Search for heavy neutral lepton production at the NA62 experiment

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on behalf of NA62 collaboration

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Heavy neutral leptons (HNL)

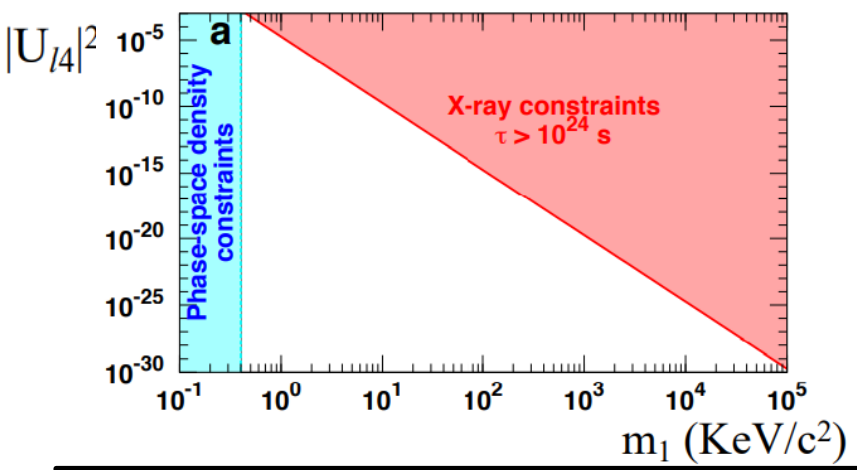
The existence of right-handed neutrinos, or heavy neutral leptons (HNL), is hypothesised in many SM extensions. Generic possibility of k sterile neutrinos mass states:

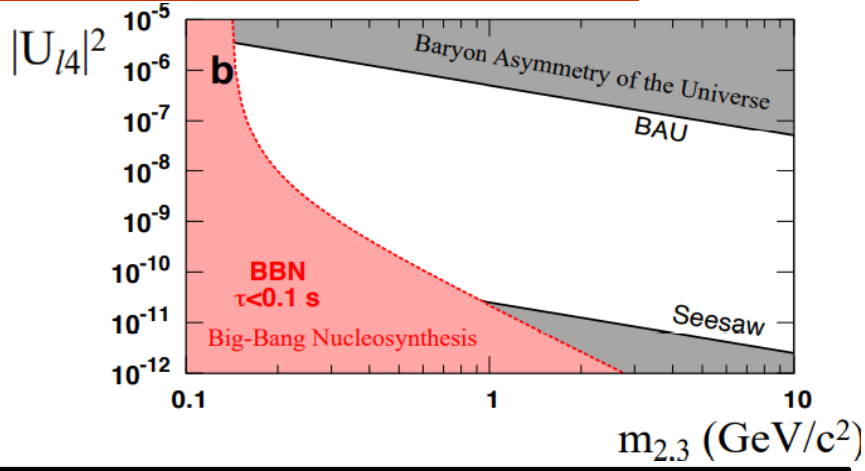
$$\nu_\alpha = \sum_{i=1}^{3+k} U_{\alpha i}\nu_i \qquad (\alpha = e, \mu, \tau)$$

***νMSM*: minimal extension of the SM able to explain ν masses, oscillations, baryogenesis and dark matter Three HNLs: m_1~10 keV [DM candidate]; $m_{2,3}$~ 1 GeV/c^2. GeV-scale HNLs can be observed via their production and decay.**

[Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151]

Astrophysical and cosmological constraints on m_k



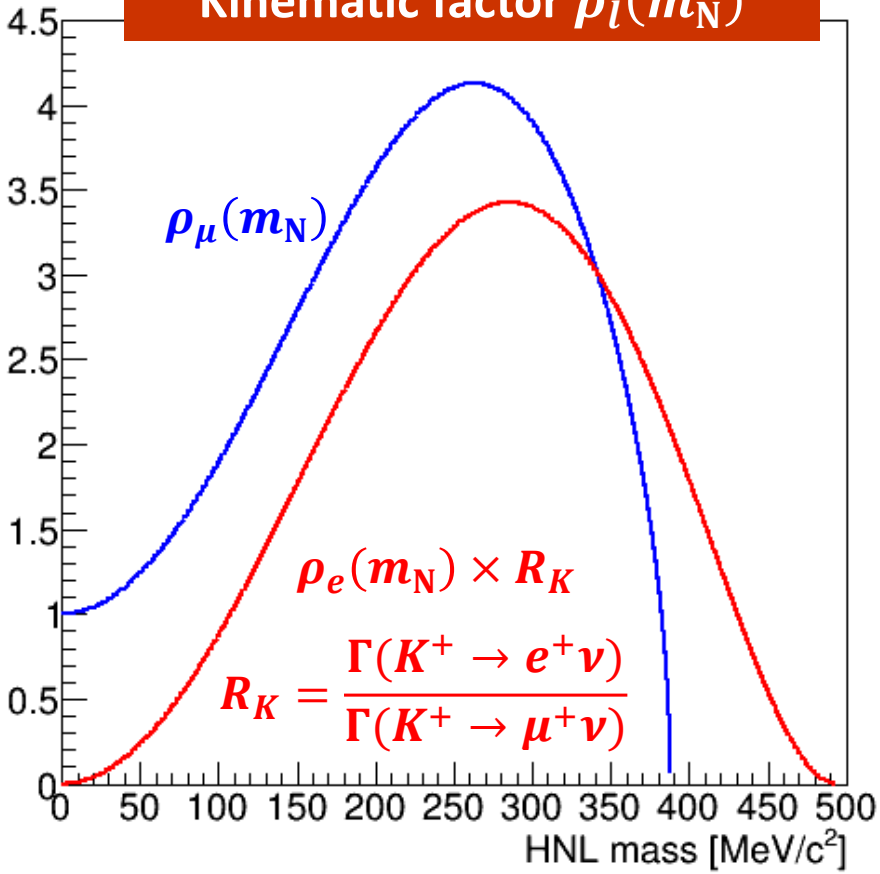


[Shaposhnikov, JHEP 0808 (2008) 008 Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191]

HNL production in K^+ decays

Master formula: $BR(P^+ \to l^+ \mathrm{N}) = \underbrace{BR(P^+ \to l^+ \nu) \times \rho_l(m_\mathrm{N})}_{O(1)} \times |U_{l4}|^2$

Kinematic factor $\rho_l(m_\mathrm{N})$



$$\rho_l(m_\mathrm{N}) = \frac{(x+y)-(x-y)^2}{x(1-x)^2}\lambda^{1/2}(1,x,y)$$

$$x = (m_l/m_P)^2, y = (m_\mathrm{N}/m_P)^2,$$

$$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab+bc+ac)$$

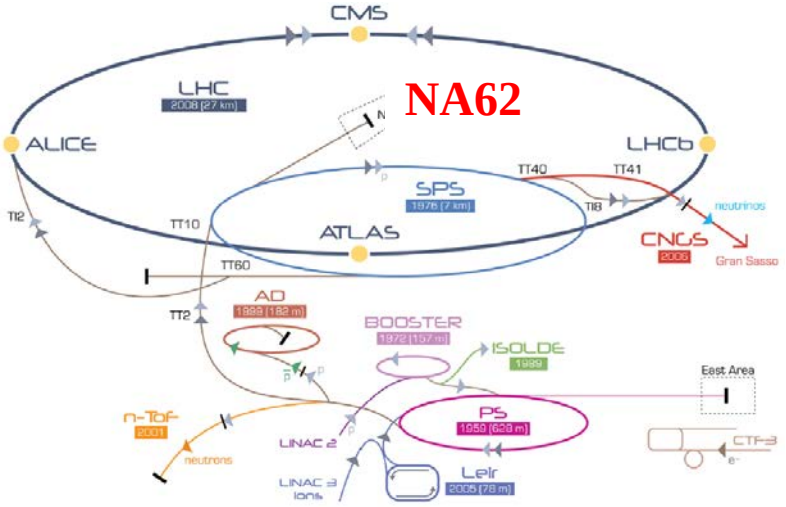
[R. Shrock, PLB96 (1980) 159]

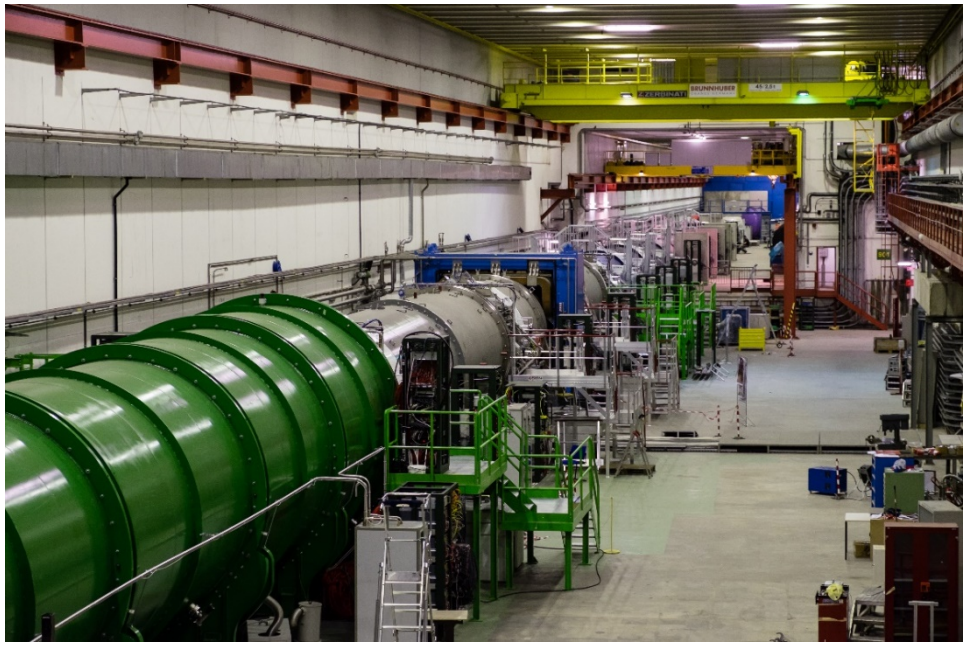
$K^+ \to l^+$ N

- **HNL production is enhanced kinematically wrt SM decays (except near kinematic endpoints).**
- **Helicity suppression relaxed in the $K^+ \to e^+$ N case: factor $\sim 10^5$ enhancement**

A kaon factory with high-frequency tracking of beam particles, redundant PID, high-efficiency vetoes would be suitable for this search.

NA62: the CERN kaon factory





Kaon physics at CERN:

- ✓ **Fixed target experiments at CERN SPS**
- ✓ **Kaon decay-in-flight**

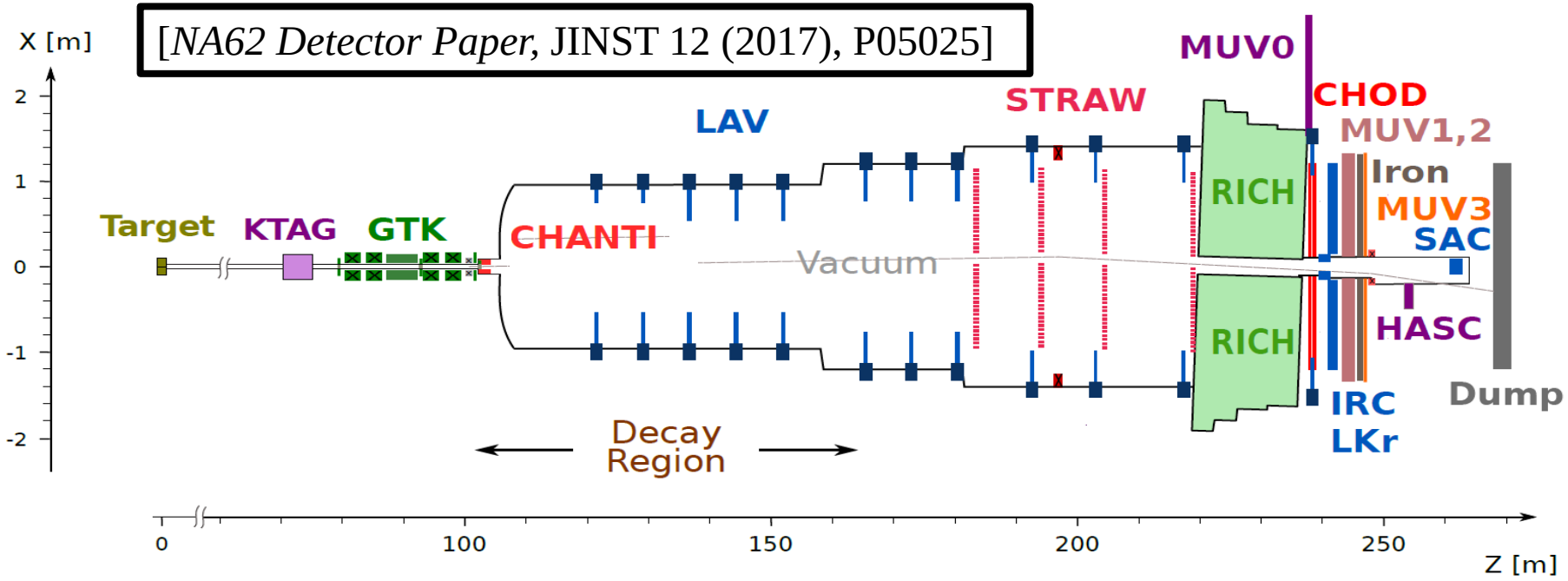
Currently in NA62:
~200 participants
29 institutions from 13 countries

Main goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement with $\mathcal{O}(10\%)$ precision

2.2×10^{18} proton on target in Run1 (2016-2018), data taking will restart in 2021

NA62 layout

[*NA62 Detector Paper*, JINST 12 (2017), P05025]



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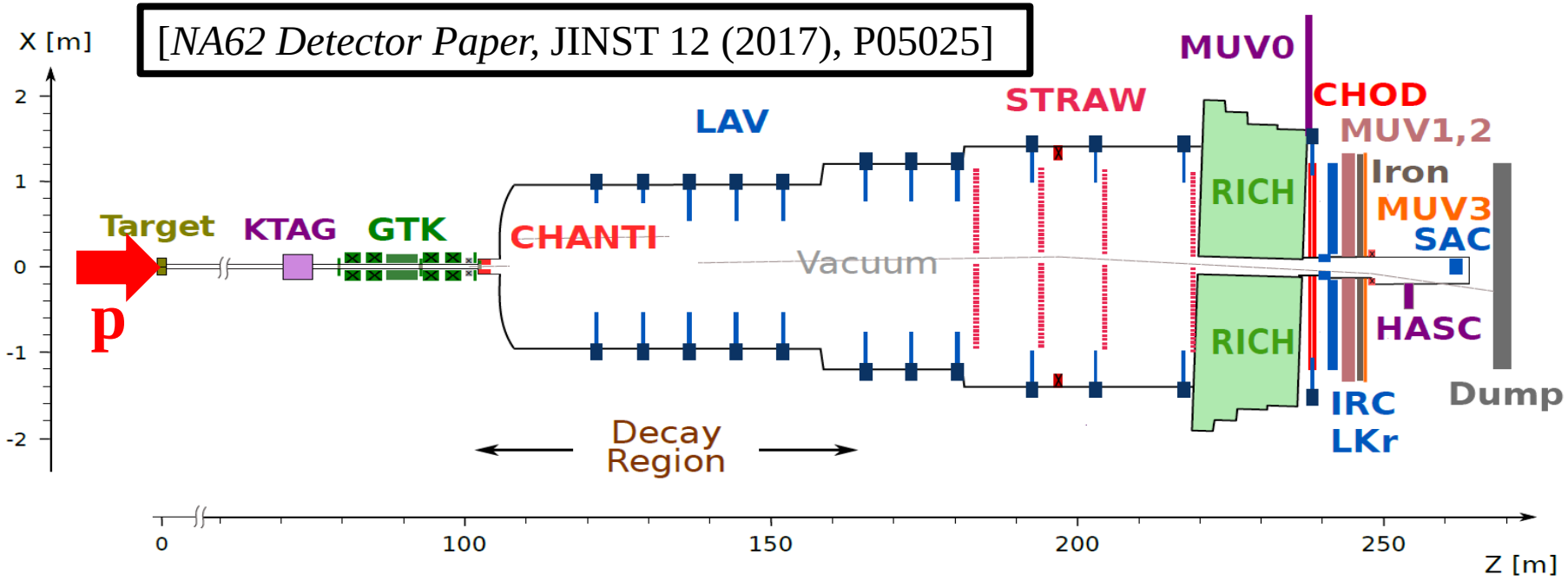

SPS protons:

400 GeV/c on beryllium target

10^{12} POT/sec on spill

3 sec effective spill length

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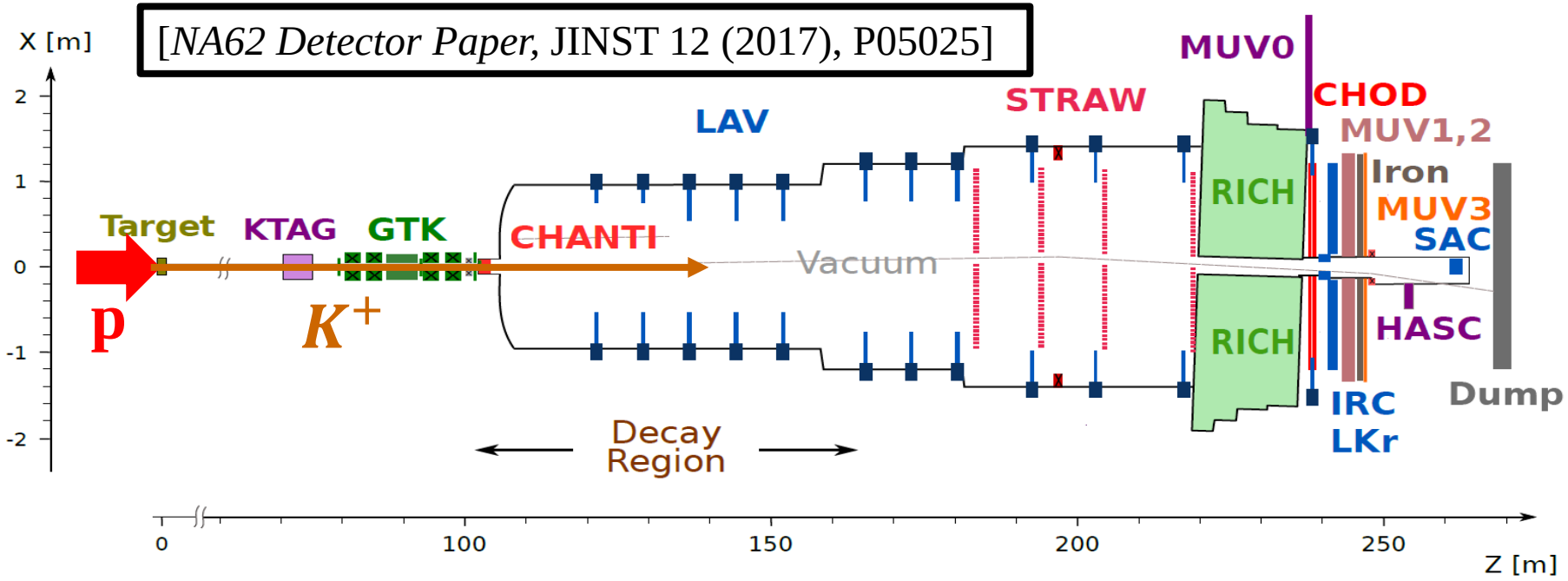

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Unseparated secondary beam:

75 GeV/c, 1% bite

100 μrad divergence

60 × 30 mm^2 transverse size

K^+(6%)/π^+(70%)/p(24%)

Beam particle rate: 750 MHz at GTK3

NA62 layout

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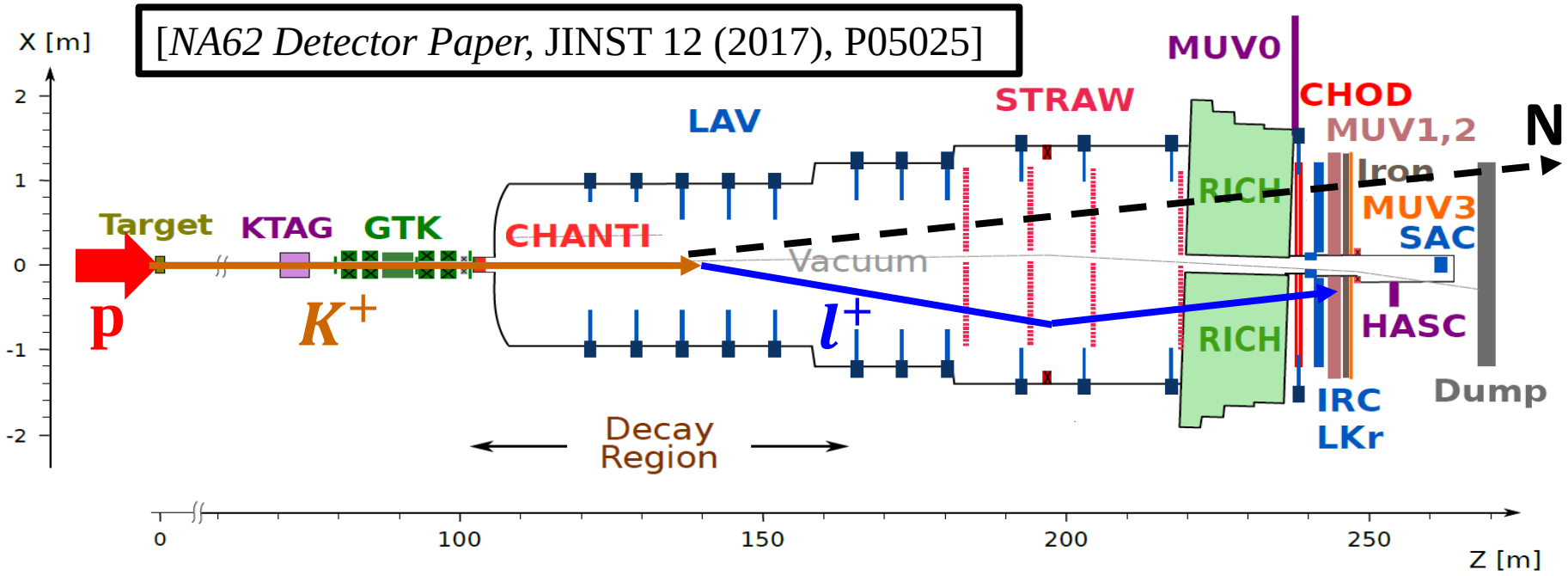

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Beam particle rate: 750 MHz at GTK3

Kaon decay region:

60 m long

~5 MHz kaon decays rate

Vacuum $\mathcal{O}(10^{-6})$ mbar

NA62 layout

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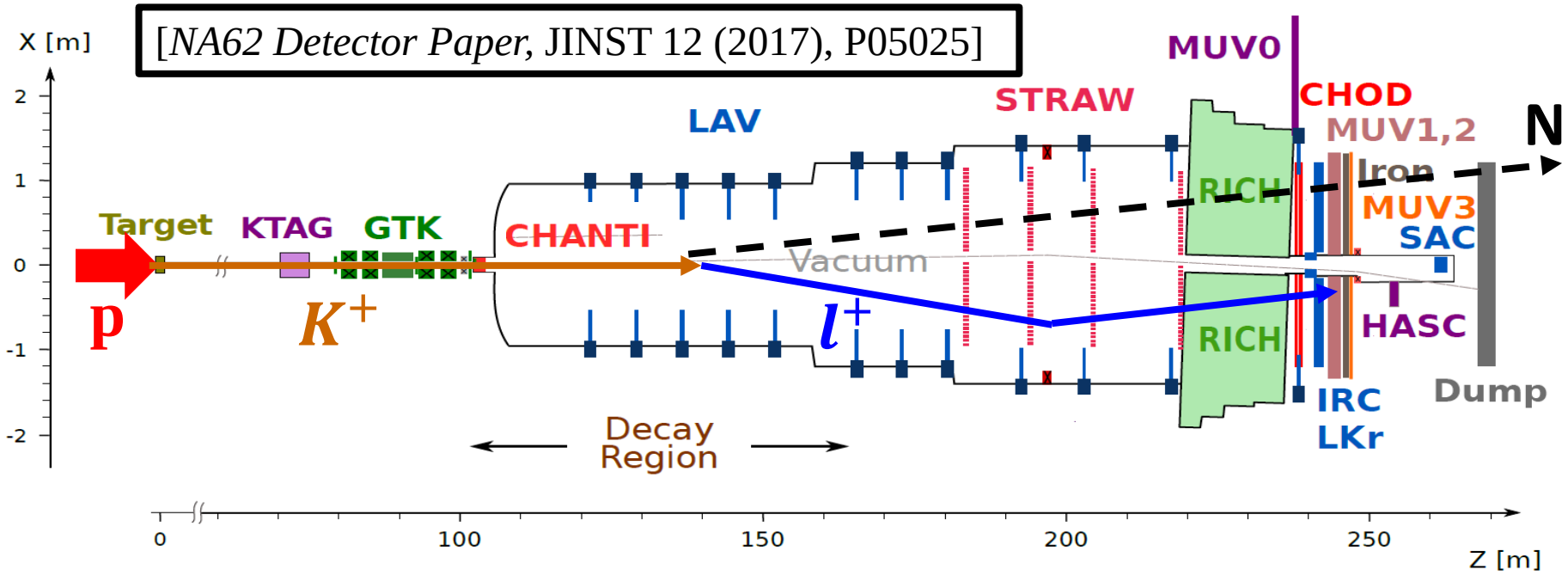
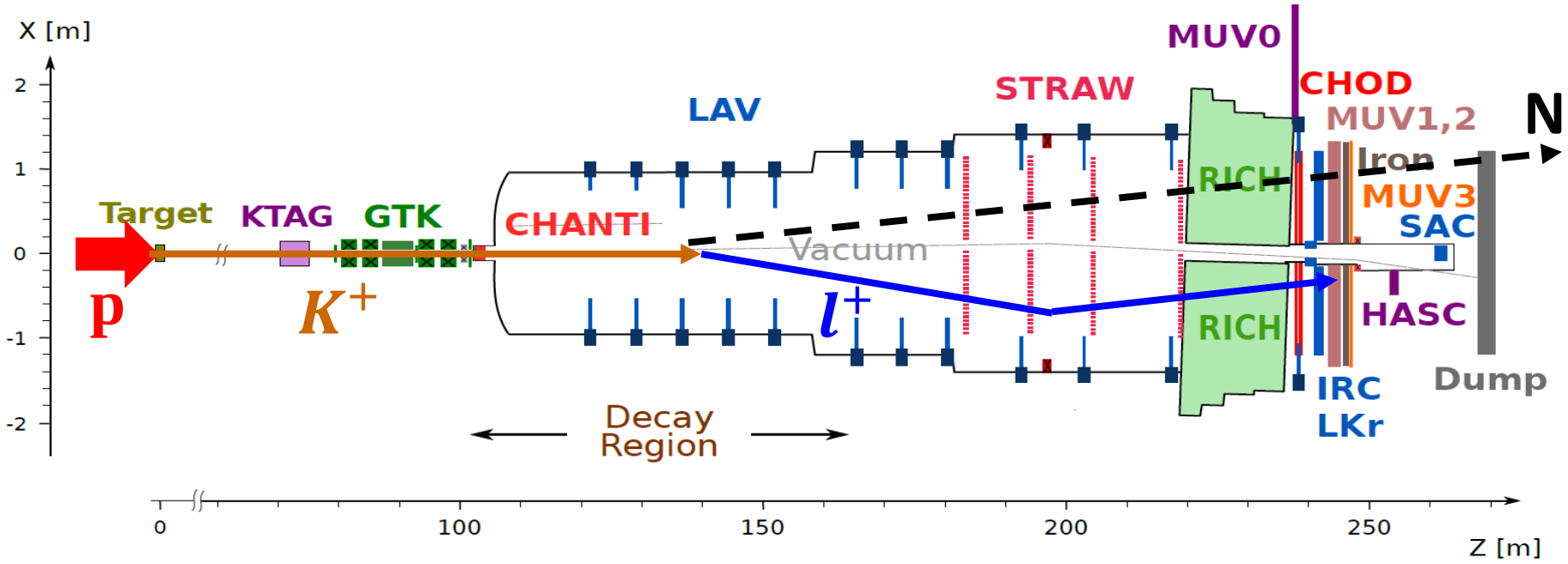


- ✓ **Excellent time resolution:** $\mathcal{O}$**(100 ps) to match beam and daughter particle information**
- ✓ **Kinematics: rejection of main** K **modes** 10^{-4} **via kinematics reconstruction**
- ✓ **PID capability (RICH+LKr+MUV):** $\mathcal{O}(10^{-8})$ **muon suppression**
- ✓ **High-efficiency photon veto:** 10^{-8} **rejection of** π^0 **for** $E(\pi^0) > 40$ **GeV**

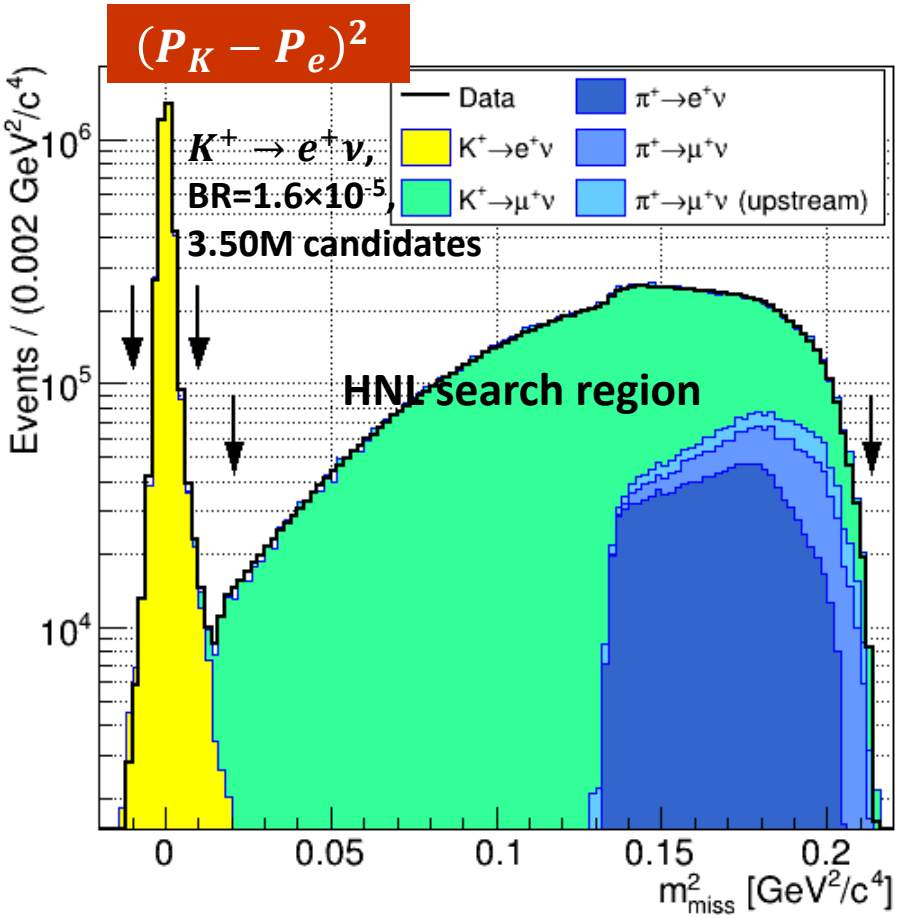
$K^+ \to l^+\mathrm{N}$ signal selection

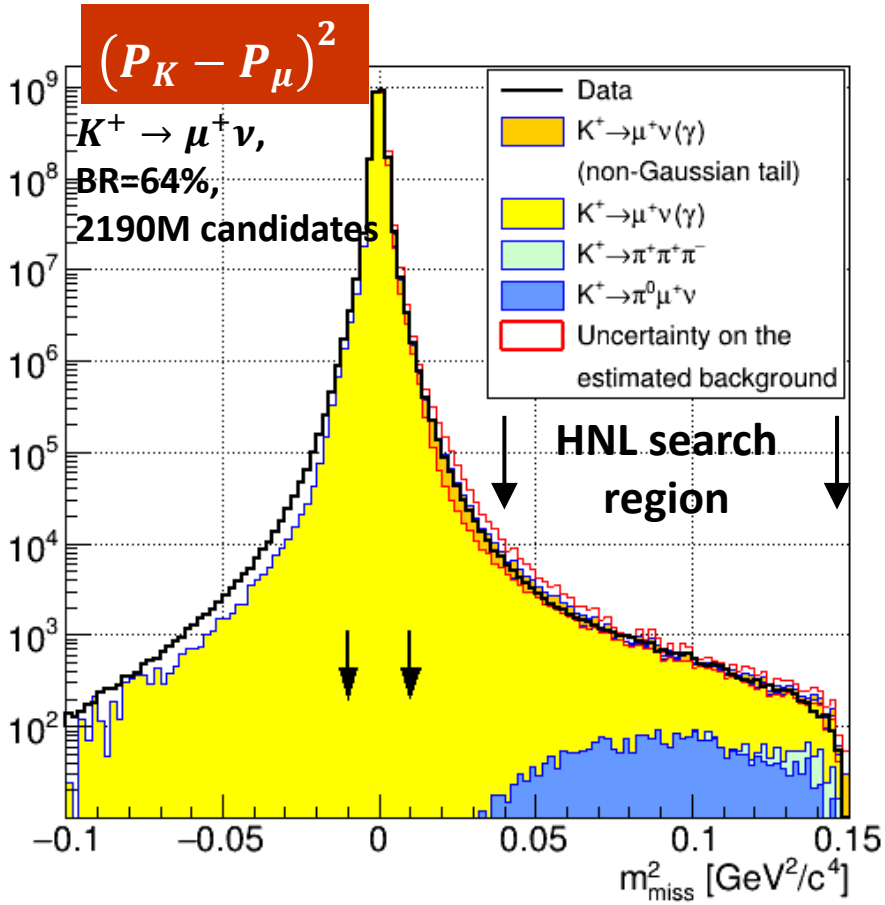


- Triggers used: $K_{\pi\nu\nu}$ for $K^+ \to e^+\mathrm{N}$ - minimum bias (downscaled by 400) for $K^+ \to \mu^+\mathrm{N}$
- Good downstream track reconstructed by the STRAW spectrometer in acceptance of LKr and MUV3
- Lepton momentum requirements: $5<p_e<30$ GeV/c - $5<p_\mu<70$ GeV/c
- Upstream track identified by KTAG and GTK matched with the downstream lepton
- Lepton PID: $0.92<E_{LKr}/p_e<1.08$, RICH and MUV3 in veto-$E_{LKr}/p_\mu<0.2$, RICH and MUV3
- Photon vetoes applied

Final samples

- Numbers of K^+ decays in fiducial volume: $N_K = (3.52 \pm 0.02) \times 10^{12}$ in e^+ mode; $N_K = (1.14 \pm 0.02) \times 10^{10}$ in μ^+ mode
- Squared missing mass $m^2_{miss} = (P_K - P_l)^2$ using STRAW and GTK detectors
- HNL production signal: a spike above continuous missing mass spectrum



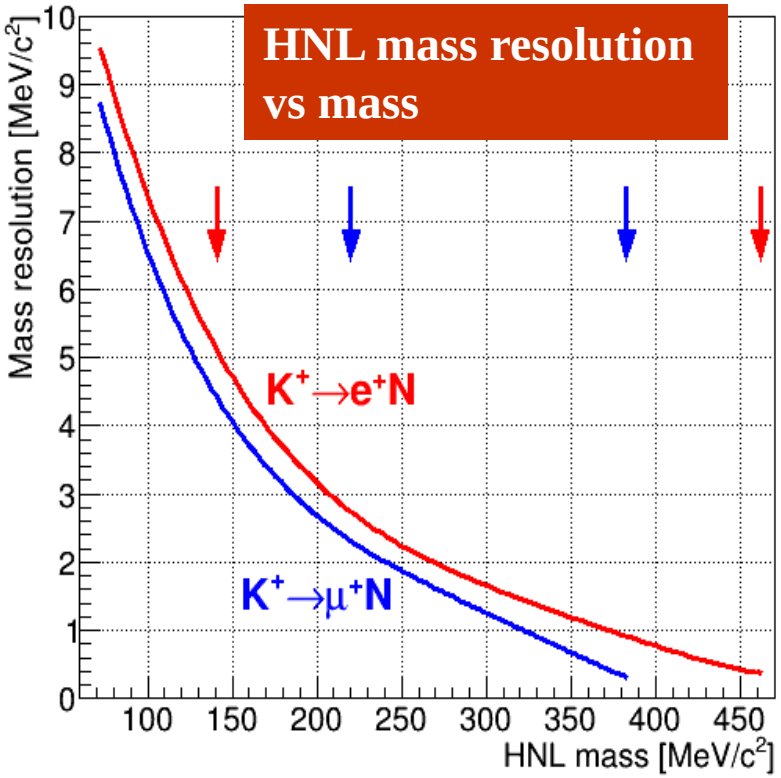


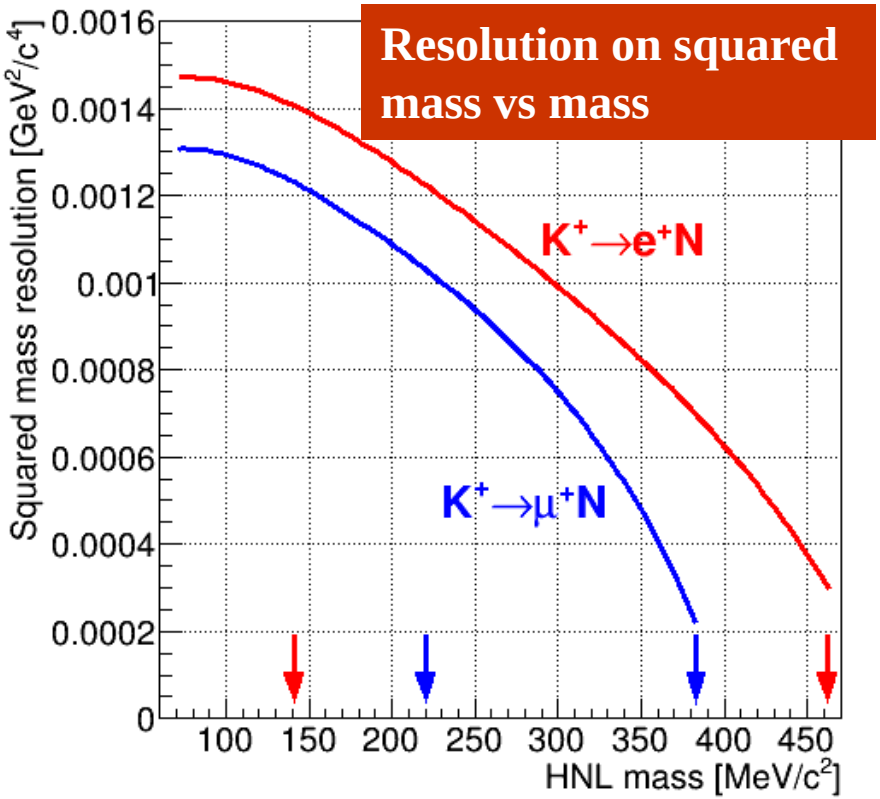
HNL mass resolution

Selection for each HNL mass hypothesis includes a «mass window» condition:

$$|m - m_{HNL}| < 1.5\,\sigma_m$$

where σ_m is the mass resolution evaluated from simulations. Modelling of the resolution outside the main peak is validated using data and simulated $K^+ \to \pi^+\pi^+\pi^-$ decay samples studying the resolution of $\Delta m_{3\pi} = \sqrt{(P_K - P_{\pi 1})^2} - \sqrt{(P_{\pi 2} + P_{\pi 3})^2}$

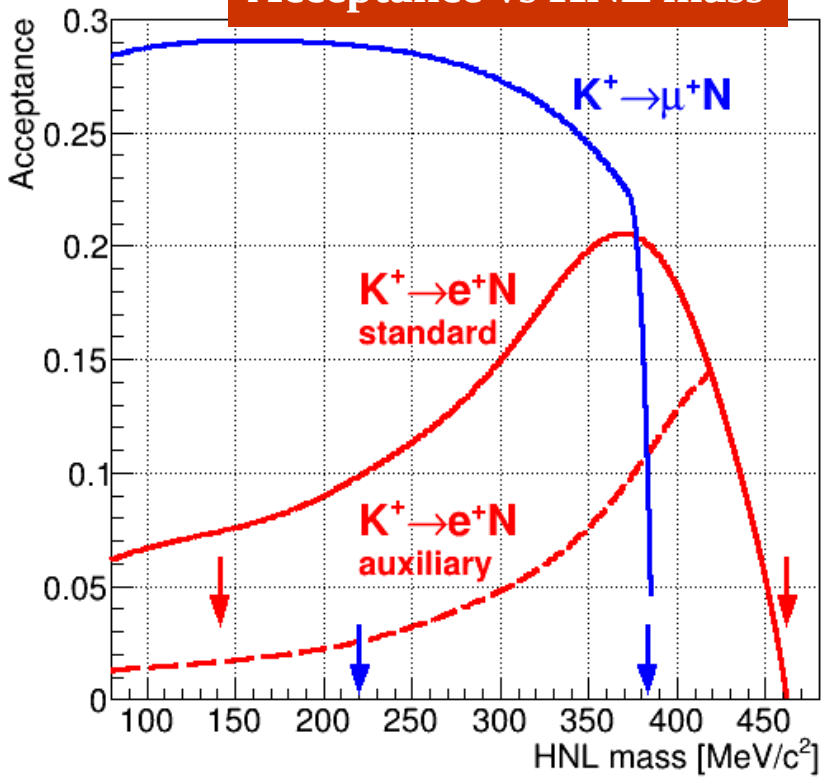




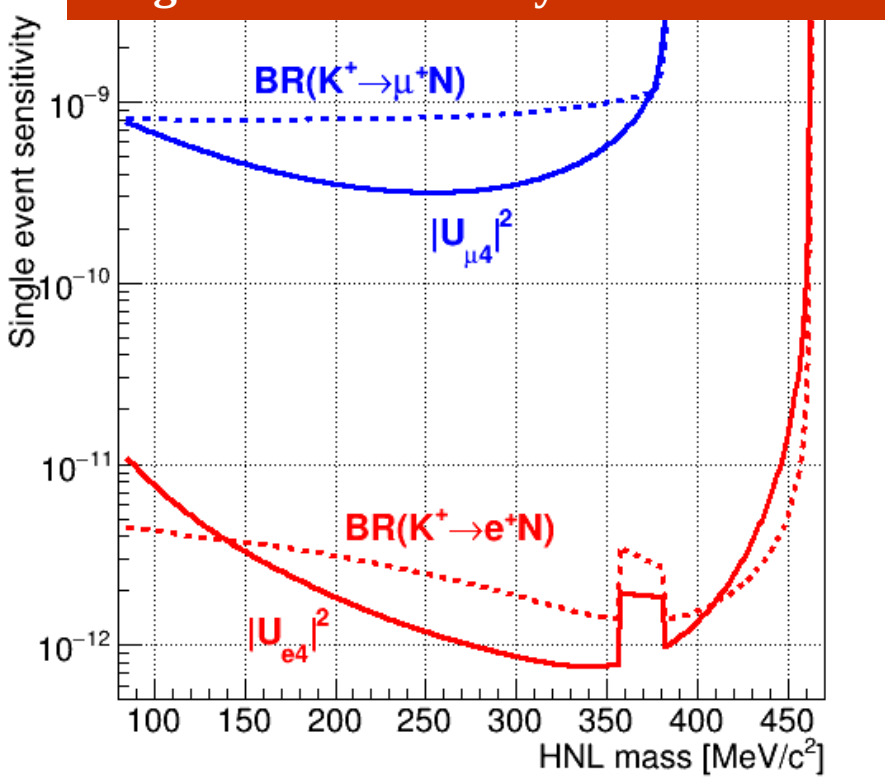
Acceptance and single event sensitivity

- Standard K_{e2} selection: p_e<30 GeV/c (as in $K_{\pi\nu\nu}$ trigger)
- Auxiliary K_{e2} (p_e<20 GeV/c): smooth background near the π_{e2} threshold
- Definitions: $BR_{SES} = 1/(N_K \times A_N)$, $|U_{l4}|^2_{SES} = BR_{SES}/[BR(K^+ \to l^+\nu)\rho_l(m_N)]$

Acceptance vs HNL mass



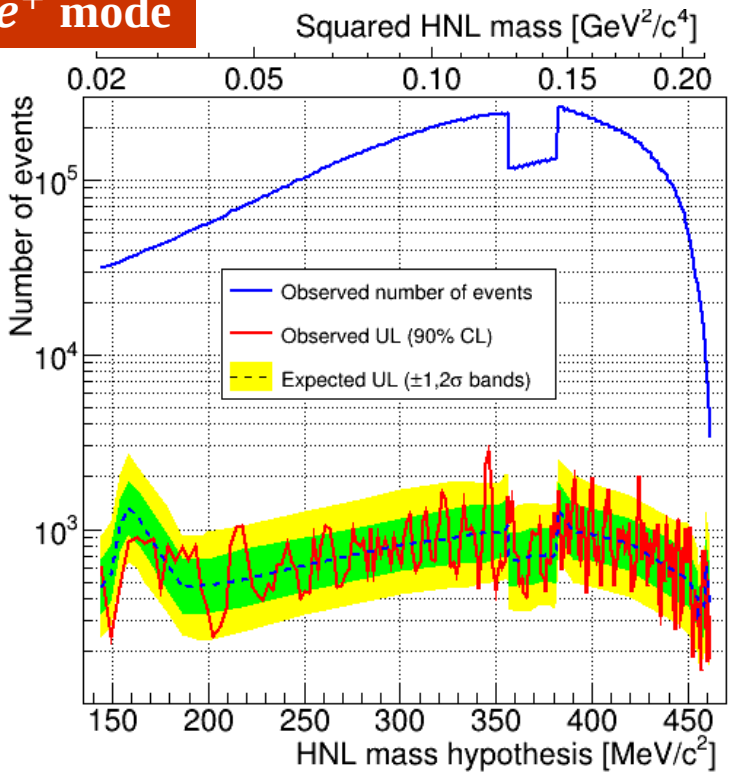
Single-event-sensitivity vs HNL mass



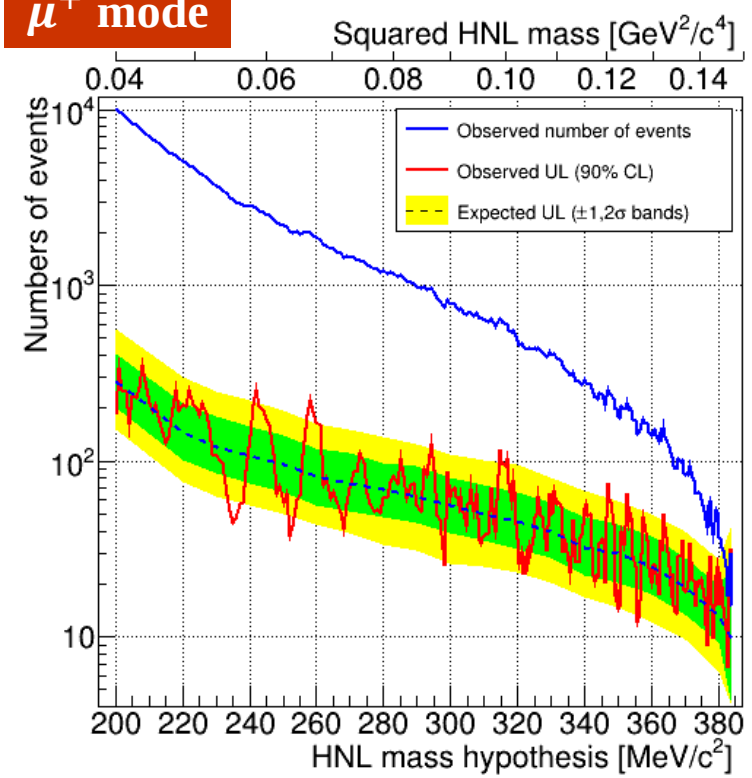
Results from NA62 Run1 data

- **Upper limit on the number of signal events at 90% CL using CLs technique with NA62 Run1 data**
- **In the e^+ case, maximum local significance of 3.6 for m_N=346 MeV/c^2. Accounting for look-elsewhere effect, global significance is 2.2**
- **No statistically significant excess is detected in μ^+ mode**

e^+ mode



μ^+ mode

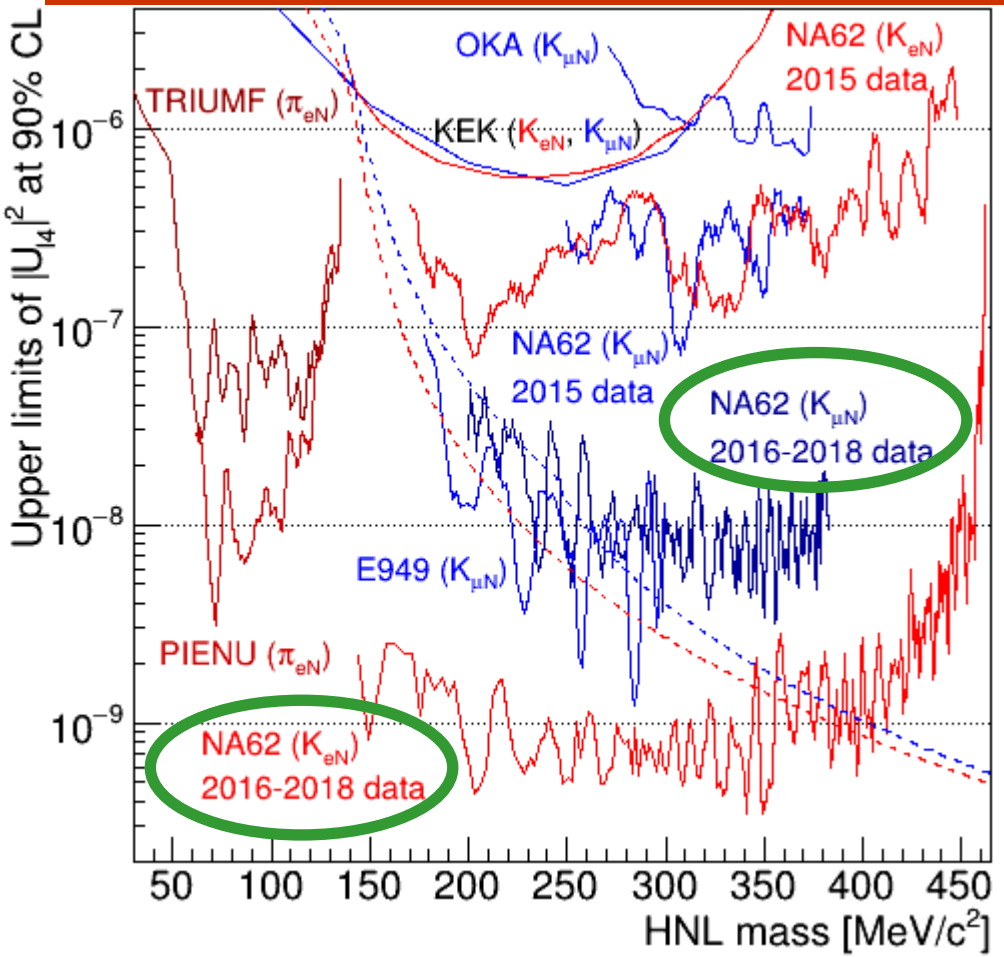


HNL production searches: summary

Limits from HNL production searches:

- ✓ **Improvements up to two orders of magnitudes**
- ✓ **For $|U_{e4}|^2$, BBN-allowed range excluded up to 340 MeV/c^2**
- ✓ **For $|U_{\mu 4}|^2$, approached E949 sensitivity and extended search to 383 MeV/c^2**

$|U_{l4}|^2$ limits vs m_{HNL} from production searches



Conclusions

- ✓ **NA62 experiment at CERN collected a sample of $\sim 6 \times 10^{12}$ K^+ decays in flight during Run 1 in 2016-2018.**

- ✓ **HNL production searches ($K^+ \to l^+$N) with the 2016-2018 data set:**
  - **$\mathcal{O}(10^{-9})$ limits on $|U_{e4}|^2$, full data set [PLB 807 (2020) 135599]**
  - **$\mathcal{O}(10^{-8})$ limits on $|U_{\mu 4}|^2$, full data set [PLB 816 (2021) 136259]**

- ✓ **With slight modifications to the $K^+ \to \mu^+$N analysis, a first search is conducted for $K^+ \to \mu^+ \nu X$ with X a scalar or vector mediator in the mass range 10-370 MeV/c^2: no signal has been detected and upper limits are obtained at 90% CL on the BR range from $\mathcal{O}(10^{-5})$for low m_X values to $\mathcal{O}(10^{-7})$for high m_X values. Also a 90% CL upper limit at 1.0×10^{-6} on the BR$(K^+ \to \mu^+ \nu\nu\bar{\nu})$ is obtained.**

- ✓ **NA62 sensitivity to $|U_{l4}|^2$ to be improved with larger data sets (new data taking period 2021-2024)**