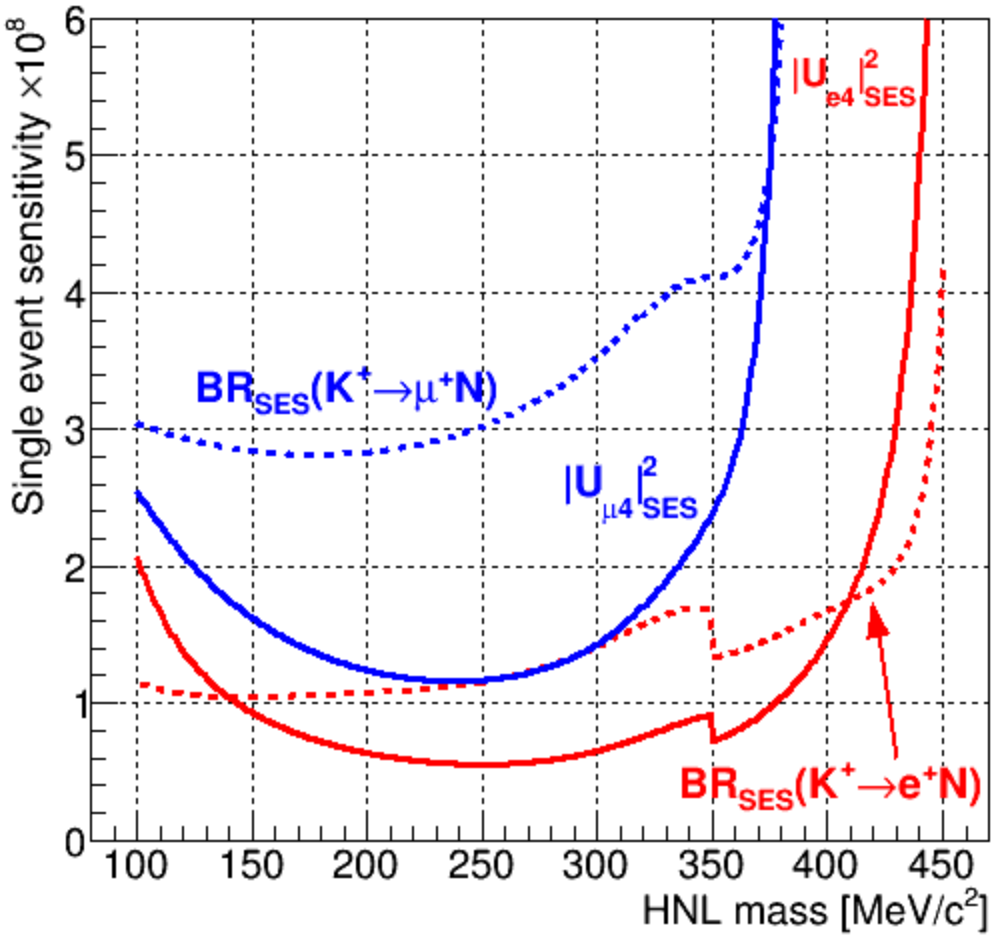
- For more information: **Phys. Lett. B778 (2018) 137**

- Outlook for HNL searches at **NA62** with the 2016-2018 data: **very promising**

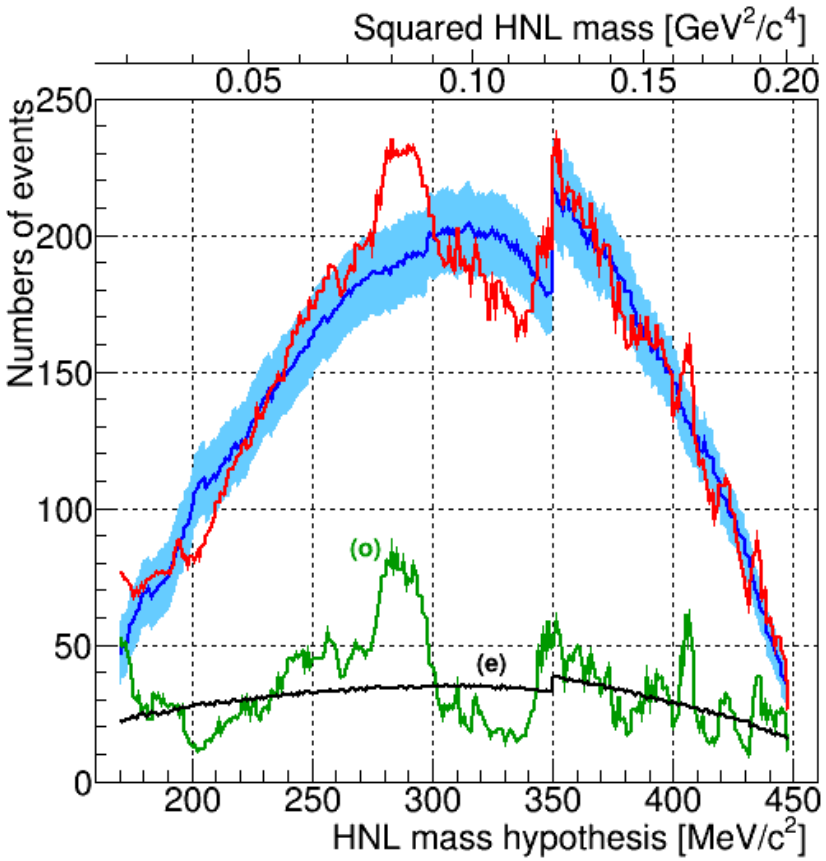
References

1. T. Asaka and M. Shaposhnikov, Phys. Lett. **B620** (2005) 17–26
2. T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. **B631** (2005) 151–156
3. R. E. Shrock, Phys. Lett. **B96** (1980) 159
4. W. A. Rolke and A. M. Lopez, Nucl. Instrum. Meth. **A458** (2001) 745

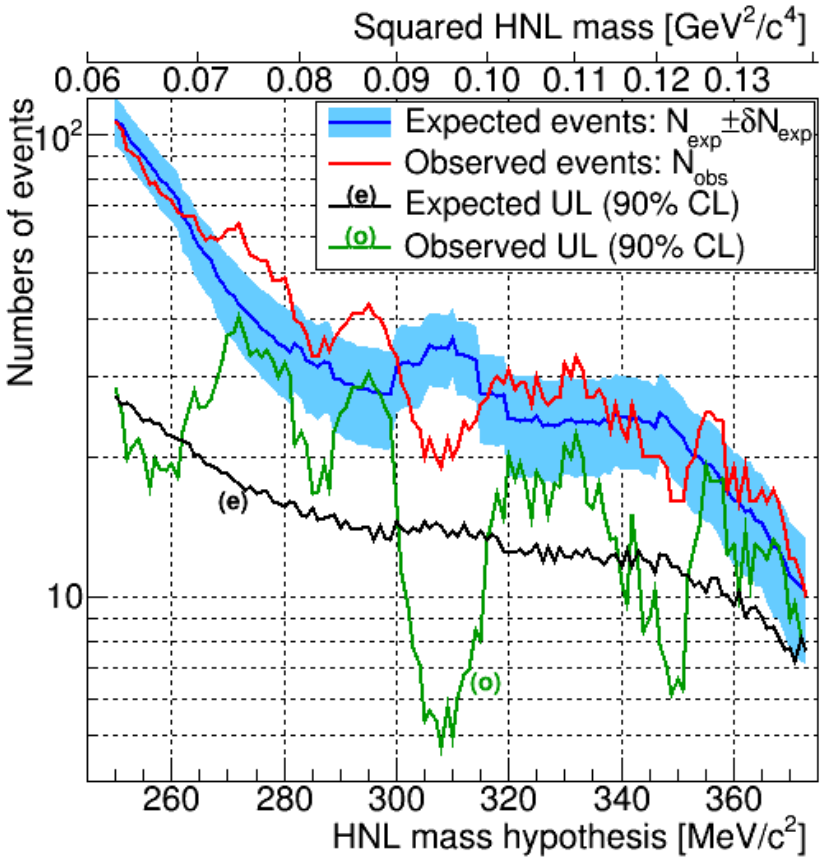
Backup 1


Single event sensitivity ×10^8
HNL mass [MeV/c^2]
BR_SES(K^+→μ^+N)
|U_μ4|^2_SES
|U_e4|^2_SES
BR_SES(K^+→e^+N)
0
1
2
3
4
5
6
100
150
200
250
300
350
400
450

Backup 2



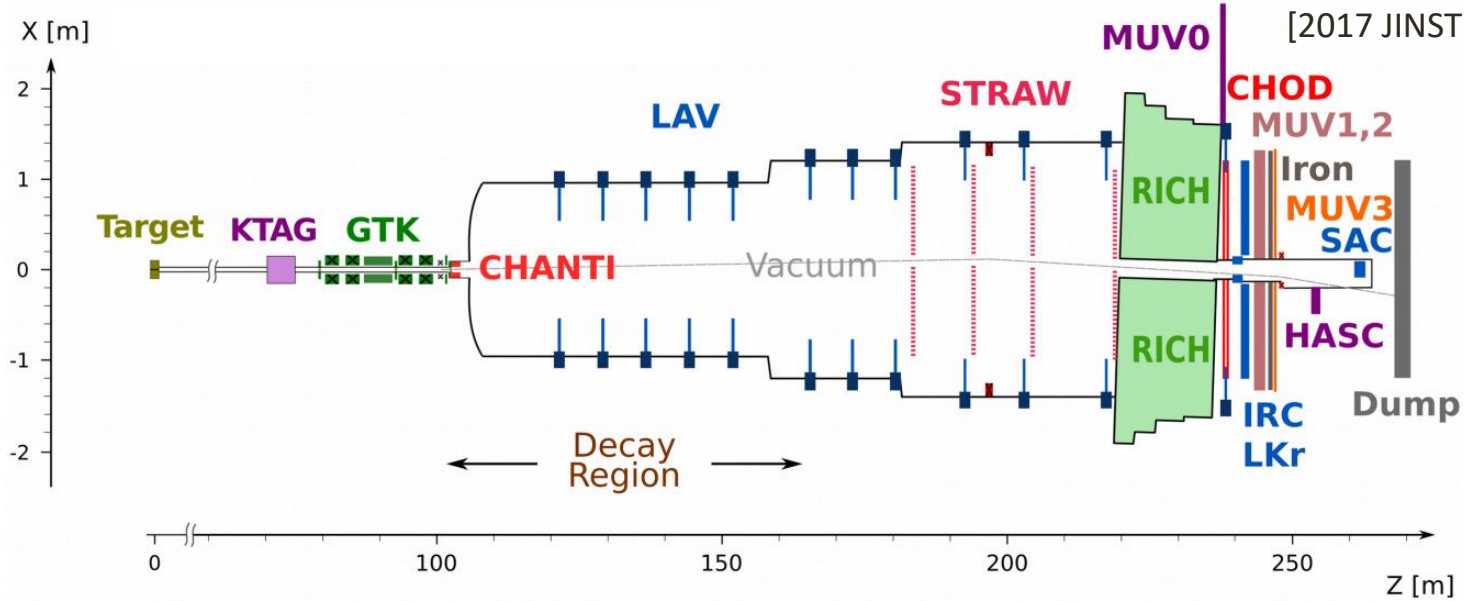
$K^+ \rightarrow e^+ N$



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

The NA62 beamline

NA62 detector paper
[2017 JINST 12 P05025]

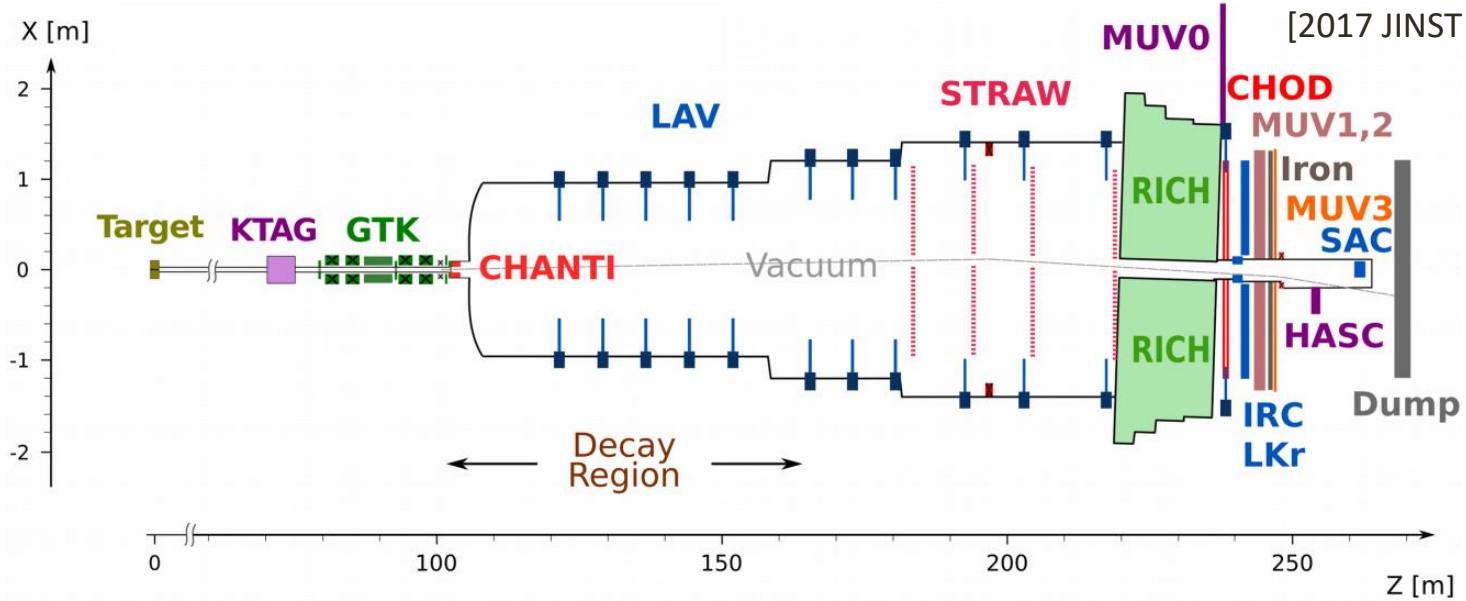


Single track selection

- Single positively-charged track reconstructed in the **STRAW**
- CDA between the track and beam axis less than 25mm
- No extra tracks within ±100ns of the track time

The NA62 beamline

NA62 detector paper
[2017 JINST 12 P05025]



Background suppression

- No clusters of energy deposition in the **LKr** that are not spatially compatible with the track within ±100ns of the track time
- No activity in the **photon veto detectors** and **CHANTI** within ±10ns
- Must be a Kaon signal in the **KTAG** within ±10ns of the track time
- Beam-muon vertex position inconsistent with **muon halo**

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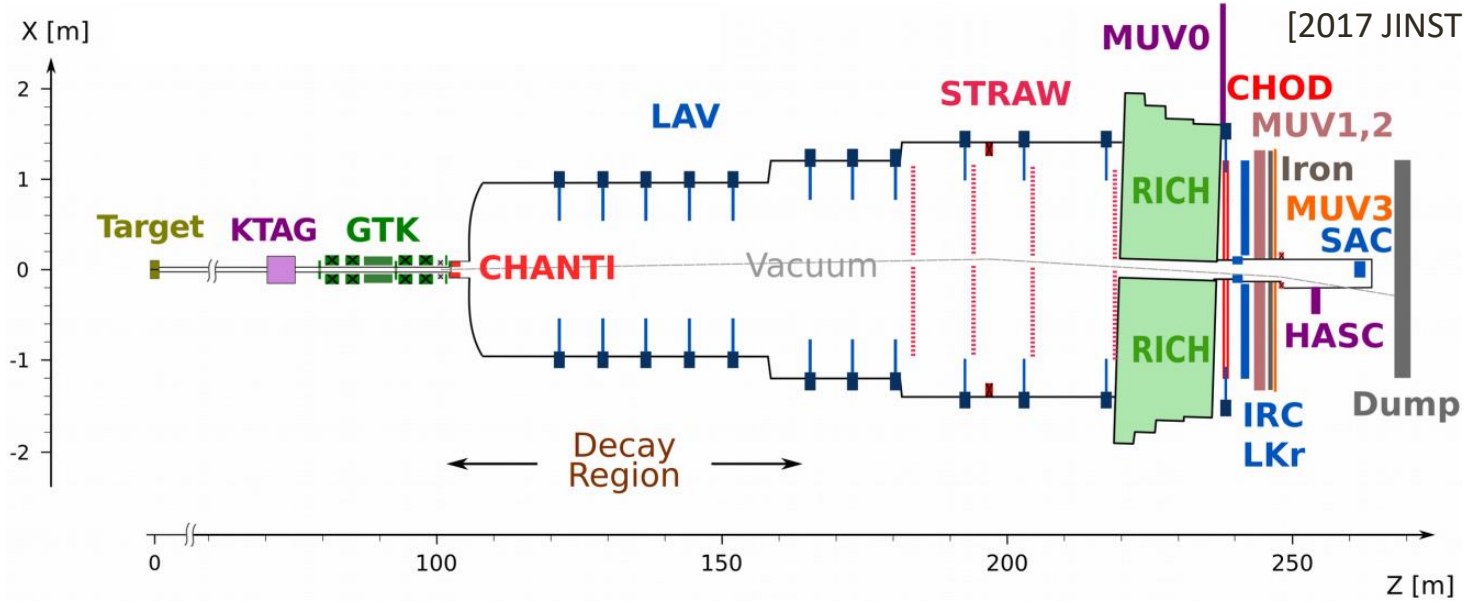

Particle Identification

- Ratio of track momentum and energy deposited in the **LKr**: **0.9 < E/p < 1.15 (electron)**; **E/p < 0.2 (muon)**
- Signals in **MUV**: **no compatible signal within ±10ns of track (electron)**; **compatible signals in MUV (muon)**
- **RICH** hit-pattern algorithm applied for tracks with p < 40 GeV/c