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

On behalf of the NA62 collaboration

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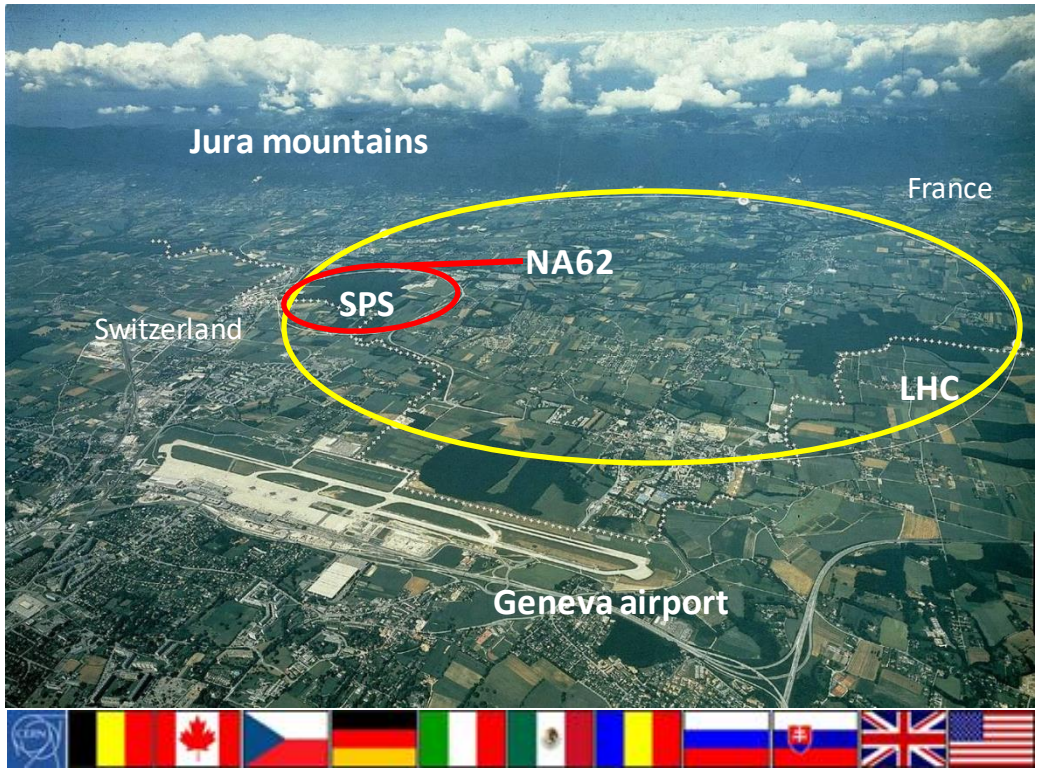
Outline

- The NA62 experiment and detector
- Searches for HNL production: $K^+ \to e^+ N$ and $K^+ \to \mu^+ N$
- Related searches: $K^+ \to \mu^+ \nu\nu\nu$ and $K^+ \to \mu^+ \nu X$

The NA62 experiment and detector

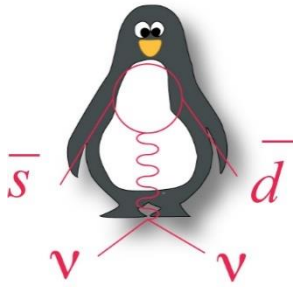
The NA62 Experiment

Fixed target Kaon experiment at CERN SPS

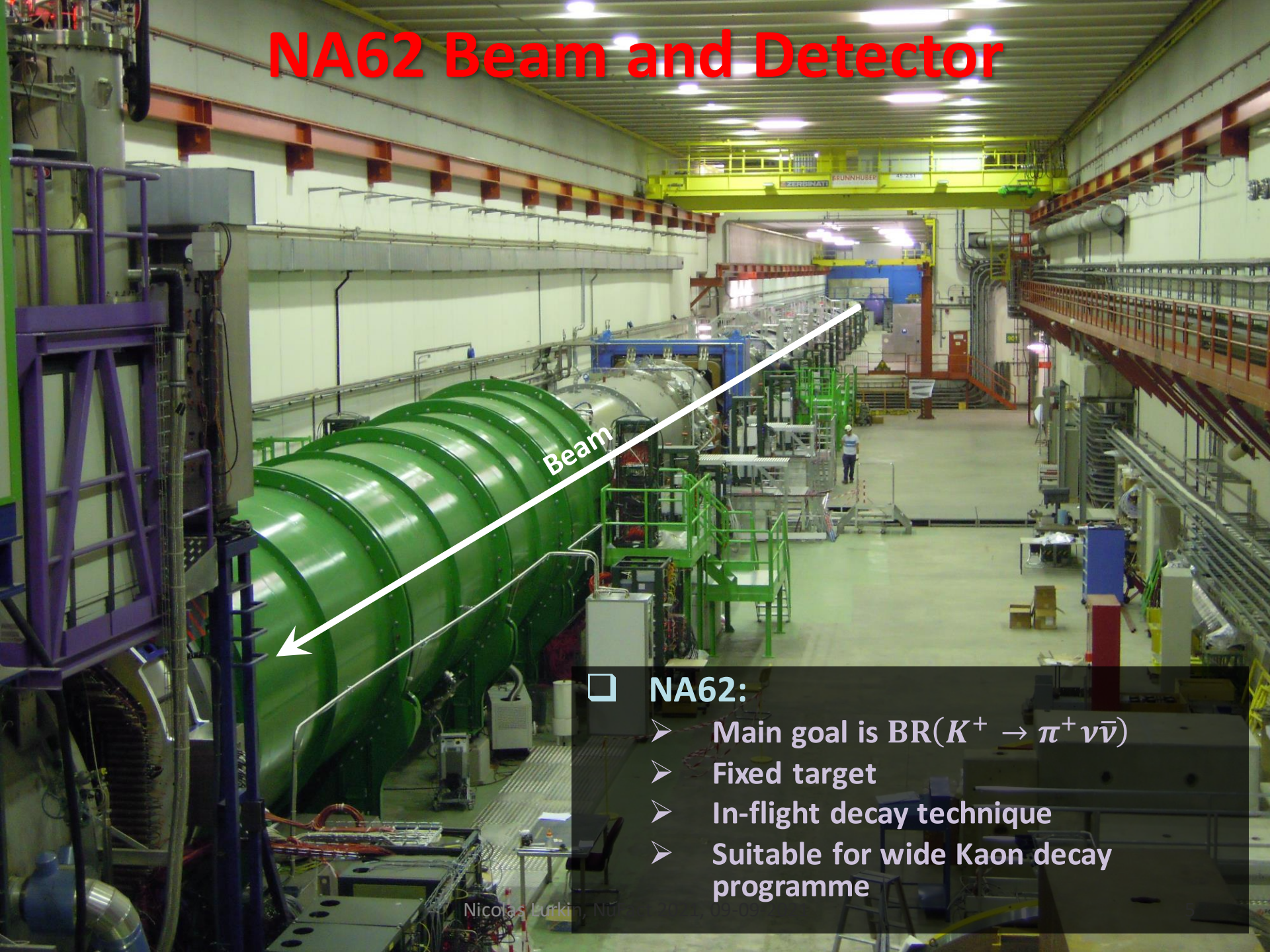


- **2008** • NA62 Approval
- **2009-2014** • Detector R&D and Installation
- **2014** • Pilot Run
- **2015** • Commissioning run
- **2016-2018** • Physics runs
- **2021-2023** • Physics runs (with upgrades)

~200 participants: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain-La-Neuve, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

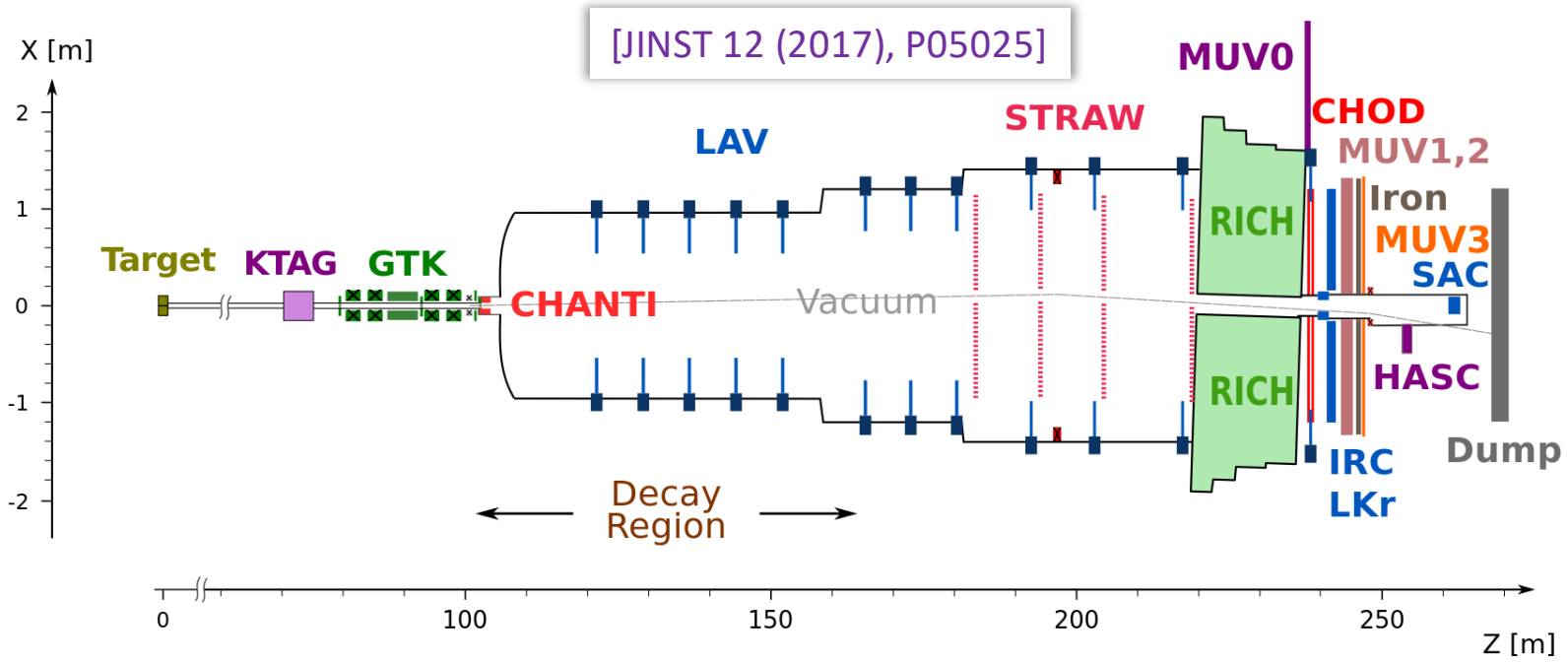


NA62 Beam and Detector



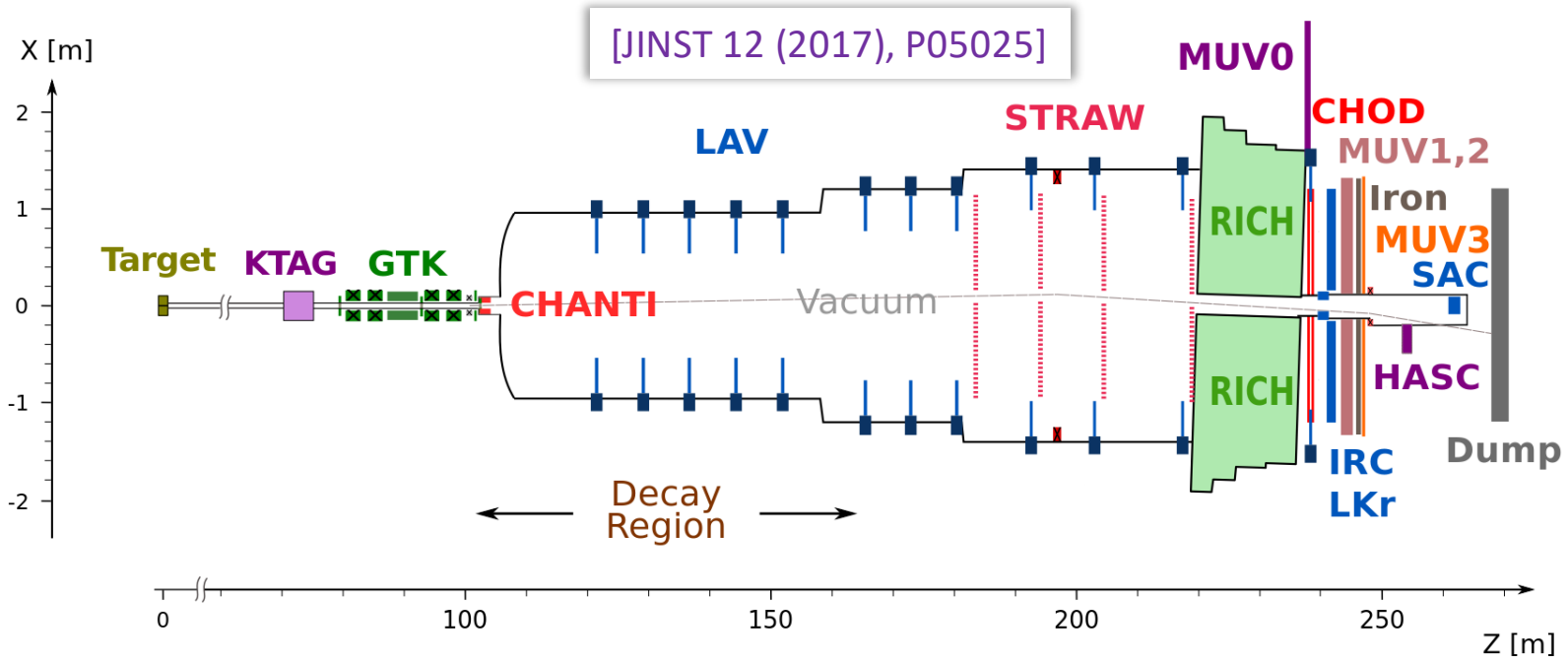
- **NA62:**
  - Main goal is $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$
  - Fixed target
  - In-flight decay technique
  - Suitable for wide Kaon decay programme

NA62 Beam & Detector



- SPS Beam:
  - 400 GeV/c protons
  - 2×10^{12} protons/spill
  - 3.5 s spill
- Secondary positive beam
  - 75 GeV/c momentum, 1% bite
  - $100\ \mu$rad divergence (RMS)
  - $60 \times 30\ \mathrm{mm}^2$ transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- Decay region
  - 60 m long fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum $\sim\mathcal{O}(10^{-6})$ mbar

NA62 Beam & Detector



- $\mathcal{O}(100\ ps)$ time resolution to match upstream-downstream information
- Beam kaon identification and measurement (KTAG + GTK)
- Particle ID (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
- Kinematic rejection factor: 1×10^{-3} for $K^+ \to \pi^+\pi^0$, 3×10^{-4} for $K^+ \to \mu^+\nu$

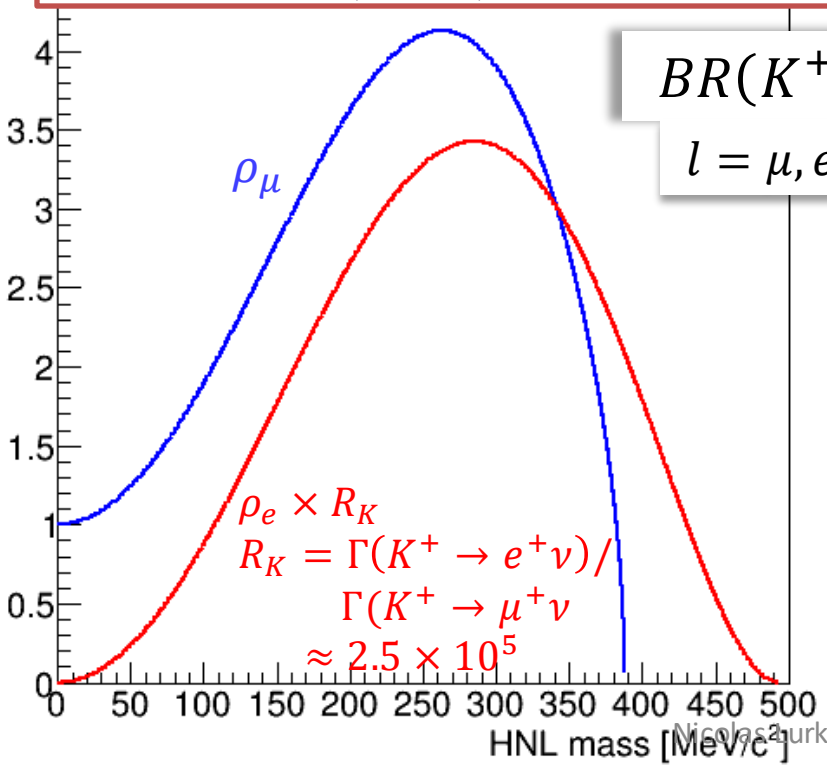
Data collection

- **Statistics**
  - 2015: 1% of nominal intensity, 3×10^8 kaon decay
  - 2016: 30 days, 40% of nominal intensity, 2×10^{11} useful kaon decay
  - 2017: 161 days, 60% of nominal intensity, 2×10^{12} useful kaon decay
  - 2018: 217 days, 60% of nominal intensity, 4×10^{12} useful kaon decays
- **Trigger streams**
  - PNN trigger: 1 track, γ/μ veto, used for $l^+ = e^+$ channels
  - CTRL trigger/400: single charged particle in the CHOD acceptance(minimum bias trigger), used for $l^+ = \mu^+$ channels

Searches for HNL production: $K^+ \to e^+ N$ and $K^+ \to \mu^+ N$

HNL production in K^+ decays

- **No neutrino mass in the SM**
- **νMSM extension: explain neutrino oscillations, dark matter and baryon asymmetry of the universe.** [Asaka et al., Phys.Lett.B 620 (2005) 17]
  - Adds 3 right-handed sterile neutrinos
    - N_1: $m_1 \sim 10$ keV - dark matter candidate
    - $N_{2,3}$: $m_{2,3} \sim 100$ MeV $-$ 100 GeV - baryon asymmetry



$$BR(K^+ \to l^+ N) = BR(K^+ \to l^+ \nu) \times \rho_l \times |U_{l4}|^2$$

$l = \mu, e$

$\mathcal{O}(1)$

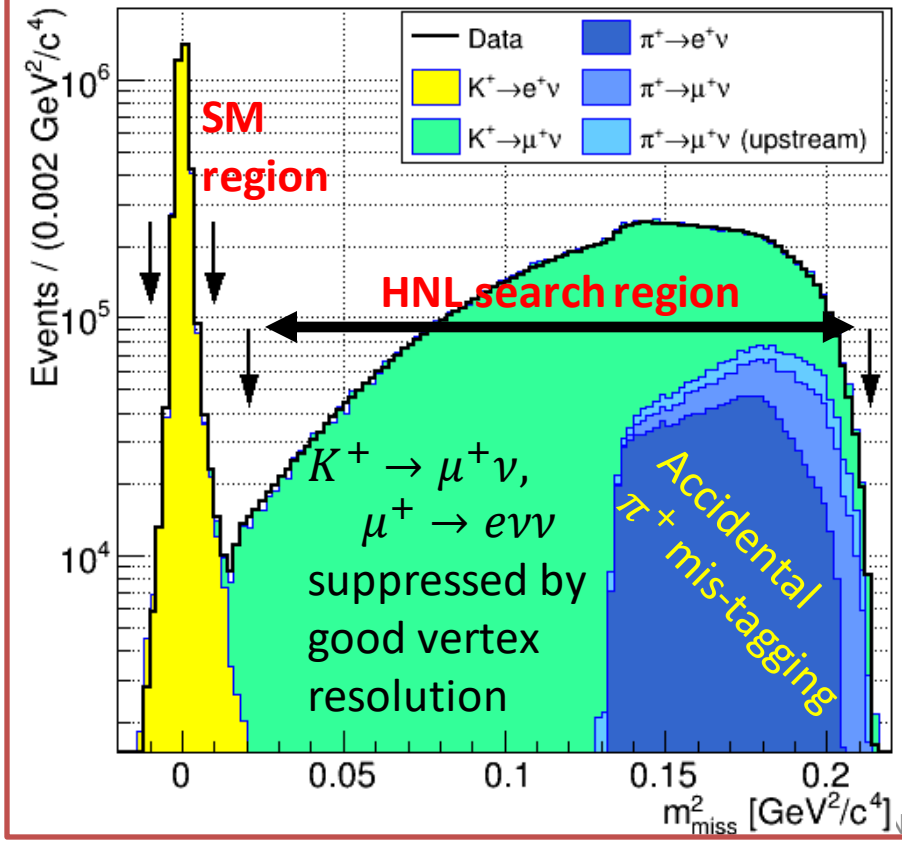
[R. Shrock, PLB96 (1980) 159]

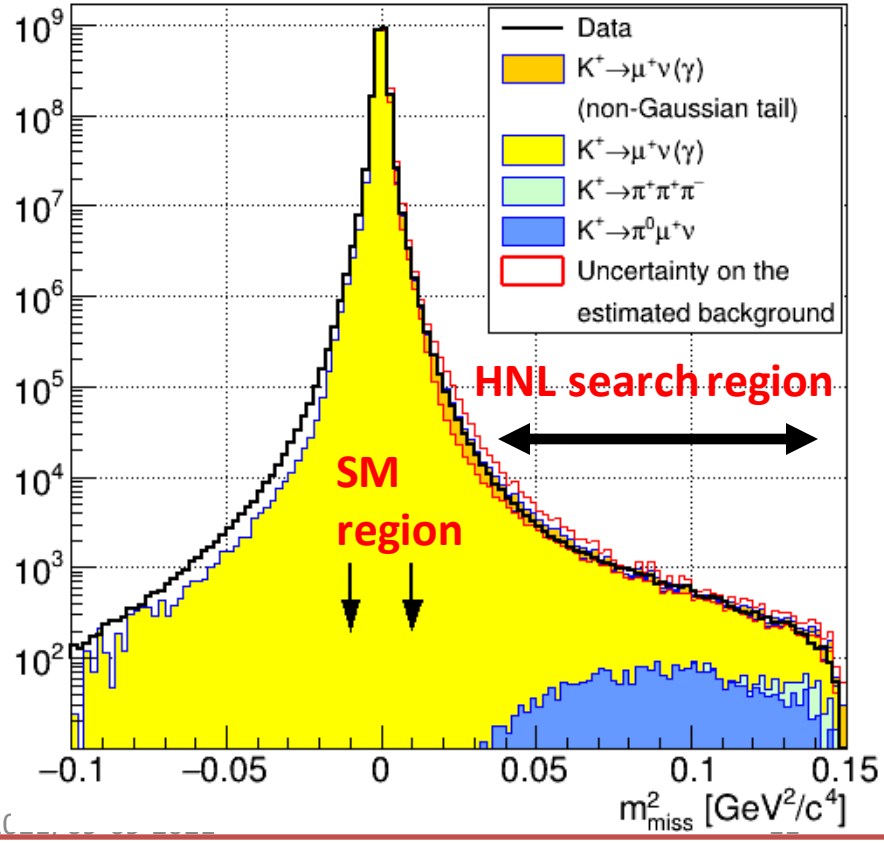
- HNL production is enhanced kinematically (ρ_l) with respect to SM decays, except near kinematic endpoint
- Enhancement $\sim \mathbf{10^5}$ in the $\boldsymbol{K^+ \to e^+ N}$ case as the helicity suppression is relaxed

HNL selection

- $m^2_{\text{miss}} = (P_K - P_l)^2$, P_K and P_l are the Kaon and lepton 4-momenta
- HNL signal: sharp peak in the m^2_{miss} spectrum

- Selection
  - K^+ and l^+ tracks reconstruction and matching
  - Powerful PID (RICH, LKr, MUV3)
  - Extra activity vetoing

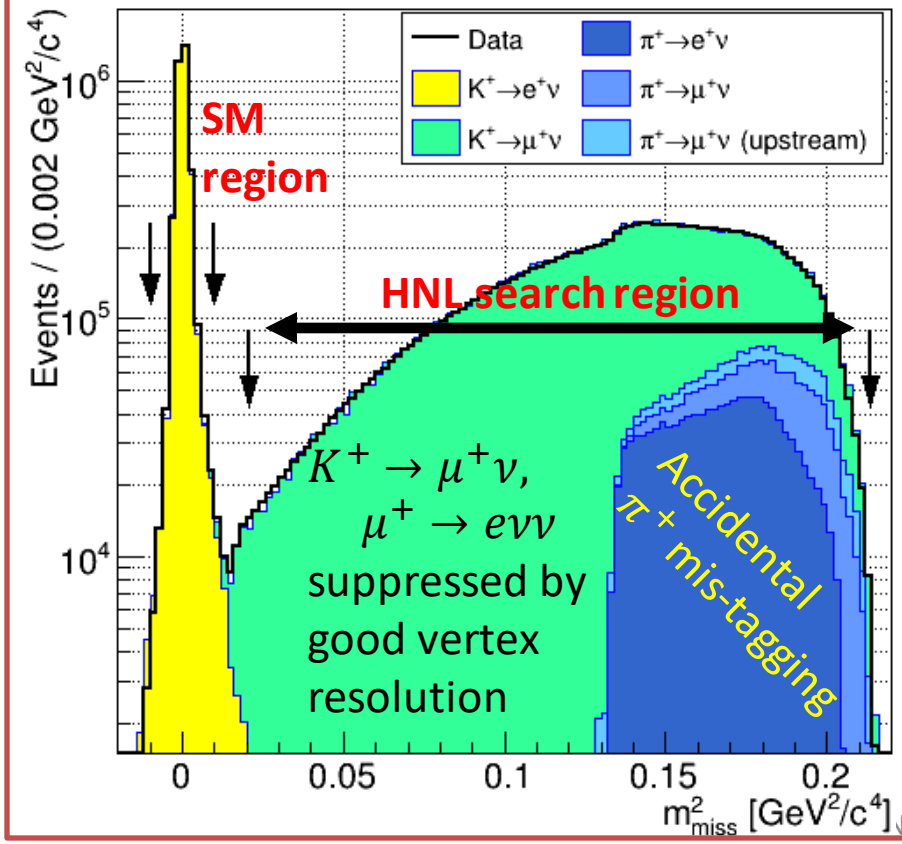


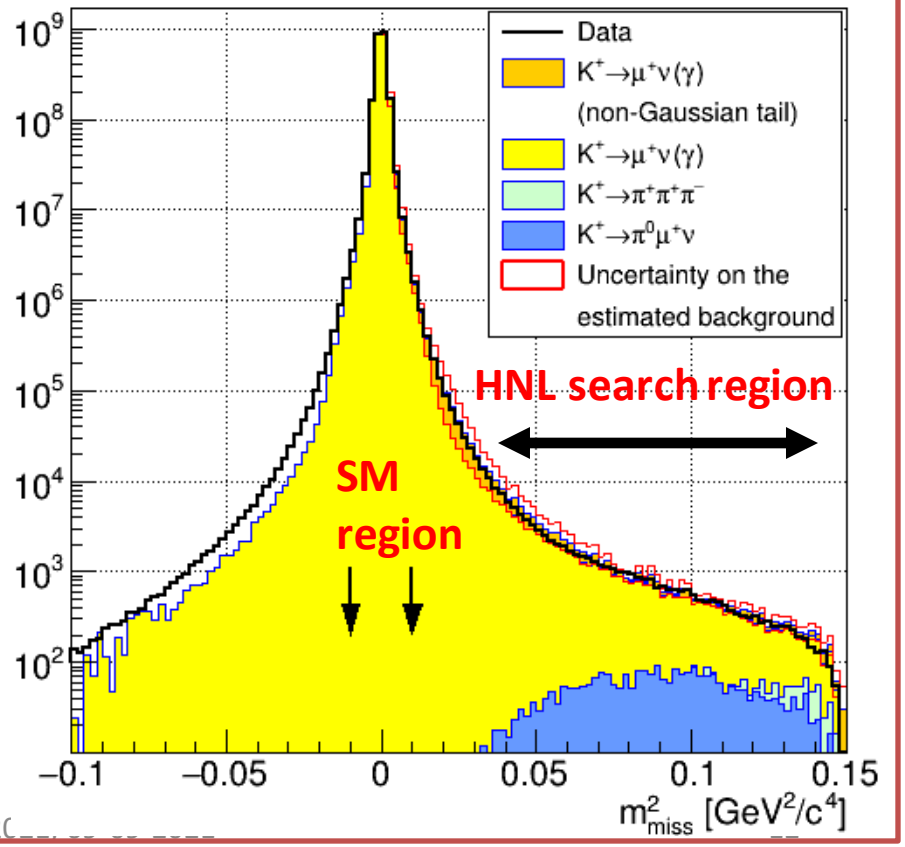


HNL selection

- $m^2_{\text{miss}} = (P_K - P_l)^2$, P_K and P_l are the Kaon and lepton 4-momenta
- HNL signal: sharp peak in the m^2_{miss} spectrum

	$K^+ \to e^+ N$	$K^+ \to \mu^+ N$
Trigger	PNN	CTRL/400
$N_{K,\text{fiducial}}$	$(3.52 \pm 0.02) \times 10^{12}$	$(1.14 \pm 0.02) \times 10^{10}$
N_{SM}	3.495×10^6	2.19×10^9



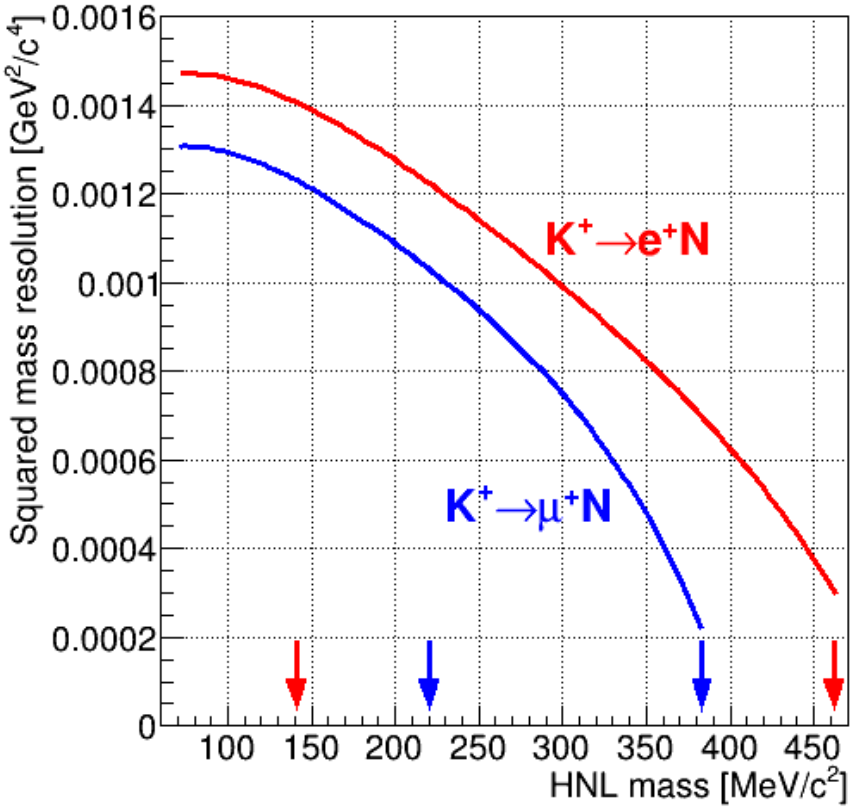


HNL mass scan

- Scan m^2_{miss} spectrum based on m^2_{miss} resolution (σ)

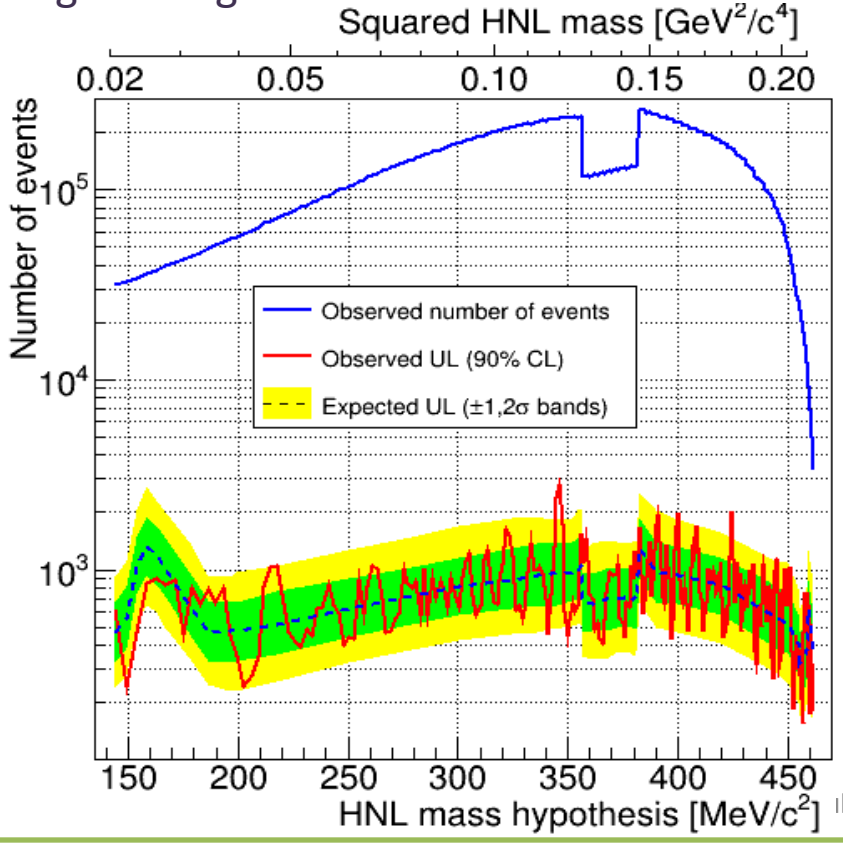
	$K^+ \to e^+ N$	$K^+ \to \mu^+ N$ $(m_N < 300\ \mathrm{MeV}/c^2)$	$K^+ \to \mu^+ N$ $(m_N > 300\ \mathrm{MeV}/c^2)$
Step size	$\sigma/2$	$1\ \mathrm{MeV}/c^2$	$0.5\ \mathrm{MeV}/c^2$
Window width		1.5σ	

- In each window, expected (SM) events from polynomial fit to data sidebands.
- Limits on $|U_{l4}|^2$: CLs comparison of observed with expected number of event

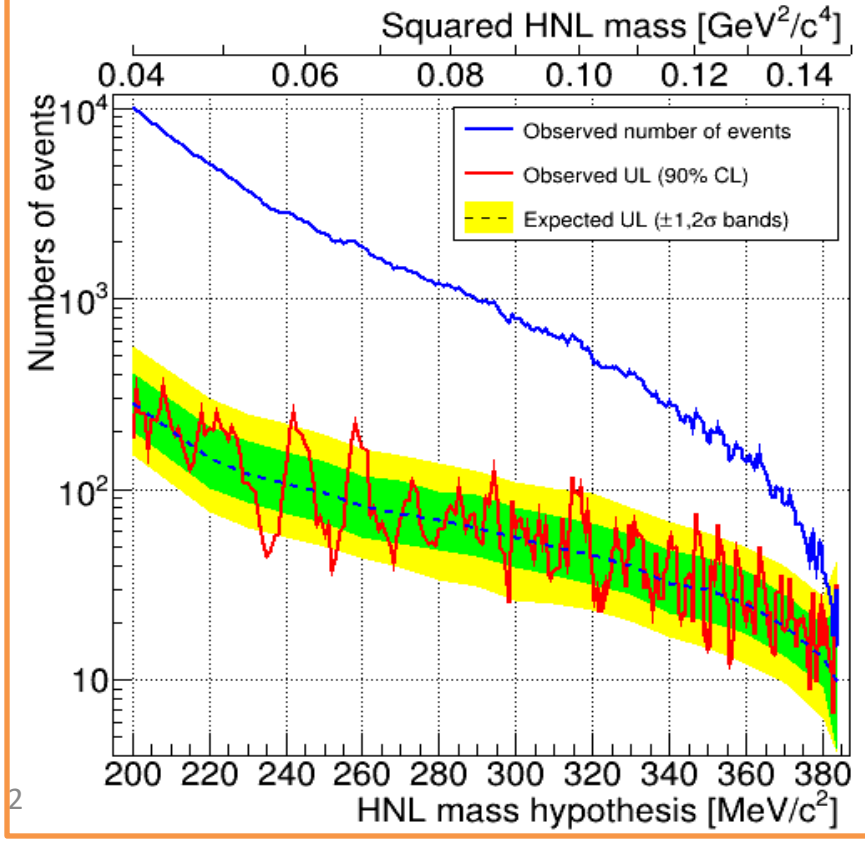


HNL upper limits

- Limit less stringent close to the π^+ decay threshold (stricter selection to shift π^+ background to higher m^2_{miss})
- Maximum local significance of 3.6 for $m_N = 346\ \mathrm{MeV}/c^2$
- Accounting for look-elsewhere effect: global significance = 2.2

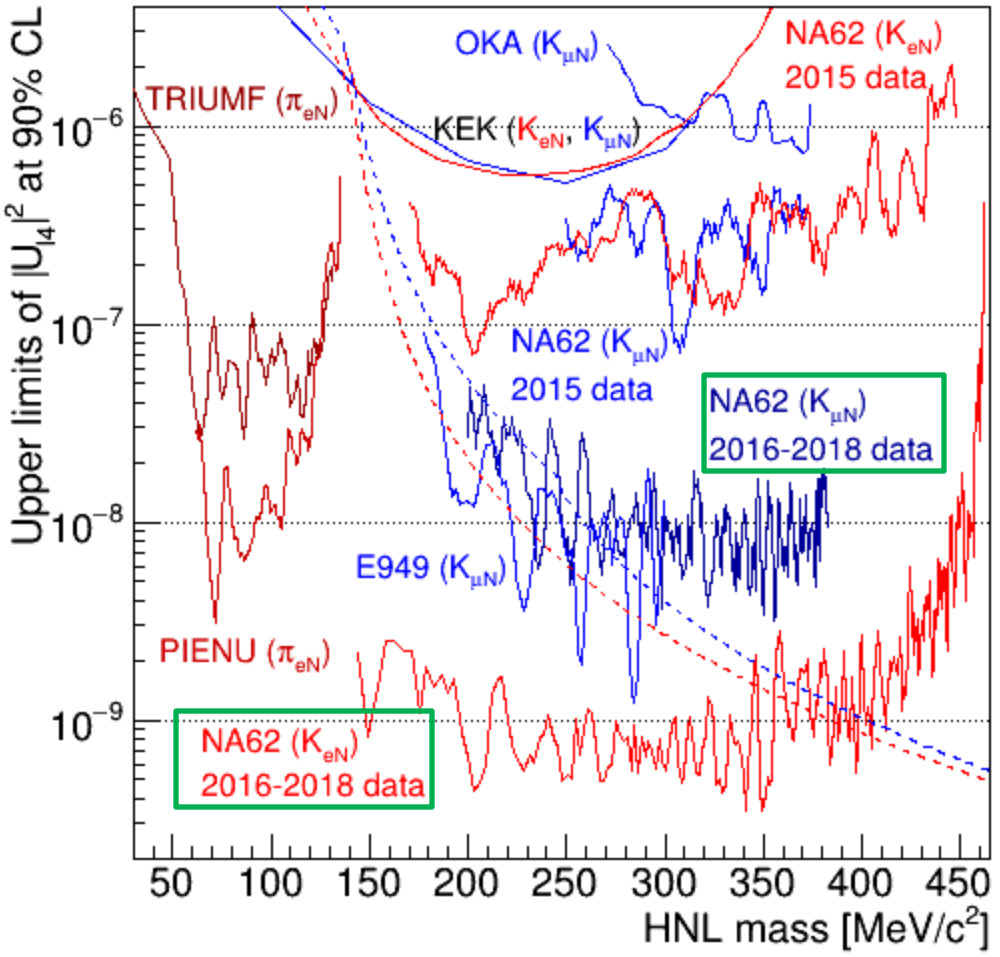


- Local significance never exceeds 3 → no HNL production signals are observed.



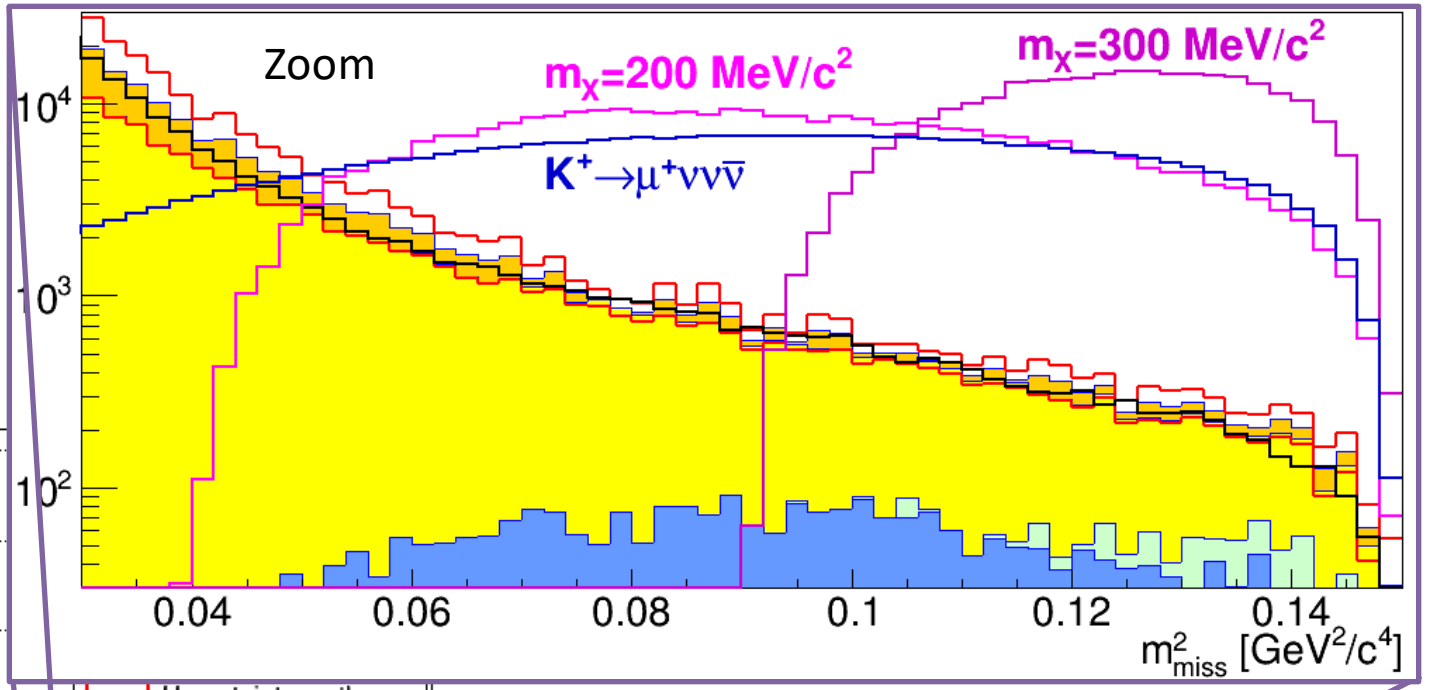
HNL result

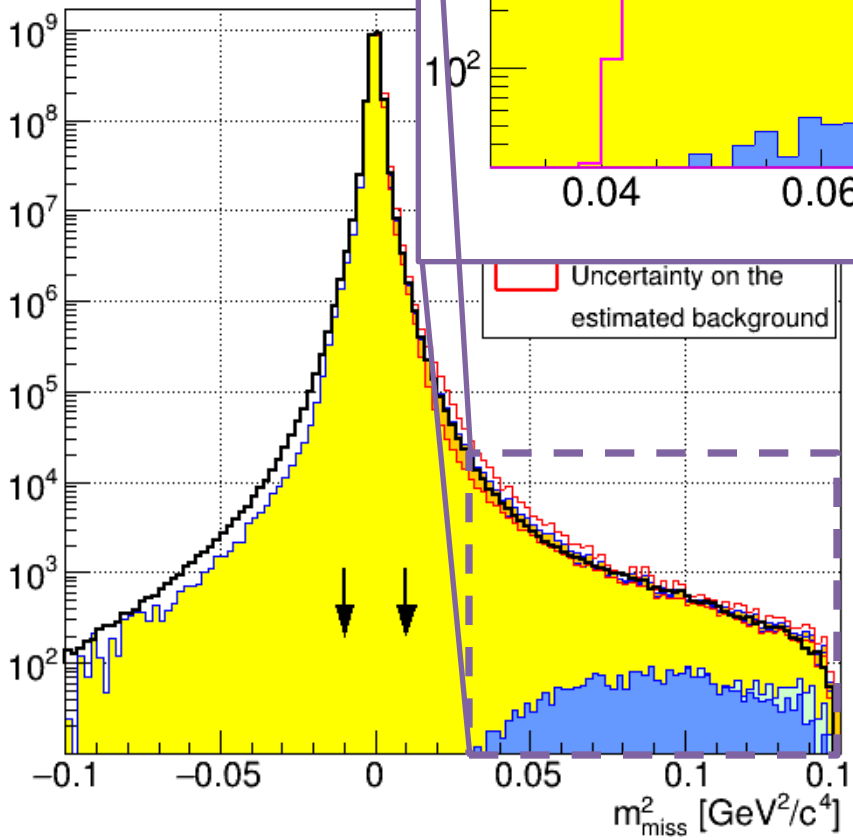
- No HNL signal observed
- $\mathcal{O}(10^{-9})$ **limits on** $|U_{e4}|^2$ and $\mathcal{O}(10^{-8})$ **limits on** $|U_{\mu 4}|^2$
- More than **2(1)** orders of magnitude improvements from run 1 data for e^+ (μ^+) with respect to previous results.
- For μ^+: NA62 consistent with the E949 result and extends UL to higher masses
- For e^+: values favored by the Big Bang Nucleosynthesis (BBN) constraint (dashed red line) are excluded for HNL masses up to $340\ \mathrm{MeV}/c^2$
- Closely related study: $K^+ \to l^+\nu\nu\nu$ and $K^+ \to l^+\nu X$ where X is invisible: predict background from MC simulation



Related searches: $K^+ \to \mu^+ \nu\nu\nu$ and $K^+ \to \mu^+ \nu X$

$K^+ \to \mu^+\nu\nu\nu$ and $K^+ \to \mu^+\nu X$



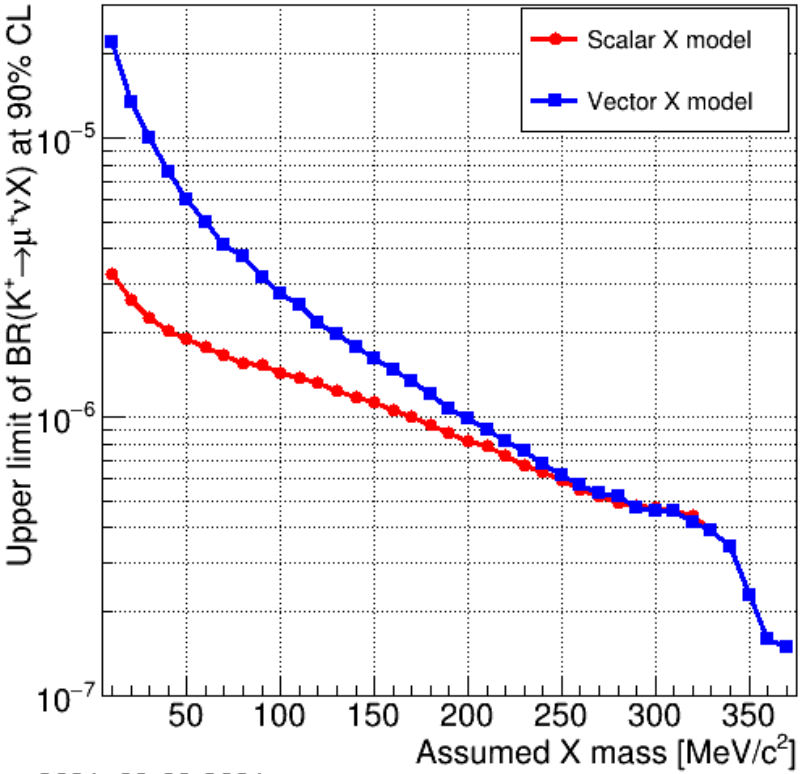


- $K^+ \to \mu^+\nu\nu\nu$ [JHEP1610 (2016) 039]
  - Very rare in the Standard Model, BR: 1.6×10^{-16}
  - The current limit: $< 2.4 \times 10^{-6}$ [E949,PRD94 (2016) 032012]
- $K^+ \to \mu^+\nu X$ [PRL124 (2020) 041802]
  - X is scalar or vector

$K^+ \to \mu^+\nu\nu\nu$ and $K^+ \to \mu^+\nu X$

- $K^+ \to \mu^+\nu\nu\nu$
  - Search region $m^2_{miss} > 0.1\ GeV^2/c^4$ (optimized to extract strongest limit)
  - Observed events: 6894, expected from MC: 7549 ± 92
  - Set upper limit: $\mathbf{1.0 \times 10^{-6}}$ **at 90%CL** in the SM framework

- $K^+ \to \mu^+\nu X$
  - Mass range $10 - 370\ \mathrm{MeV}/c^2$
  - N_{exp} vs N_{obs} for each mass hypothesis and extract limit
  - **No signal observed**
  - The ULs in the scalar model are stronger than those in the vector model due to larger mean m^2_{miss}



Conclusions

- **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 $|U_{\mu 4}|^2$, full data set [PLB 816 (2021) 136259]
- **First search for $K^+ \to \mu^+ \nu X$ decays has been performed in the mass range $10 - 370\ \mathrm{MeV}/c^2$:** [PLB 816 (2021) 136259]
  - Upper limits $\mathcal{O}(10^{-7})$ for high m_X and $\mathcal{O}(10^{-5})$ for low m_X at 90% CL
  - World best UL on $BR(K^+ \to \mu^+ \nu\nu\nu)$ set: 1.0×10^{-6} at 90% CL
- **This July, NA62 started a new data-taking period covering the full extent of LHC run**
  - Expectation to run at 30% higher beam intensity and collect $\mathcal{O}(10^{13})$ K^+ decays
  - Expect to collect 10^{18} protons-on-target in "dump mode" to further probe HNL parameters, with new muon tagger to reduce muon backgrounds from the target