Search for K^+ decays to a charged ℓepton and invisible particles with NA62

- The Kaon Factory @ CERN SPS -

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PANIC 21 Conference, Lisbon

08.09.2021

Content

$K^+ \rightarrow \ell^+$ + invisible with NA62: search for new physics and particles beyond the Standard Model:

- Heavy Neutral Lepton (HNL) searches:
  - $K^+ \rightarrow e^+ N$ and $K^+ \rightarrow \mu^+ N$ (N = HNL)
- Related searches:
  - $K^+ \rightarrow \mu^+ \nu\nu\bar{\nu}$ versus $K^+ \rightarrow \mu^+ \nu X$

  X = invisible scalar or vector hidden sector mediator
- Results and prospects

Heavy Neutral Leptons (HNL)

- Heavy neutral leptons: three right-handed (sterile) neutrinos N_i are added to the Standard Model (SM), they mix with classical neutrinos:

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

k=3

- to account for neutrino masses and oscillations, for the evidence of Dark Matter and for the baryon asymmetry of the universe.
- **The neutrino minimal Standard Model extension (νMSM)** considers mass ranges and couplings: ([Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151])
  - N_1: m_1 ~ 10 keV — dark matter candidate
  - $N_{2,3}$: $m_{2,3}$ ~ 100 MeV — 100 GeV
  - Yukawa couplings in the range 10^{-11} to 10^{-6}
- If HNLs exist, they would be produced in every process containing active neutrinos with a branching fraction proportional to the **mixing parameters $|U_{\ell 4}|^2$** (here considering k = 1).
- **Masses of $\mathcal{O}$(GeV) are observable at NA62 via Kaon decays: HNL production and decay searches.**

HNL production in K^+ decays

[R. Shrock, PLB96 (1980) 159]

$$\Gamma(K^+ \to \ell^+ N) = \Gamma(K^+ \to \ell^+ \nu) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2.$$

$\rho_\ell(m_N) \times |U_{\ell 4}|^2$: $\mathcal{O}(1)$

$|U_{\ell 4}|^2$: elements of the extended neutrino mixing matrix

$\rho_\ell(m_N)$: kinematic enhancement factor

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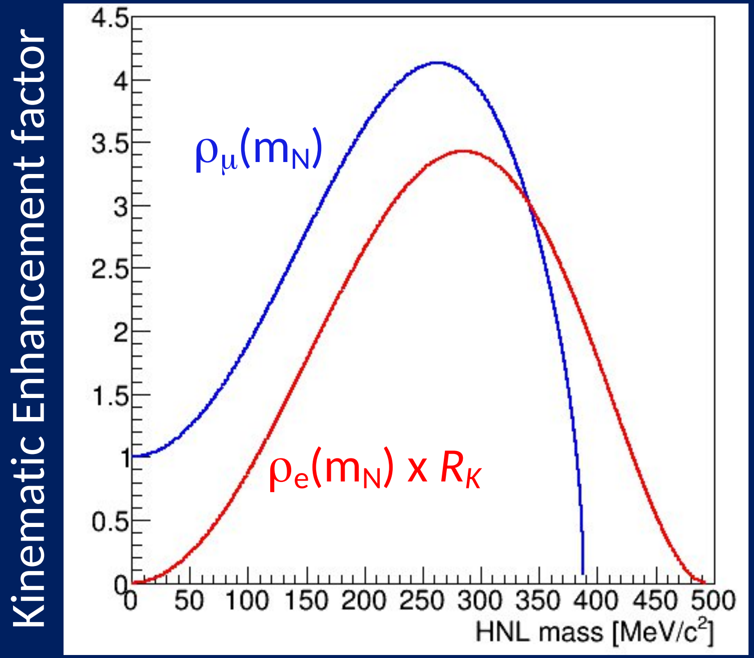


$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} \approx 2.5\cdot 10^{-5}$$

$$\rho_l(m_N) = \left[(x+y) - (x-y)^2\right] / \left[x(1-x)^2\right] \times \lambda^{1/2}(1,x,y)$$

$$x = (m_l/m_K)^2,\ y = (m_N/m_K)^2$$

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

- HNL production kinematically enhanced with respect to SM decays, except near kinematic endpoints
- Enhancement ~10^5 in the $K^+ \to e^+N$ case: relaxed helicity suppression

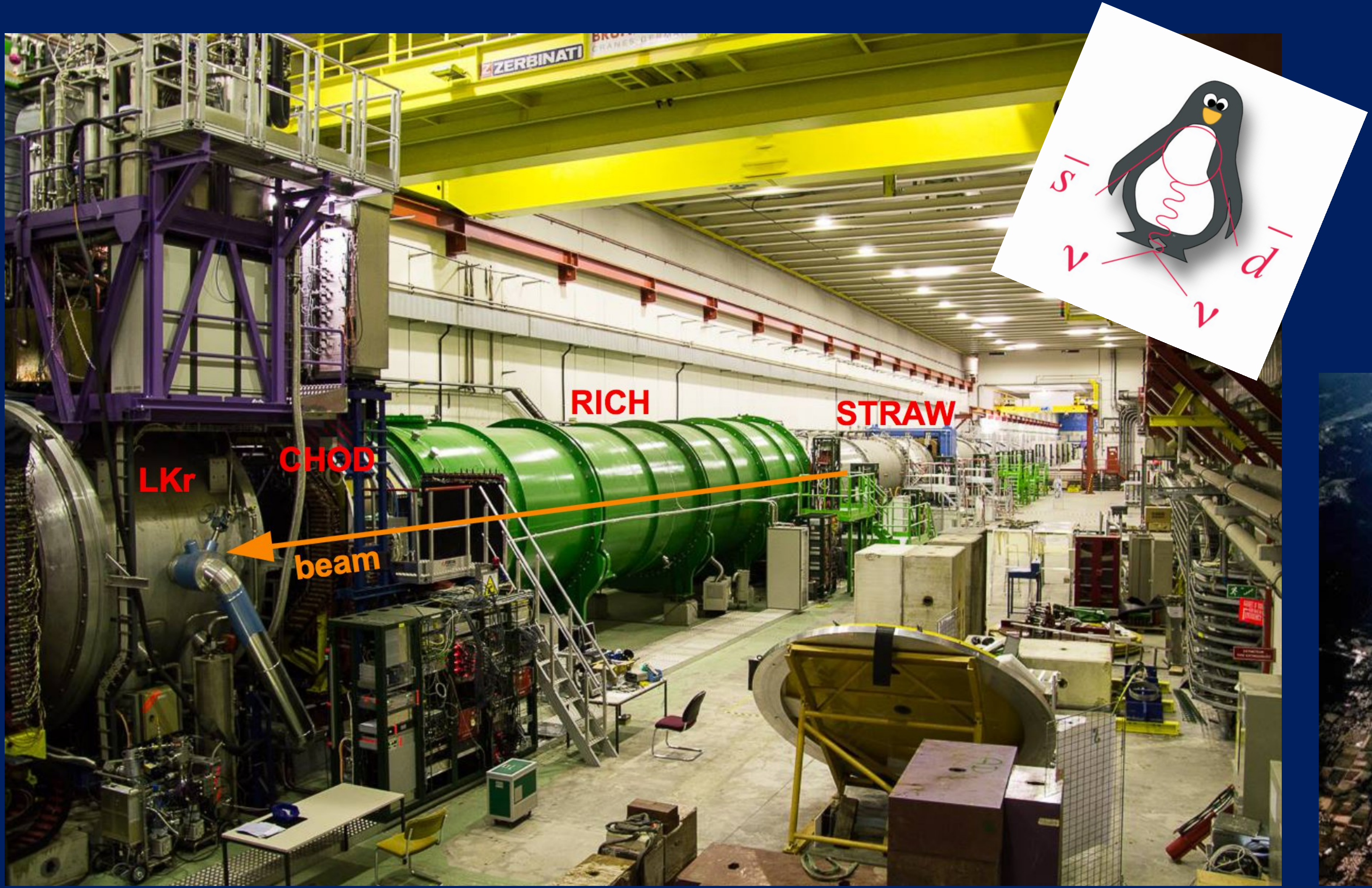
$K^+ \to \mu^+ \nu X$: $X \to$ invisible or $X \to \mu\mu/\gamma\gamma$

[PRL 124 (2020) 041802]

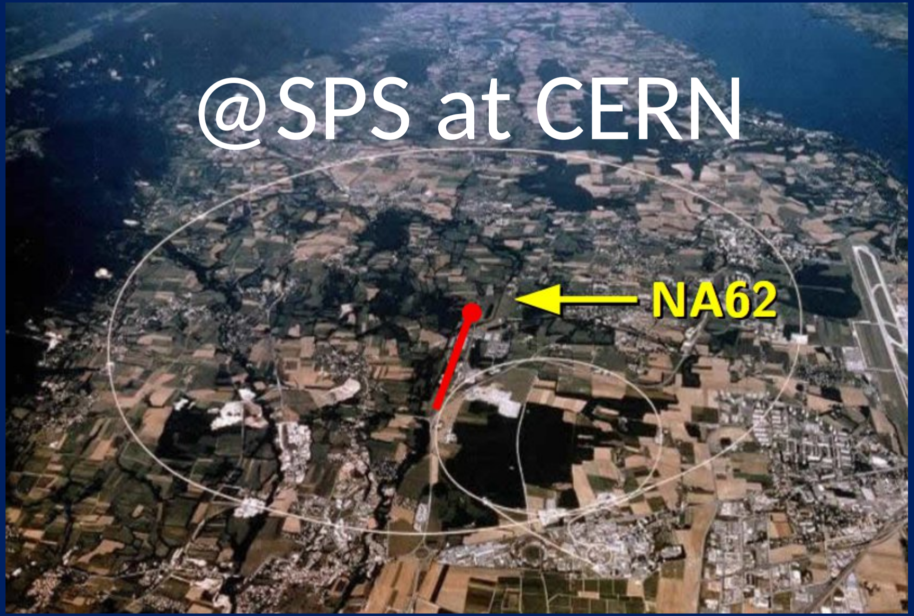
- $X \to$ invisible:
  - probe remaining parameter space in which muonic forces reconcile the $(g\text{-}2)_\mu$ anomaly
  - Dark Matter candidate (thermal DM production)
  - neutrinos: reduce the H_0 (Hubble constant) tension
- $X \to \mu\mu/\gamma\gamma$:
  - improve coverage for scalar and vector forces, covering $(g\text{-}2)_\mu$ favoured region
- Background potentially also from $K^+ \to \mu^+ \nu\nu\bar{\nu}$:
  - ➢ Search for new physics with ultra-rare decay: probe the new chiral perturbation theory form factors related to the neutral weak boson exchange BR: 1.6×10^{-16} [JHEP 1610 (2016) 039]

➢ **Here: X->invisible and $K^+ \to \mu^+ \nu\nu\bar{\nu}$ as variation of the HNL analysis**

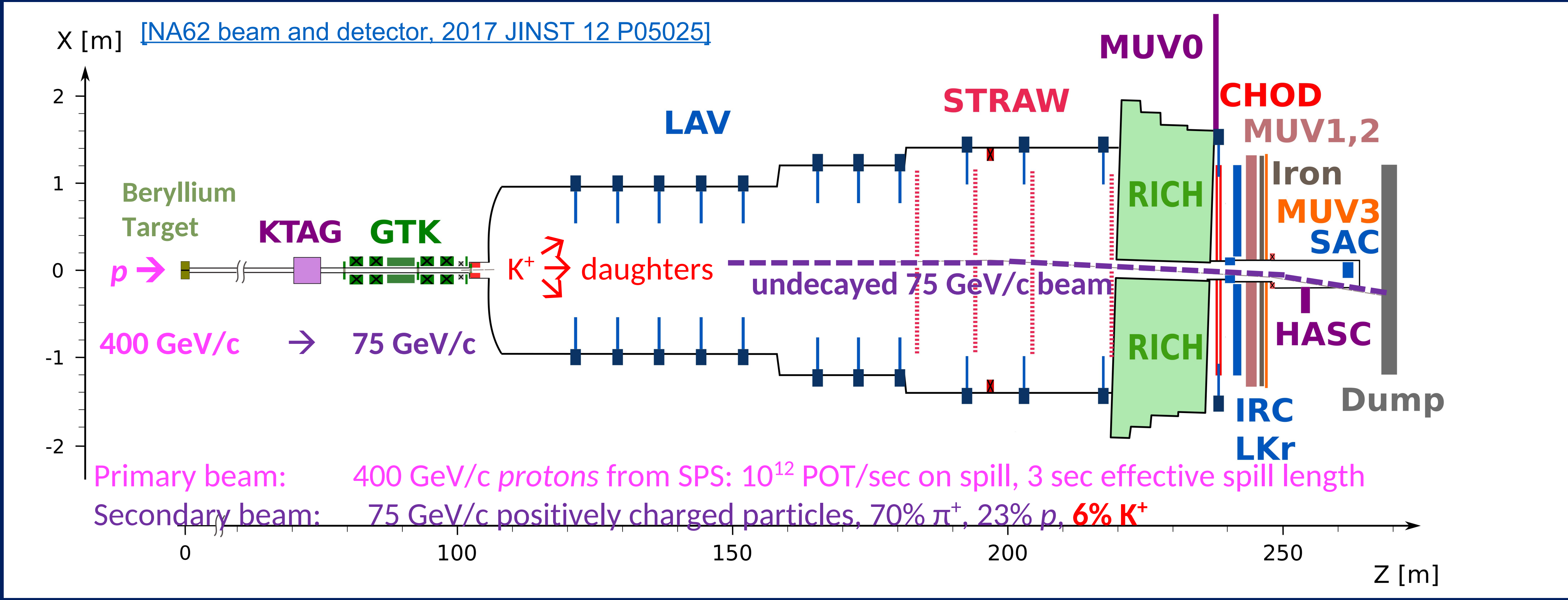
The Kaon Factory: NA62 @ CERN SPS



- Fixed target experiment
- Kaon decay-in-flight
- Main goal: BR($K^+ \to \pi^+\nu\nu$) measurement with $\mathcal{O}$(10%) precision
  - Results: [PLB791 (2019) 156-166, JHEP11 (2020)]



The Kaon Factory: NA62 @ CERN SPS

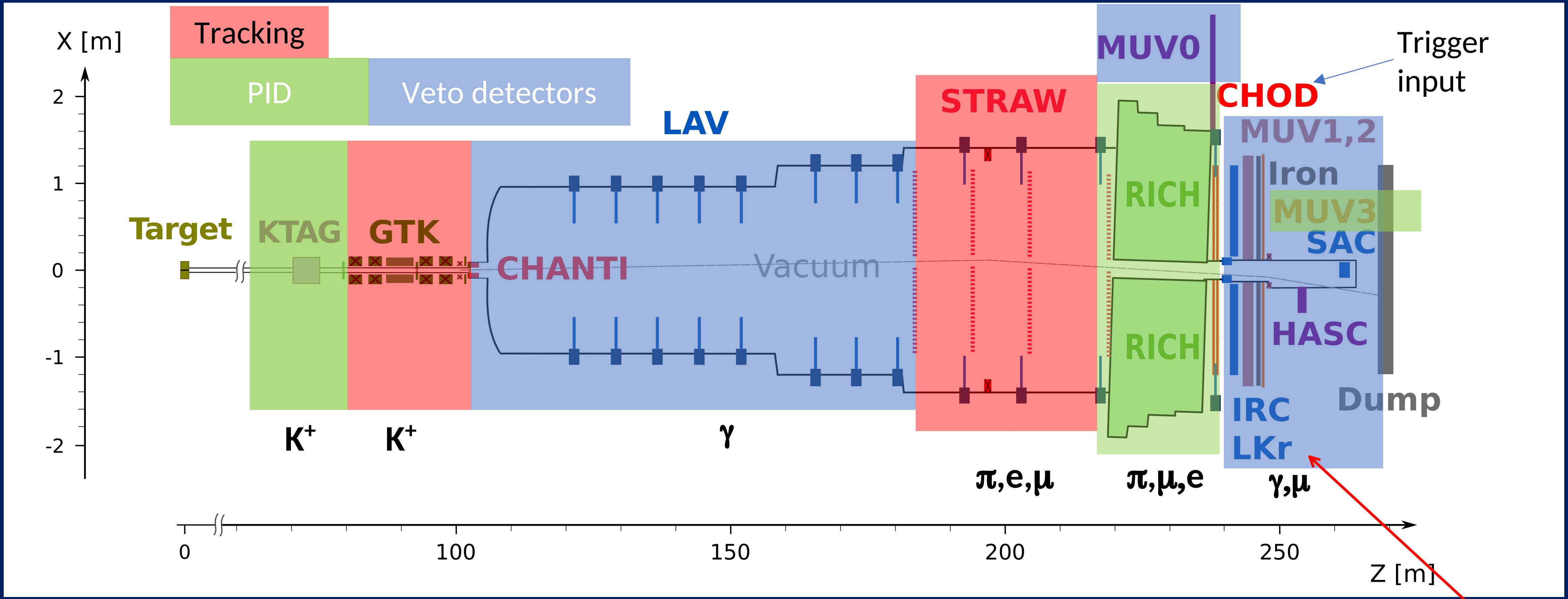


Primary beam: 400 GeV/c *protons* from SPS: 10^{12} POT/sec on spill, 3 sec effective spill length

Secondary beam: 75 GeV/c positively charged particles, 70% π^+, 23% p, **6% K^+**

Nominal beam rate: 750 MHz: K^+ rate 45 MHz and 3.7 MHz mean K^+ decay rate in fiducial volume (FV)

The Kaon Factory: NA62



Energy measurement:
Liquid Krypton calorimeter LKr

Data taking, trigger conditions and selections

- 2.2 x 10^{18} proton-on-target events (POT) in Run1 (2016 - 2018): 6 x 10^{12} K^+ decays recorded
- **Excellent time resolution: $\mathcal{O}$(100 ps)** to match beam and daughter particle information
- **PID capability (RICH+LKr+HAC+MUV): $\mathcal{O}(10^{-8})$ muon suppression**
- **High-efficiency photon veto: $\mathcal{O}(10^{-8})$ rejection** of $\pi^0 \to \gamma\gamma$ for $E(\pi^0) > 40$ GeV
- Kinematics: rejection of main K^+ modes down to 10^{-4} via kinematics reconstruction

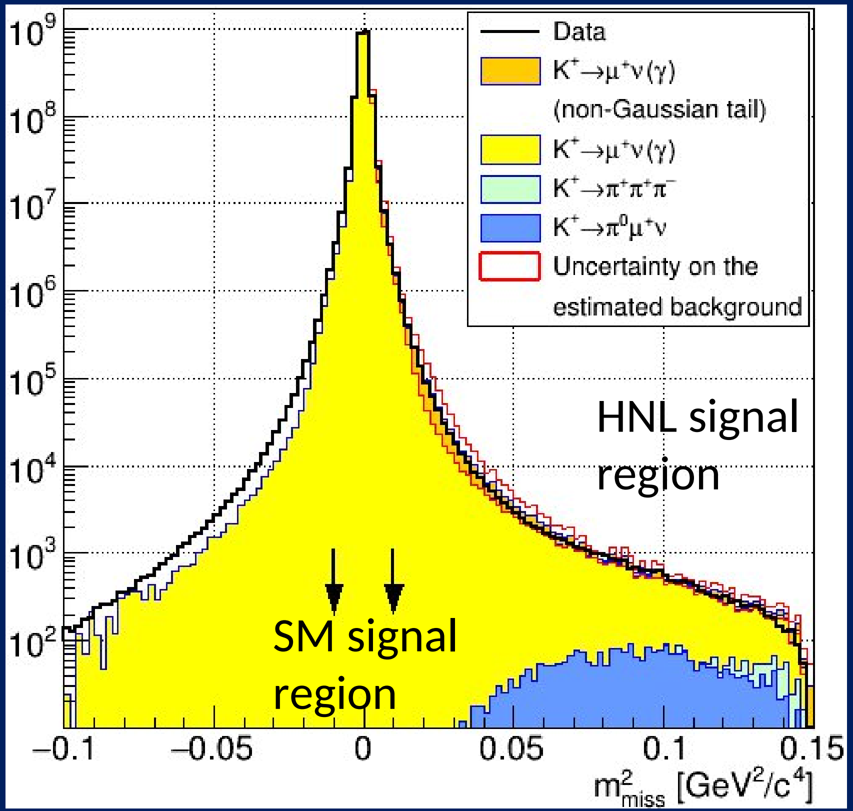
Specific selections within the considered searches:

- Triggers used: $K^+ \to \pi^+ \nu\nu$ for $K^+ \to e^+ N$; minimum bias (downscaled by 400) for $K^+ \to \mu^+ N$
- 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
- Lepton PID: e^+ : $0.92 < E_{LKr}/p_e < 1.08$, RICH and MUV3 veto ; μ^+ : $E_{LKr}/p_\mu < 0.2$, RICH and MUV3 information
- Upstream track identified by KTAG and GTK matched with the downstream lepton

HNL search with Run1 data-set

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

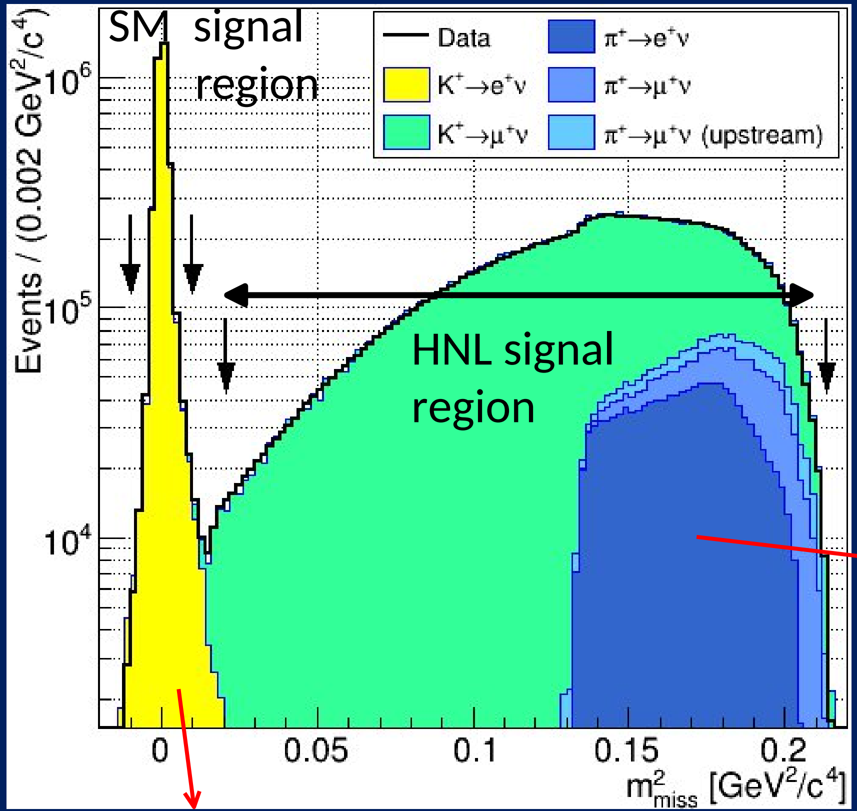
[Phys. Lett. B 816 (2021) 136259]



BR ($K^+ \to \mu^+ \nu$) = 0.64

Search for $K^+ \to e^+ N$

[Phys. Lett. B 807 (2020) 135599]



$K^+ \to e^+ \nu$ with BR = 1.6×10^{-5}

Number of kaon decays in the fiducial volume (FV):

$(1.14 \pm 0.02) \times 10^{10}$ $(3.52 \pm 0.02) \times 10^{12}$

- Peak search in the missing mass distribution $\mathbf{m^2_{miss} = (P_K - P_\ell)^2}$ with P_K (P_ℓ): kaon (lepton) four-momentum, using GTK and STRAW information
- $K^+ \to \mu^+ \nu$ with $\mu^+ \to e^+ \nu \nu$ suppressed by good vertex resolution
- $\pi^+ \to e^+ \nu$ accidental mistagging

➢ **HNL production signal: a spike above continuous missing mass spectrum**

➢ **No HNL production signals are observed.**

HNL: Mass scan and resolution

- **Signal window:** $|m_{miss} - m_N| < 1.5\,\sigma_m$ (σ_m mass resolution, evaluated with simulation)
  - ➢ background is proportional to $\sigma_m \rightarrow$ **resolution is crucial to resolve possible HNL mass splitting!**
- ***N_exp*: number of expected background events**
  - – for each hypothesis: fit of 2nd order polynomial to data in side-bands $\mathbf{1.5\,\sigma_m < |m_{miss} - m_N| < 11.25\,\sigma_m}$ of the m^2_{miss} spectrum
- **Considered HNL mass ranges:**

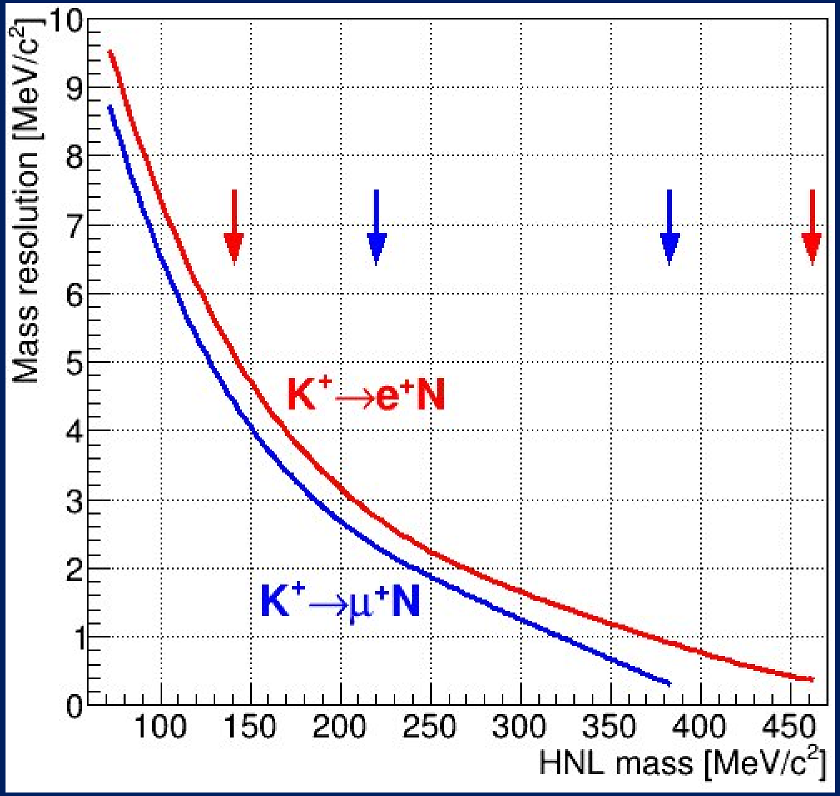
  e^+ : m_N = 144 - 462 MeV/c^2

  μ^+ : m_N = 188 - 386 MeV/c^2
- **Mass scan steps and number of hypotheses:**

  e^+ : 260 with σ_m / 2 for 260

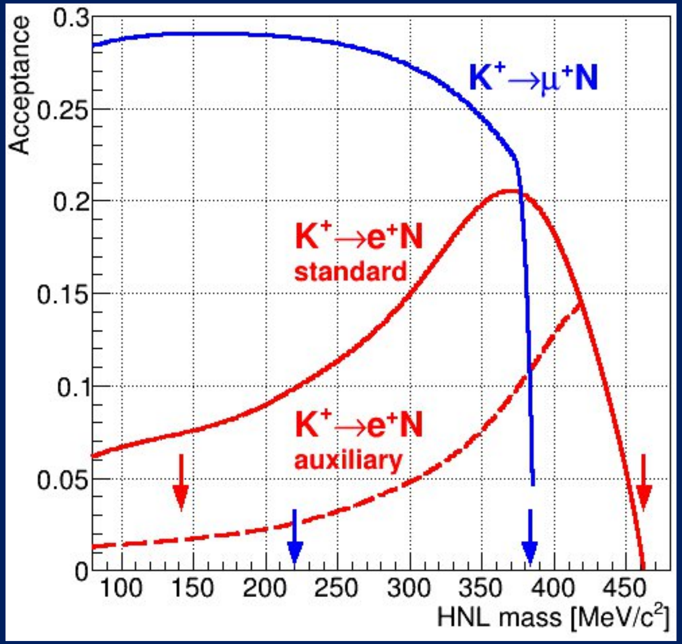
  μ^+ : 269 with 1 MeV/c^2 (0.5 MeV/c^2) for m_N < (>) 300 MeV/c^2

Mass resolution



HNL: Acceptance and sensitivity

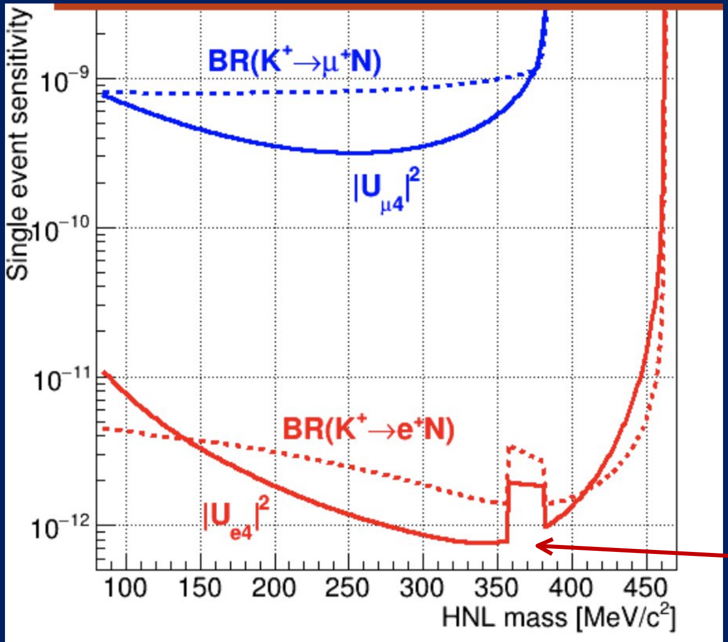
Signal selection acceptance A_N



auxiliary: p_e < 20 GeV/c

A_N from simulations assuming infinite HNL lifetime

Single event sensitivity (SES)



auxiliary selection used

$BR_{SES} = 1/(N_K \times A_N)$

$|U_{\ell 4}|^2_{SES} = BR_{SES} / [BR(K^+ \to \ell^+ \nu)\ \rho_\ell (m_N)]$

N_K : Effective number of Kaon decays in FV

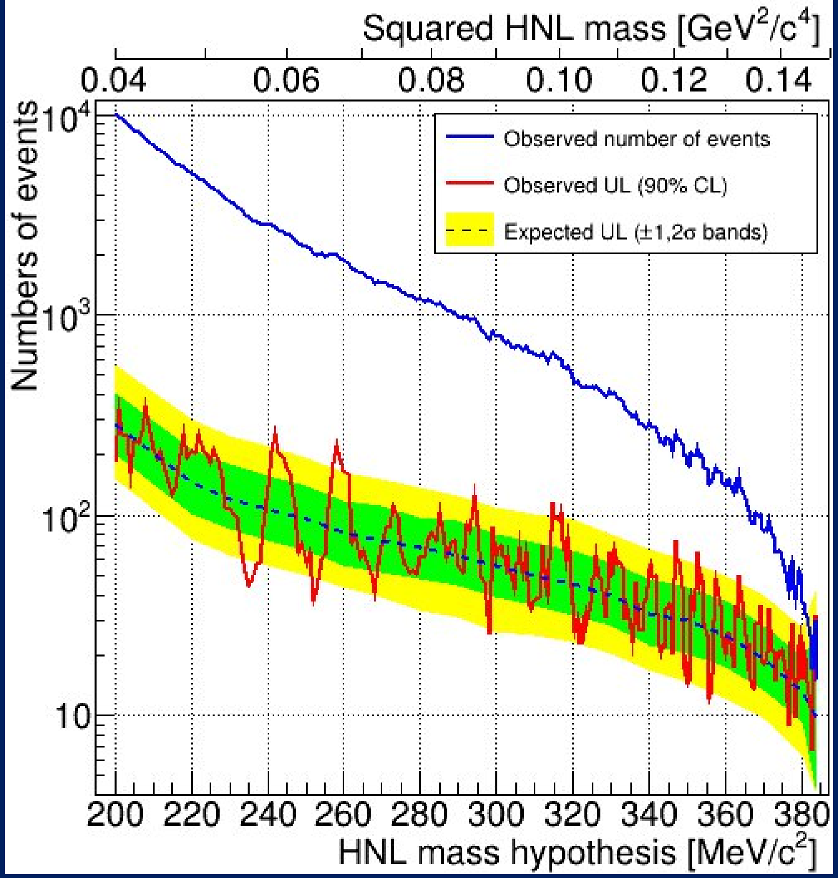
N_S : Number of expected HNL signal events:

$N_S = BR(K^+ \to \ell^+ \nu) / BR_{SES} = |U_{\ell 4}|^2 / |U_{\ell 4}|^2_{SES}$

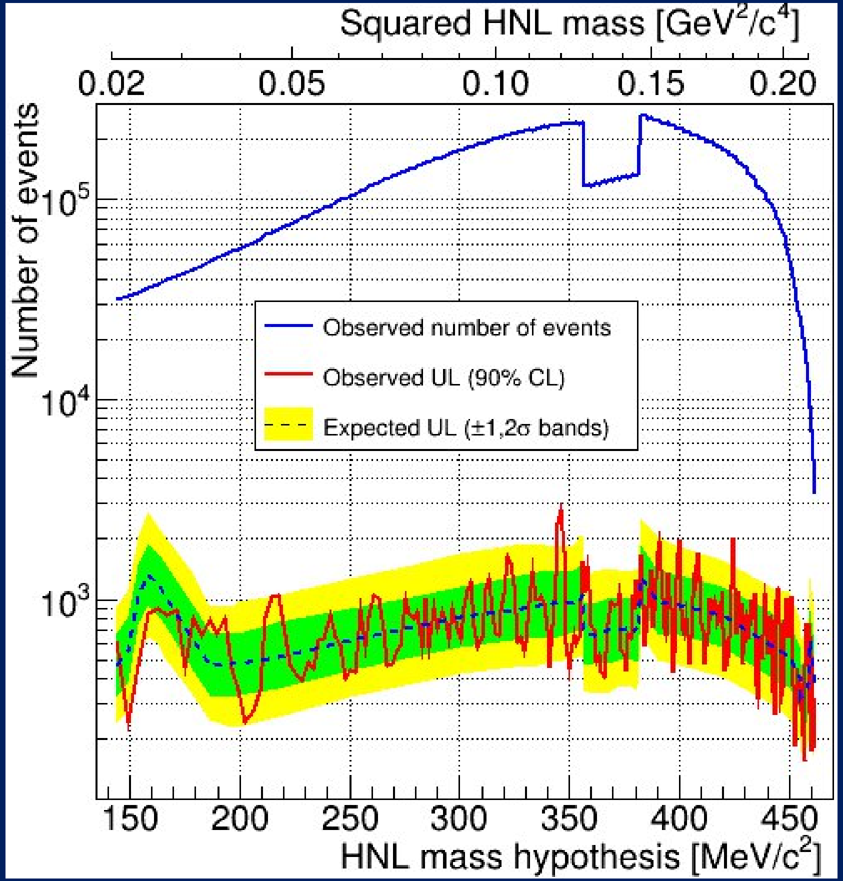
→ all ingredients to obtain upper limits @ 90% confidence level (CL)

HNL: Upper limits of N_S - Run1 data set

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



Search for $K^+ \rightarrow e^+ N$



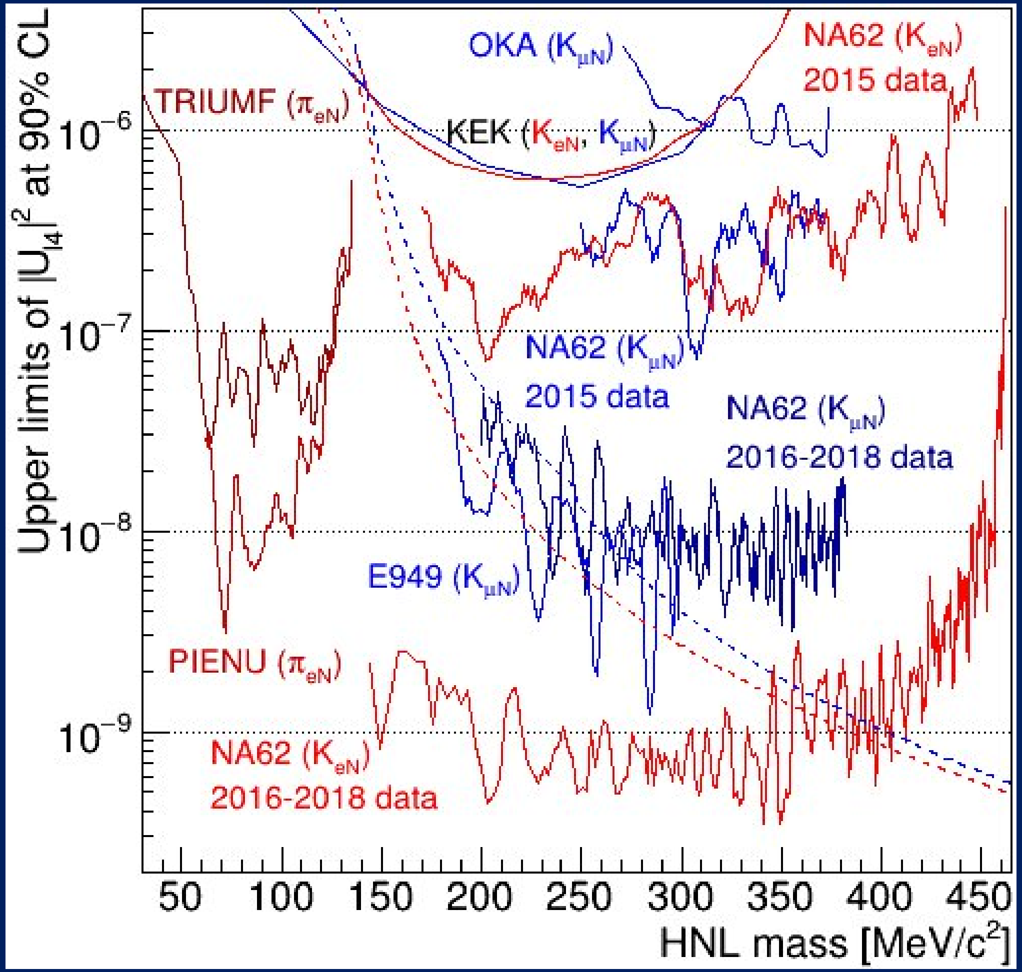
N_{obs}, and the observed UL of N_S, and the expected ±1σ and ±2σ bands of variation of N_S in the null (i.e. background-only) hypothesis.

Upper limit (UL) of the number of signal events N_S at 90% CL using CLs technique:

- Use the number of observed events (N_{obs}, δN_{obs}) within the signal window and expected background events (N_{exp}, δN_{exp}) → compute the local signal significance for each mass hypothesis and evaluate UL of N_S

- **μ^+ : significance never exceeds 3σ → no HNL production signals are observed.**
- **e^+ : maximum local significance of 3.6 for m_N = 346 MeV/c^2. Accounting for look-elsewhere effect: global significance = 2.2**

HNL: Upper limits of $|U_{\ell 4}|^2$ - Run1 data set



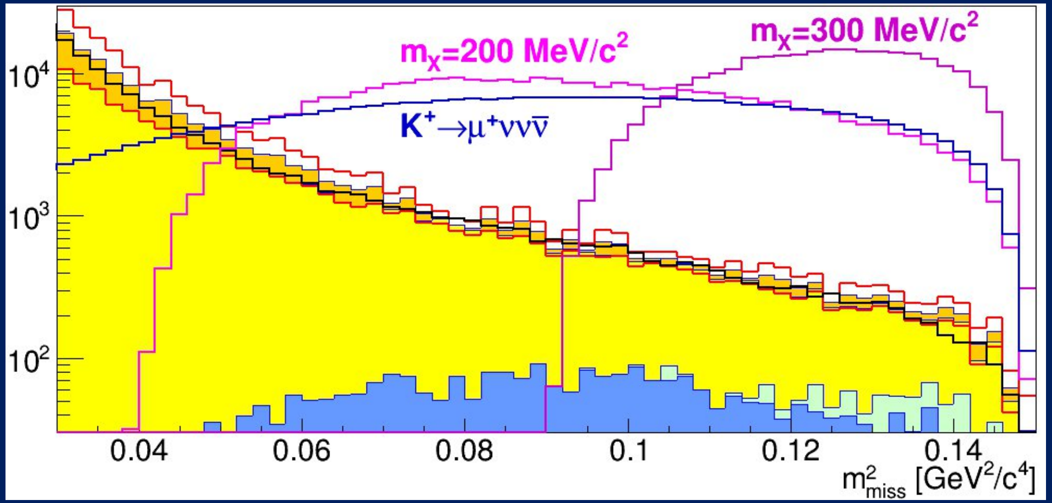
[Phys. Lett. B 816 (2021) 136259]

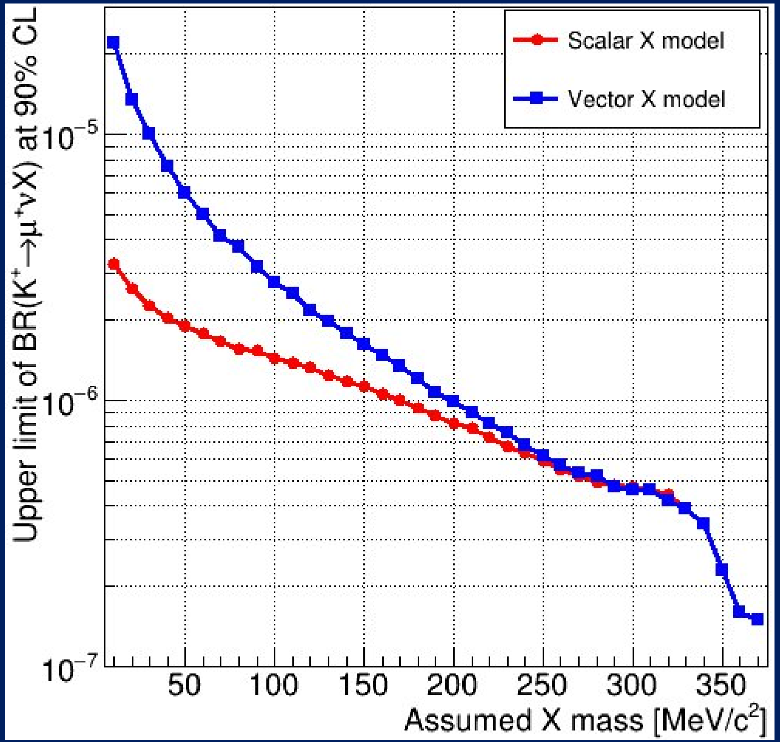
- $\mathcal{O}(10^{-9})$ limits on $|U_{e4}|^2$ and $\mathcal{O}(10^{-8})$ limits on $|U_{\mu 4}|^2$
- More than 2(1) orders of magnitude improvements from run 1 data for e^+(μ^+) with respect to previous results.
- For μ^+: NA62 consistent with the E949 result and extends UL to higher masses.
- For e^+: values favoured by the Big Bang Nucleosynthesis (BBN) constraint (dashed red line) are excluded for HNL masses up to 340 MeV/c^2

Search for new particles: $K^+ \to \mu^+ \nu X$

[Phys. Lett. B 816 (2021) 136259]

zoom from slide 11





- Mass range 10—370 MeV/c^2
- Compare expected and observed number of events for each mass hypothesis and extract limit: **→ No signal observed**
- The limits obtained in the scalar model are stronger than those in the vector model due to larger mean m^2_{miss} .

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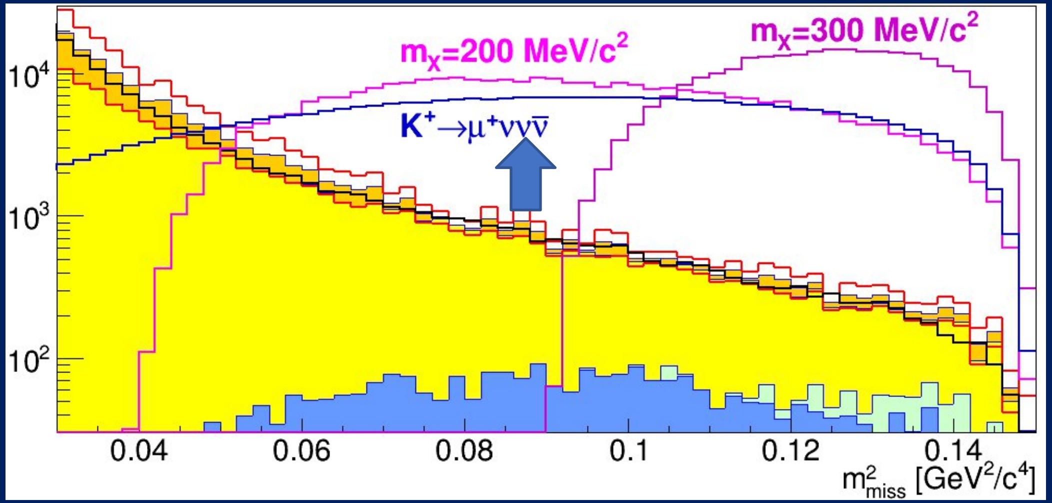

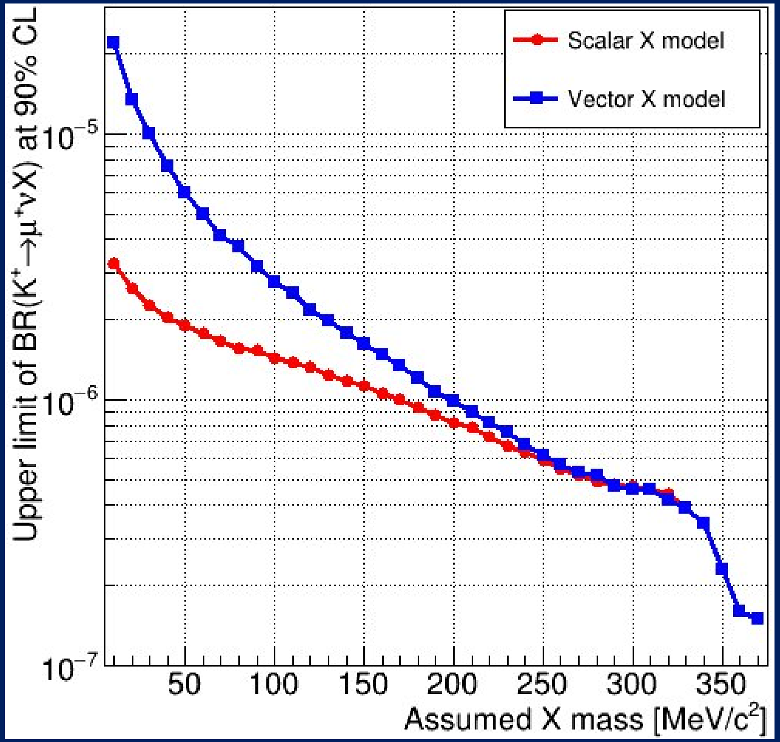

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Related search: $K^+ \to \mu^+ \nu \nu \bar{\nu}$, current limit: BR < 2.4×10^{-6} (E949, [PRD94 (2016) 032012])

- Search region m^2_{miss} > 0.1 GeV^2/c^4 (optimized to extract strongest limit)
- Observed events: 6894; expected from MC: 7549 ± 928 **→ set new upper limit: BR <1.0×10^{-6} at 90% CL in the SM framework**

Summary, conclusions and outlook

- World best upper limits on HNL mixing parameters have been set with Run1 data:
  - $\mathcal{O}(10^{-9})$ limits on $|U_{e4}|^2$, full data set [PLB 807 (2020) 135599]
  - $\mathcal{O}(10^{-8})$ limits on $|U_{\mu4}|^2$, full data set [PLB 816 (2021) 136259]
- First search for $K^+ \to \mu^+ \nu X$ decays has been performed in the mass range 10-370 MeV/c^2: upper limits between $\mathcal{O}(10^{-7})$ for high m_X and $\mathcal{O}(10^{-5})$ for low m_X at 90% CL ([PLB 816 (2021) 136259])
- World best upper limit on BR($K^+ \to \mu^+ \nu\nu\bar{\nu}$) has been set: 1.0×10^{-6} at 90% CL ([PLB 816 (2021) 136259])

- With the NA62 experiment at CERN, a considerable spectrum of ongoing and potential measurements to test and challenge the Standard Model is available.
- The high intensity Kaon beam provides the basis for rare decay studies, precision measurements as well as Dark Matter and New Physics searches …
- … and with future data recordings in Run2 with higher intensity started in July 2021 for improvements in the sensitivity to $|U_{\ell 4}|^2$

Backup

Global Constraints on a Heavy Neutrino: Upper limits estimates for HNL with k=1

- Assuming HNL decay products are not observable:

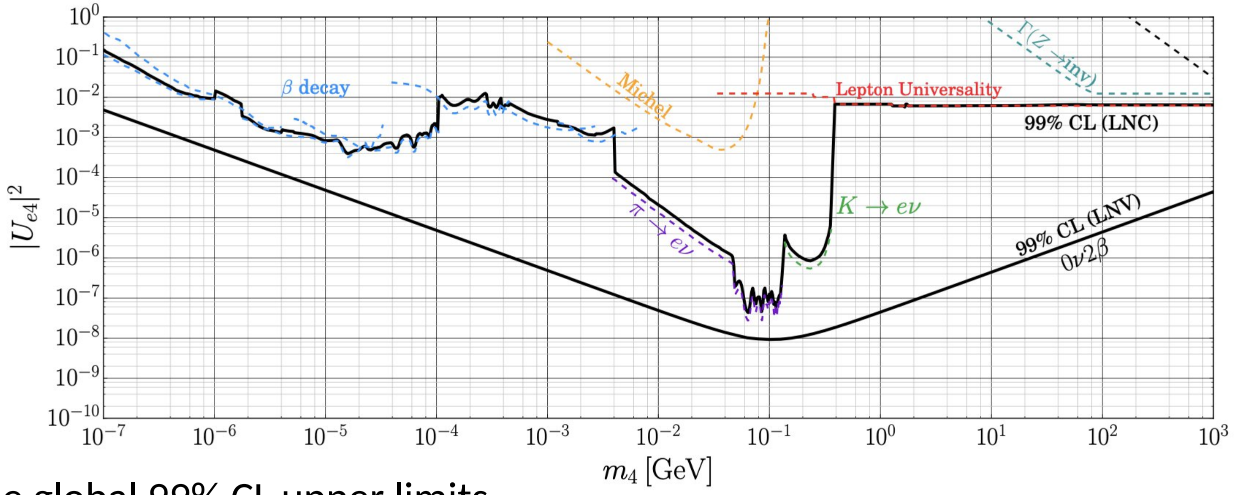
➢ HNL accessible from decays:
  - beta
  - lepton (μ, τ)
  - meson
  - neutrinoless double β-decay

➢ Lepton flavour violating processes

➢ Lepton universality tests

➢ **Mass range for Kaon decays:**

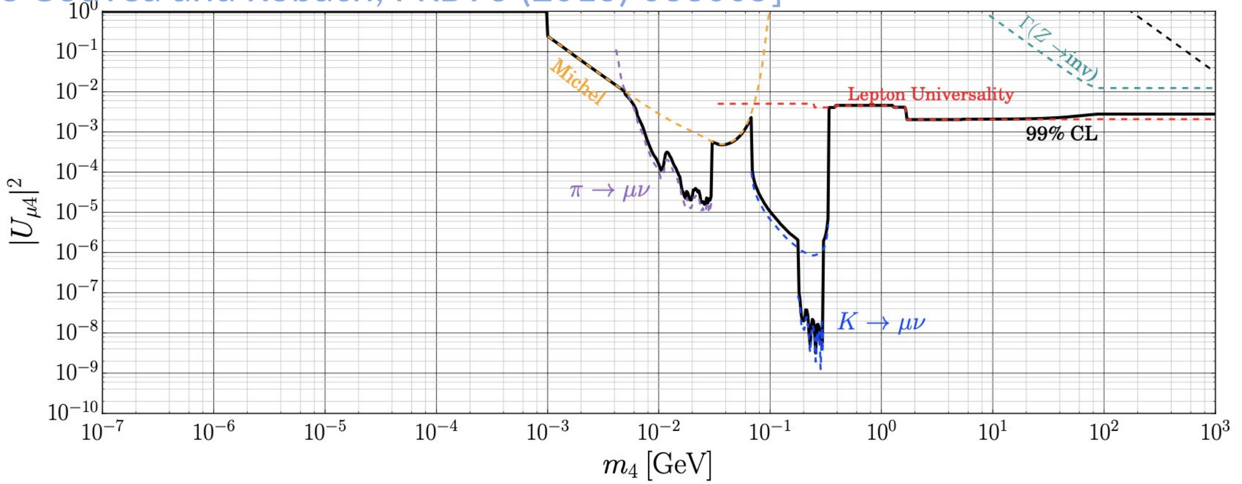
50 MeV < m_4 < 500 MeV



(a)

The global 99% CL upper limits

[De Gouvêa and Kobach, PRD93 (2016) 033005]



HNL: Systematic uncertainties

Systematic uncertainty estimation:

- Possible HNL signals in side-bands: inject artificial HNL signals corresponding to the Single Event Sensitivity (SES) into side-bands
  - ➢ negligible
- Background shape: compare 2nd and 3rd order polynomials
  - ➢ dominant contribution to $\boldsymbol{\delta N_{exp}}$ is statistical, systematic uncertainties become comparable as m_N approaches the boundaries of the HNL search region.
- Total uncertainty of background estimates, $\boldsymbol{\delta N_{exp}/N_{exp}}$:
  - ➢ e^+: 0.2% - few % ; μ+: 1-2% for $m_N < 300$ MeV, increases up to 10% in HNL search region