Search for heavy neutral lepton production at NA62 experiment

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Outline:

1) The NA62 experiment at CERN
2) Searches for HNL production: $K^+ \to e^+N$ and $K^+ \to \mu^+N$
3) Comparison to other production and decay searches
4) Summary

CERN

ICHEP 2020

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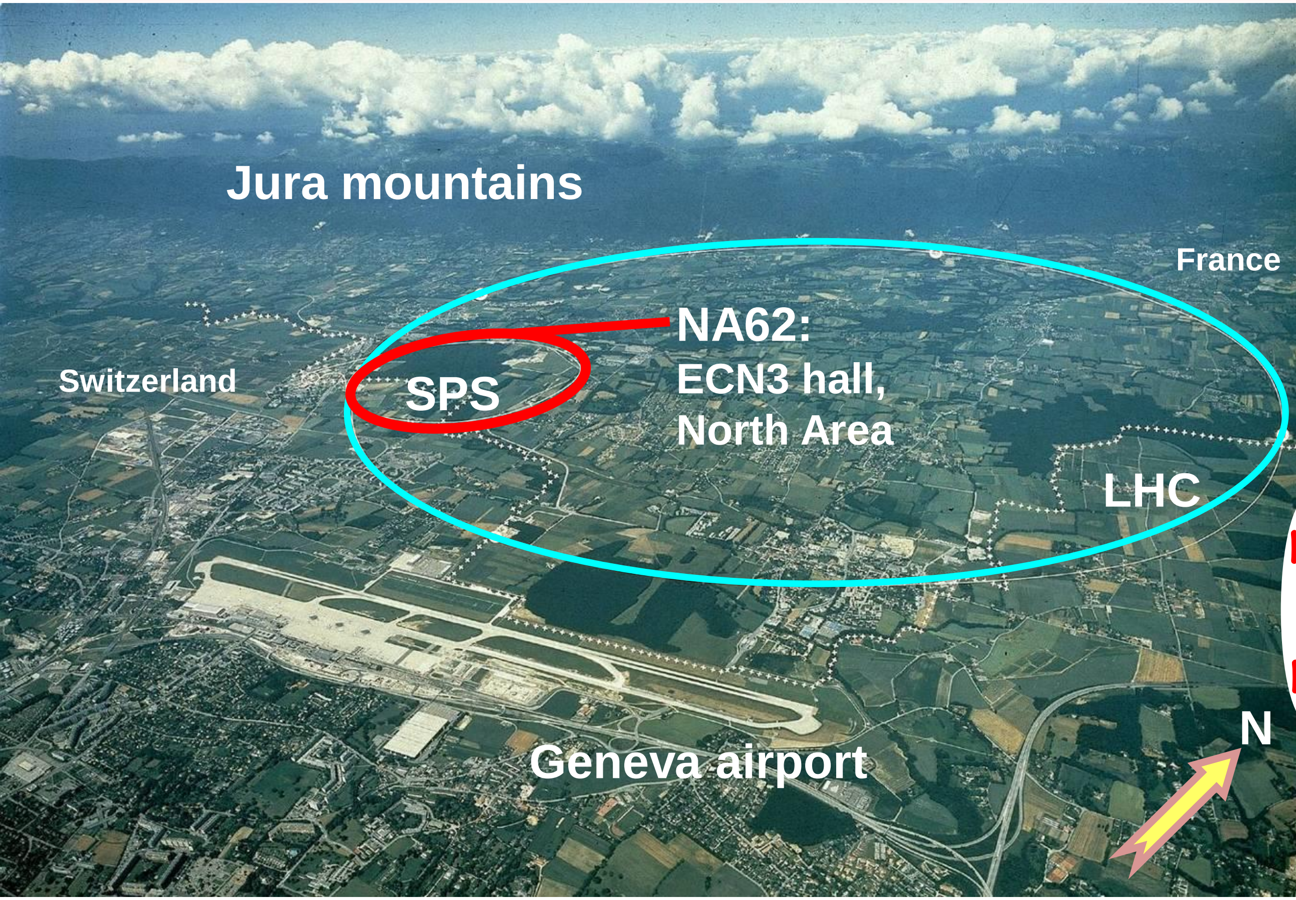
Kaon programme at CERN



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

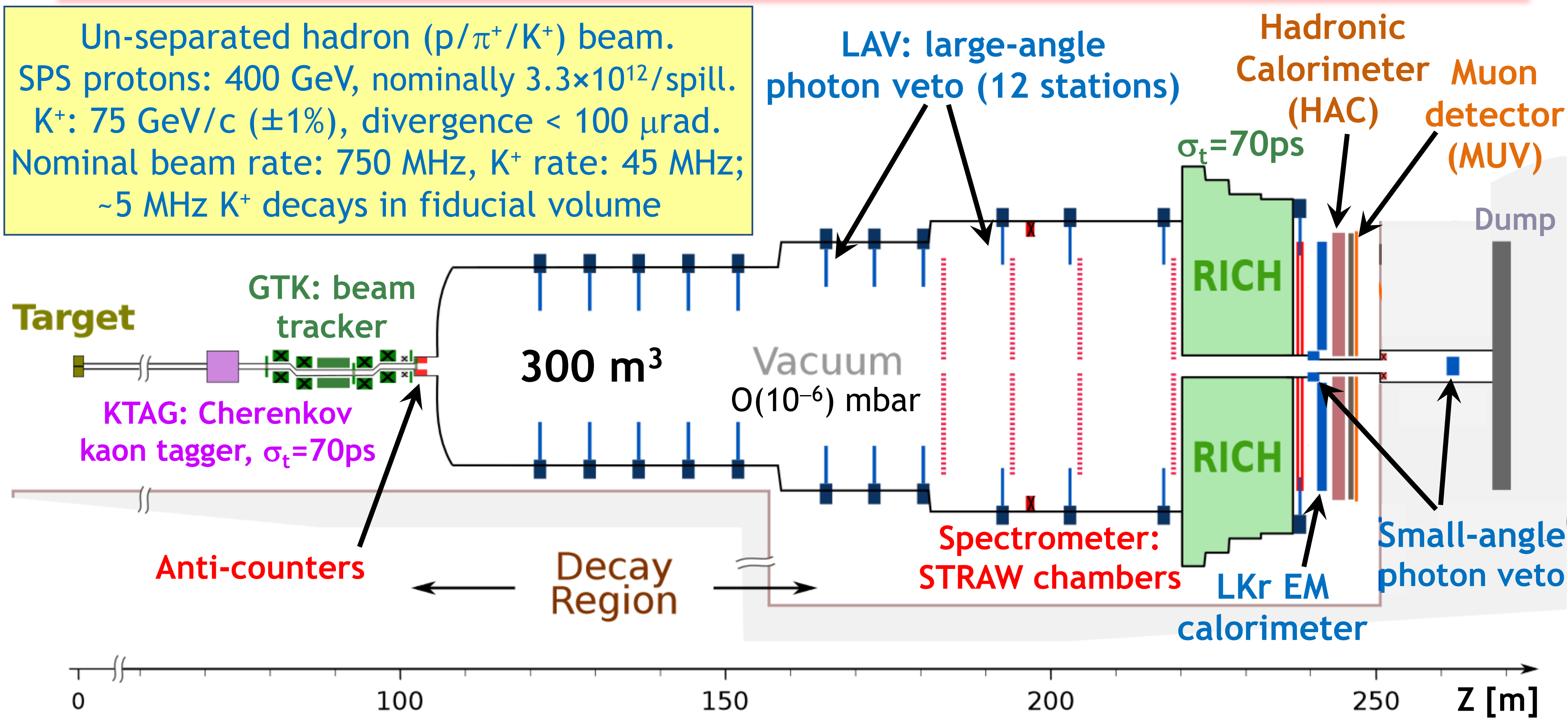
NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

Main NA62 goal: $K^+\to\pi^+\nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

[A new result: R.Marchevski at ICHEP 2020]

NA62 collaboration, JINST 12 (2017) P05025

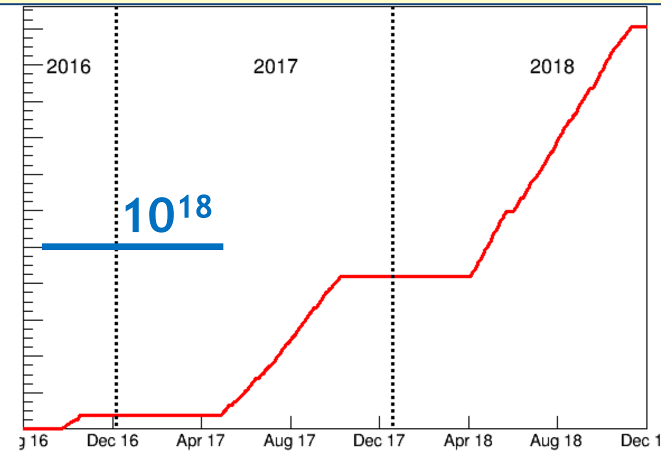
Beamline & detector



- Currently, 1 year of operation ≈ 2×10^{18} protons on target; 4×10^{12} K^+ decays.
- Single event sensitivities for K^+ decays: down to BR~10^{-12}.
- Kinematic rejection factors: 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi0}$>40 GeV) ~10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 data collection

Run 1 integrated luminosity



2.2×10^{18} POT collected

- Commissioning run **2015**: minimum bias data (~3×10^{10} protons/pulse).
- Physics run **2016** (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.
- Physics run **2017** (161 days, ~1.9×10^{12} ppp): 2×10^{12} useful K^+ decays.
- Physics run **2018** (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.
- Starting **Run 2** after Long Shutdown 2 in **2021** (~3×10^{12} ppp).

Search for HNL production in $K^+ \to \ell^+ N$ decays

- $|U_{e4}|^2$: final result (**full** NA62 Run 1 data sample), **PLB 708 (2020) 135599**
- $|U_{\mu 4}|^2$: preliminary result (**~1/3** of NA62 Run 1 data sample), paper in preparation

Dark fermions (HNLs)

A generic possibility of **k** sterile neutrino mass states:

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

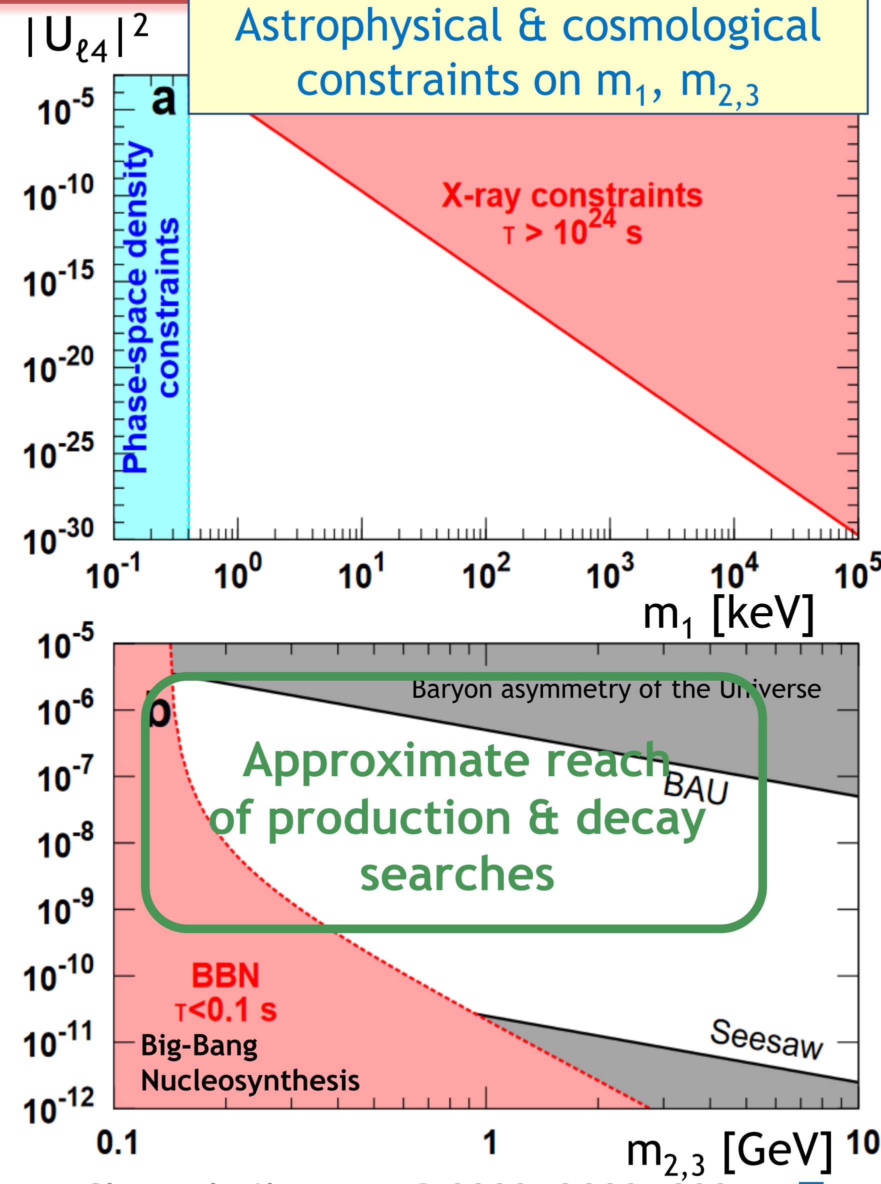
The "neutrino portal" is motivated by its relation to neutrino mass generation.

The νMSM: the most economical theory accounting for **ν** masses and oscillations, baryogenesis, and dark matter.
[Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151]

Three Heavy Neutral Leptons (HNLs):
m_1~10 keV [DM candidate]; **$m_{2,3}$~1 GeV/c²**.

GeV-scale HNLs can be observed via their **production** and **decay**.

Astrophysical & cosmological constraints on m_1, $m_{2,3}$

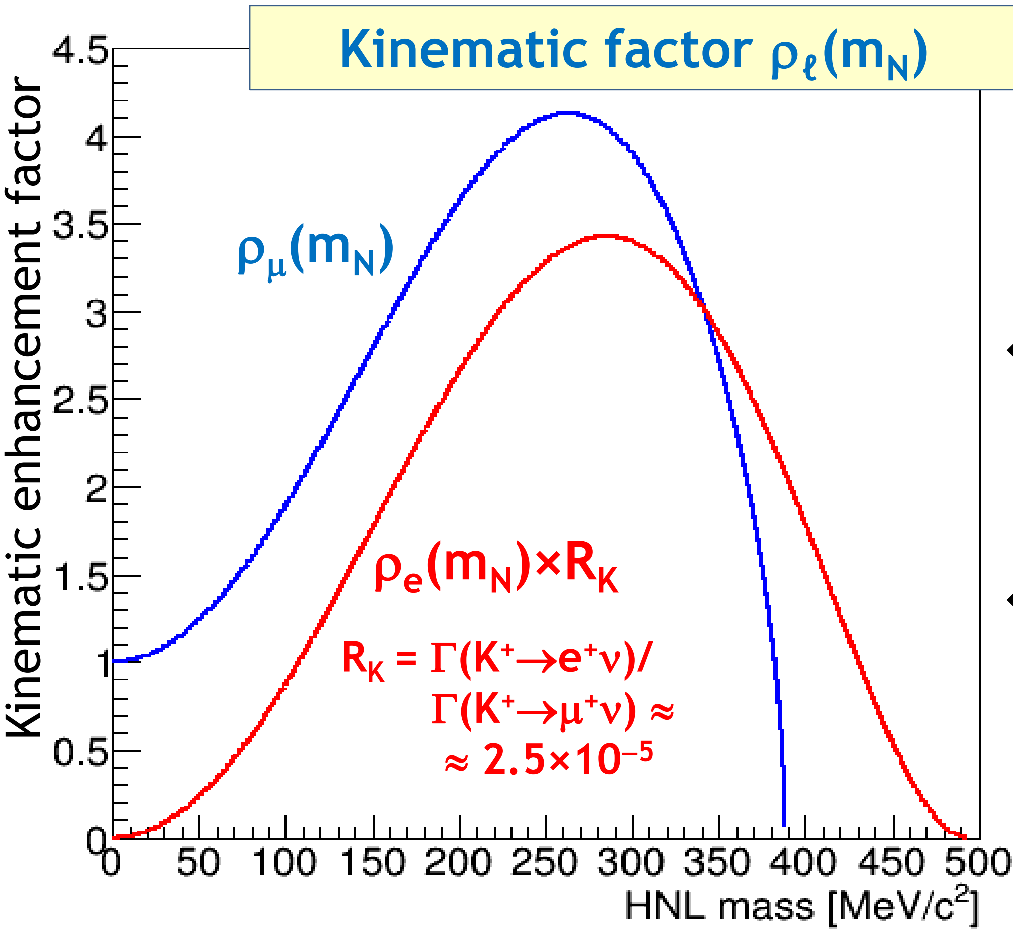


Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

HNL production in K^+ decays

$$BR(P^+ \to \ell^+ N) = \underbrace{BR(P^+ \to \ell^+ \nu) \times \rho_\ell(m_N)}_{O(1)} \times |U_{\ell 4}|^2$$

R. Shrock, PLB96 (1980) 159



$K^+ \to \ell^+ N$

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

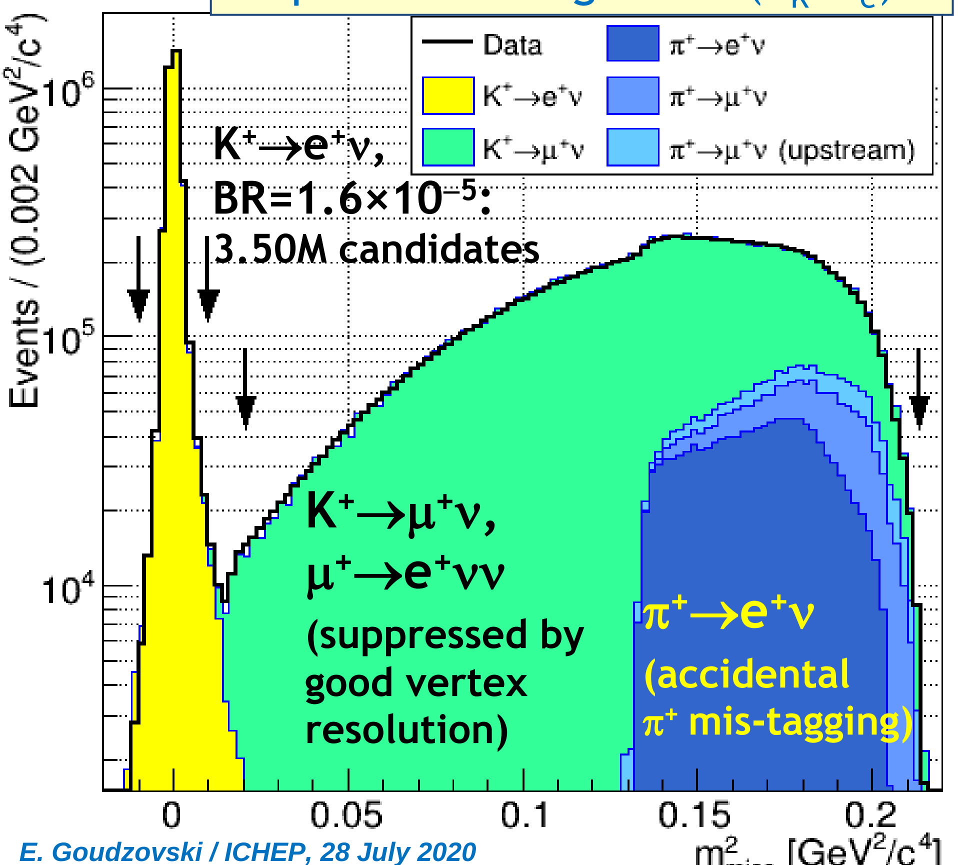
$$\rho_\ell(m_N) = [(x+y)-(x-y)^2] \,/\, [x(1-x)^2] \times \lambda^{1/2}(1,x,y),$$

$$x=(m_\ell/m_P)^2, \quad y=(m_N/m_P)^2, \quad \lambda(a,b,c) = a^2+b^2+c^2-2(ab+bc+ac).$$

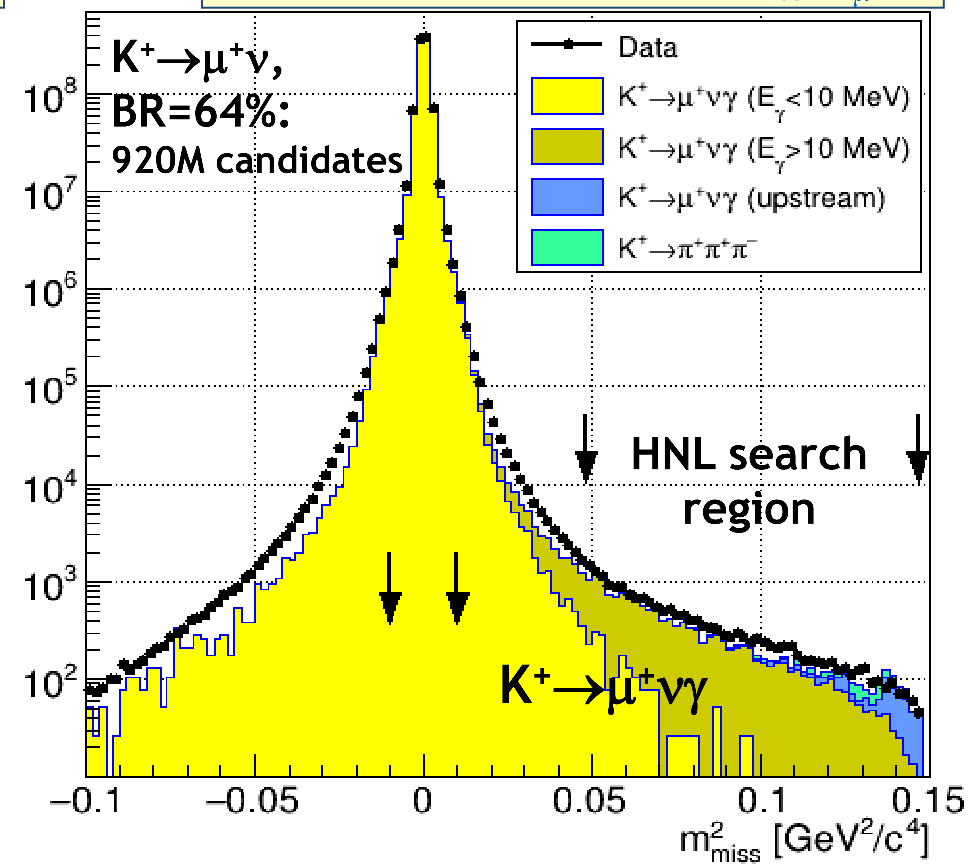
Data sample

- Triggers used: $K_{\pi\nu\nu}$ for $K^+\to e^+N$; Control/400 for $K^+\to\mu^+N$.
- Numbers of K^+ decays in fiducial volume:
  $N_K=(3.52\pm0.02)\times10^{12}$ in positron case; $N_K=(4.29\pm0.02)\times10^{9}$ in muon case.
- Squared missing mass: $m^2_{miss}=(P_K-P_\ell)^2$, using STRAW and GTK detectors.
- HNL production signal: **a spike above continuous missing mass spectrum**.

Squared missing mass: $(P_K-P_e)^2$

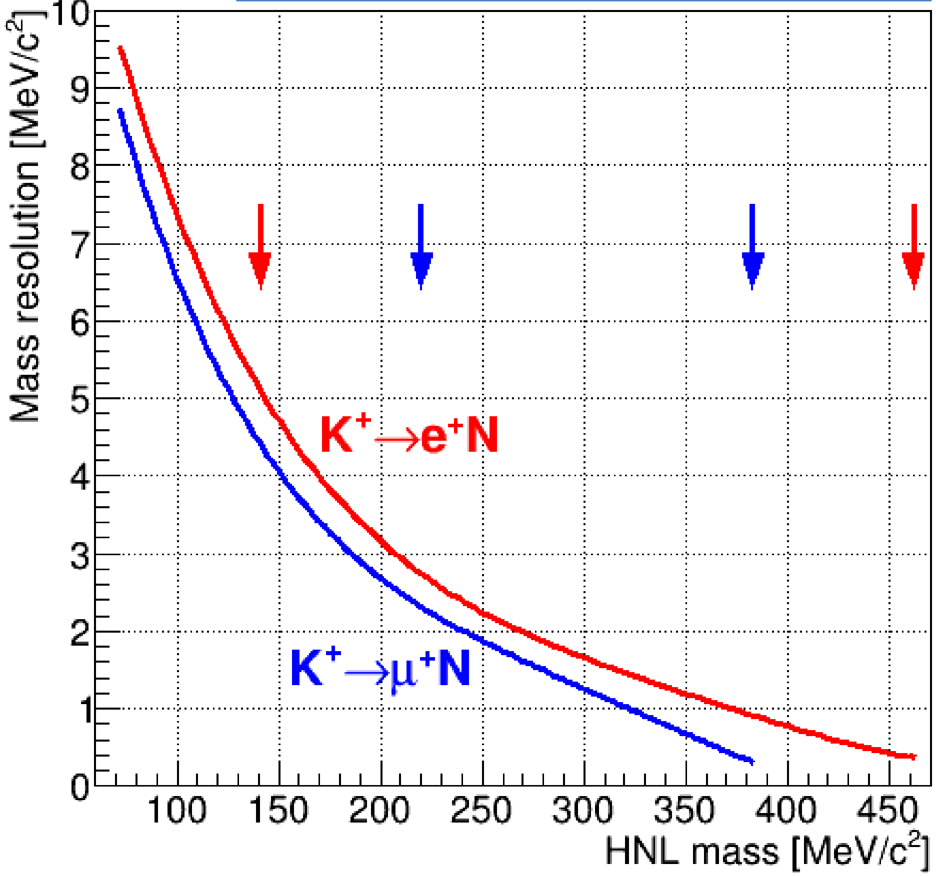


Squared missing mass: $(P_K-P_\mu)^2$

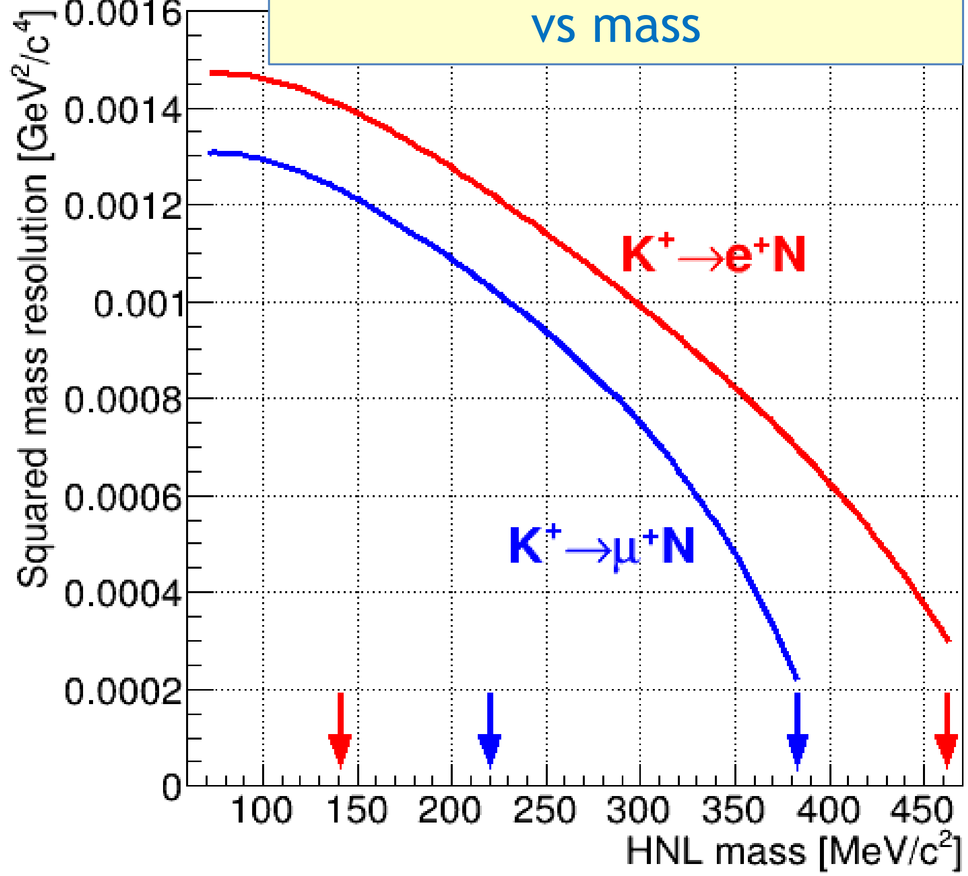


HNL mass resolution

HNL mass resolution vs mass



Resolution on squared mass vs mass

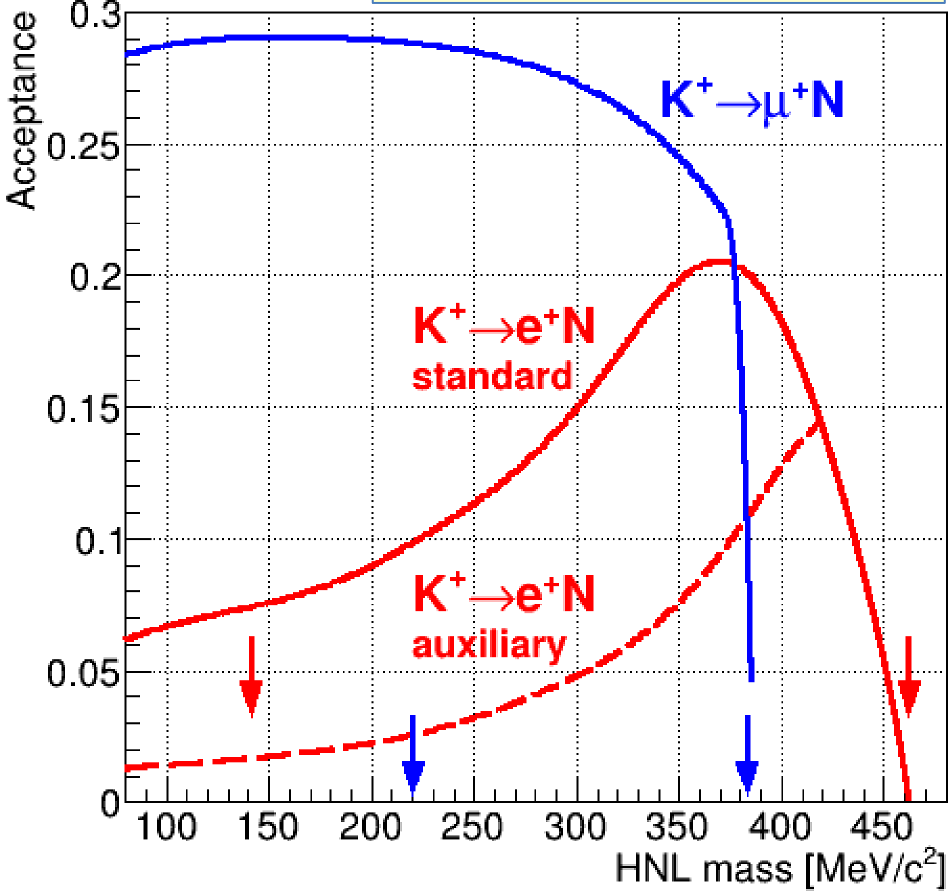


- Selection for each HNL mass hypothesis (**m_{HNL}**) includes a "mass window" condition: **$|m-m_{HNL}|<1.5\sigma_m$**: background is proportional to mass resolution.
- Resolution is crucial to resolve possible HNL mass splitting.

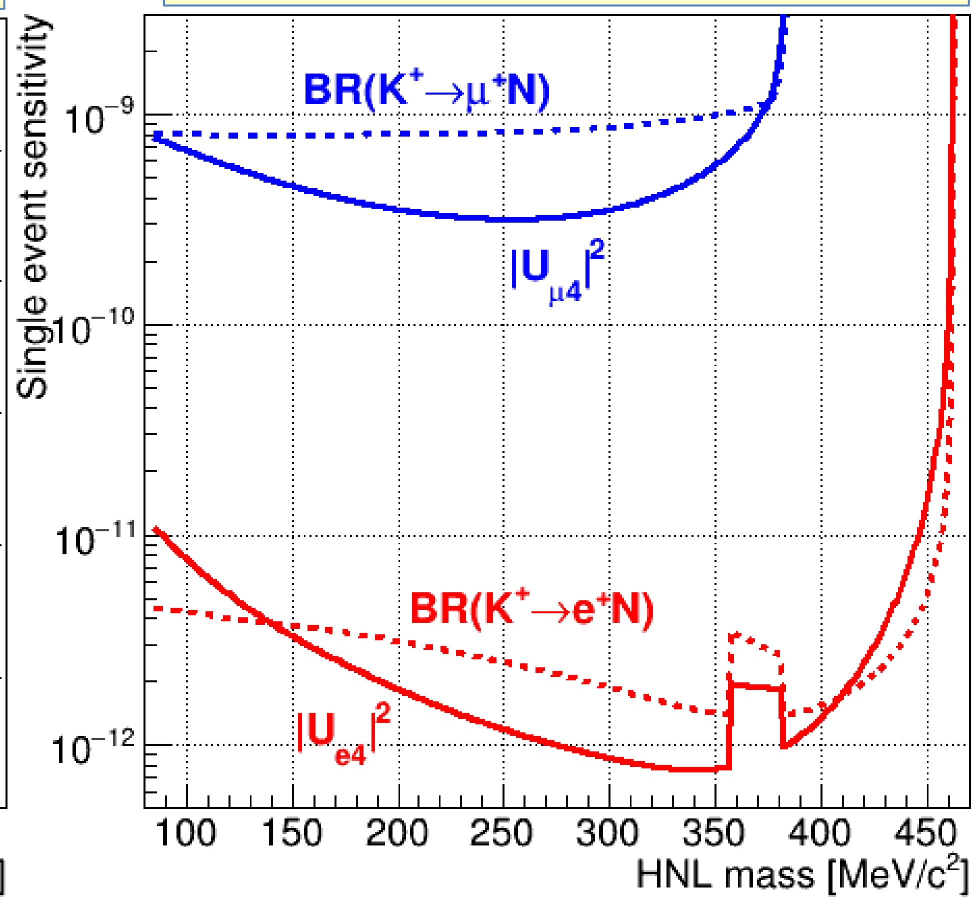
[Baryogenesis: 2 quasi-degenerate mass states; Canetti et al., PRD87(2013)093006]

Acceptance & single event sensitivity

Acceptance vs mass



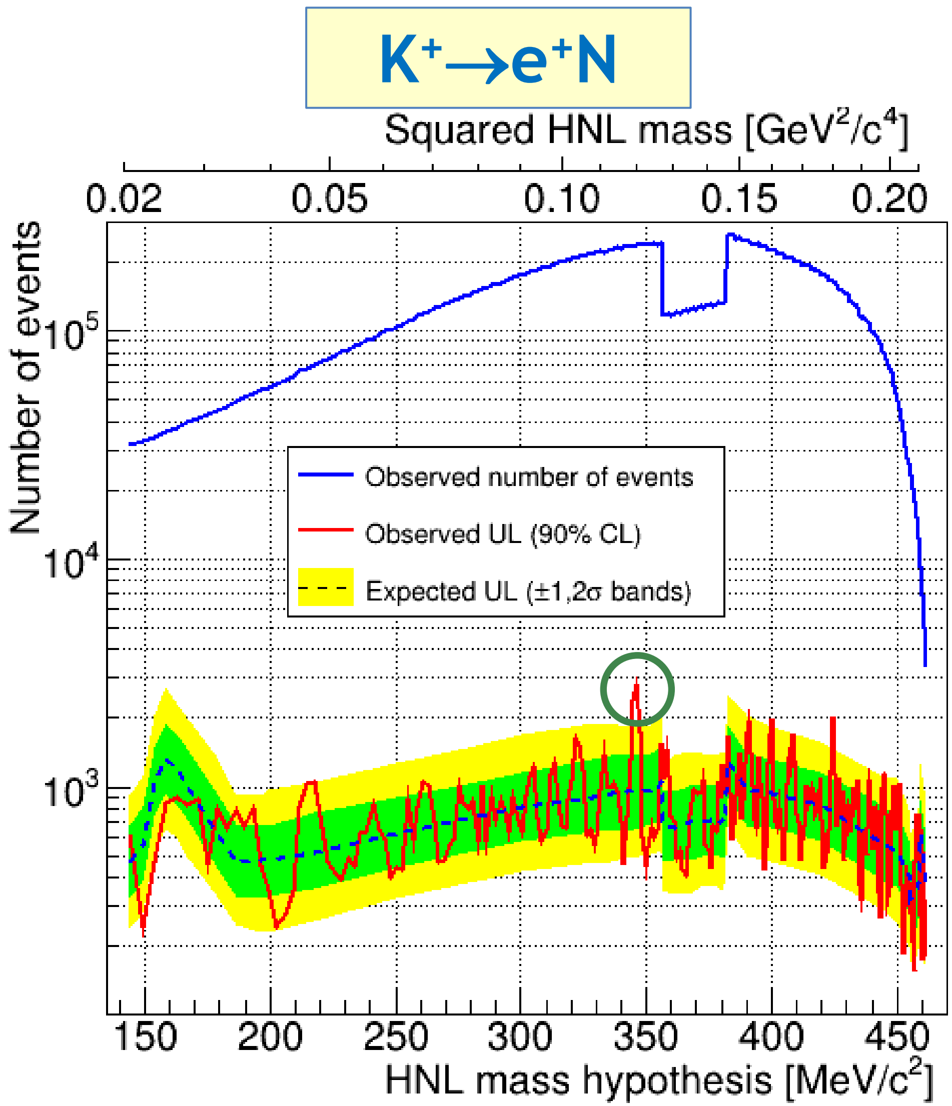
Single-event sensitivity vs mass

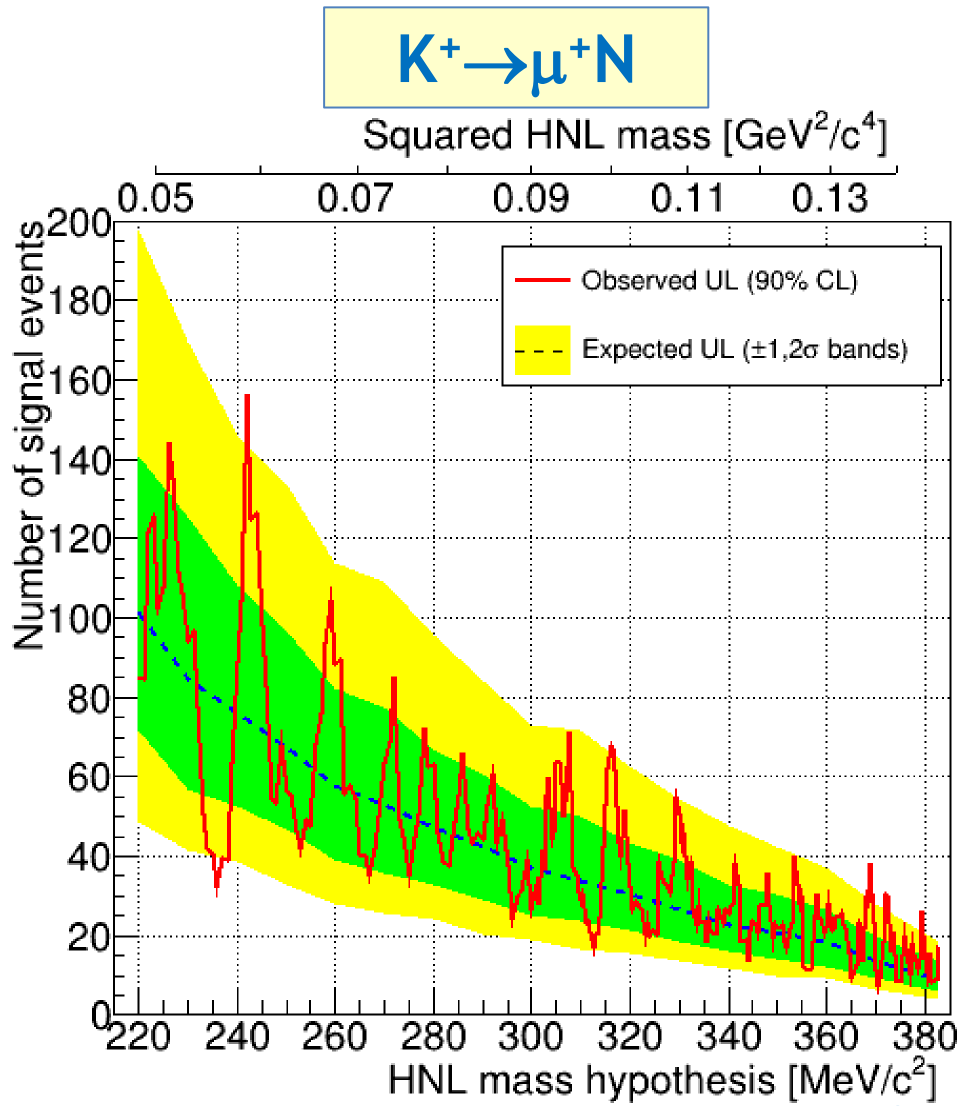


- Standard K_{e2} selection: p_e<30 GeV/c (as in $K_{\pi\nu\nu}$ trigger).
- Auxiliary K_{e2} (p_e<20 GeV/c): smooth background near the π_{e2} threshold.
- Definitions: $BR_{SES} = 1/(N_K A)$, $|U_{\ell 4}|^2_{SES} = BR_{SES} / [BR(K^+\to\ell^+\nu)\,\rho_\ell(m_N)]$.

Upper limits on N(signal events)

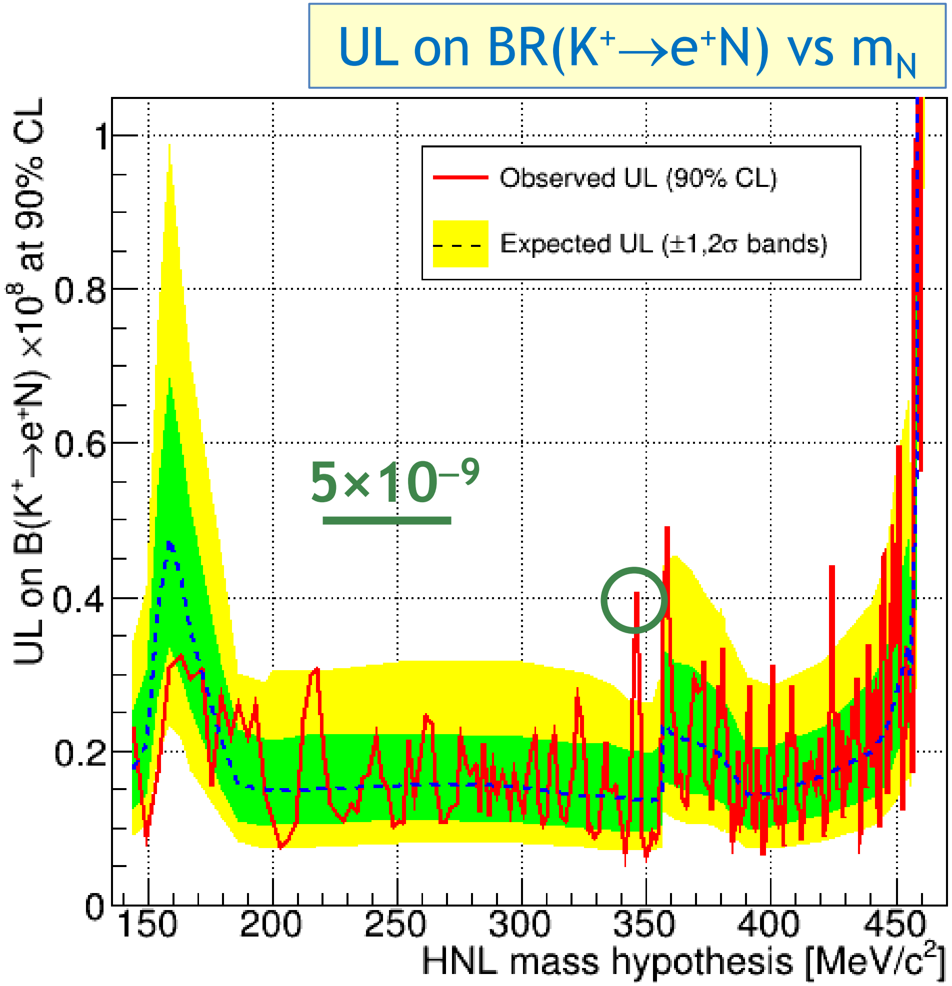
at 90% CL, vs HNL mass hypothesis

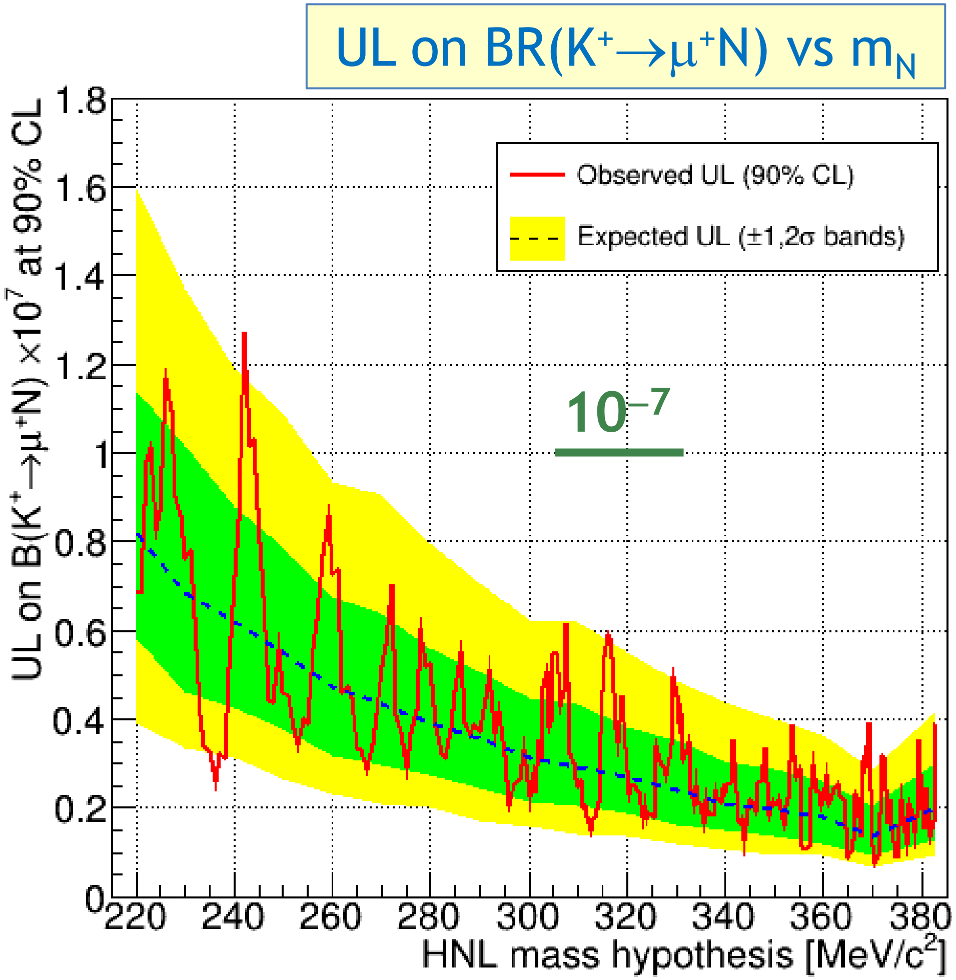




Upper limits on BR($K^+ \to \ell^+ N$)

at 90% CL, vs HNL mass hypothesis

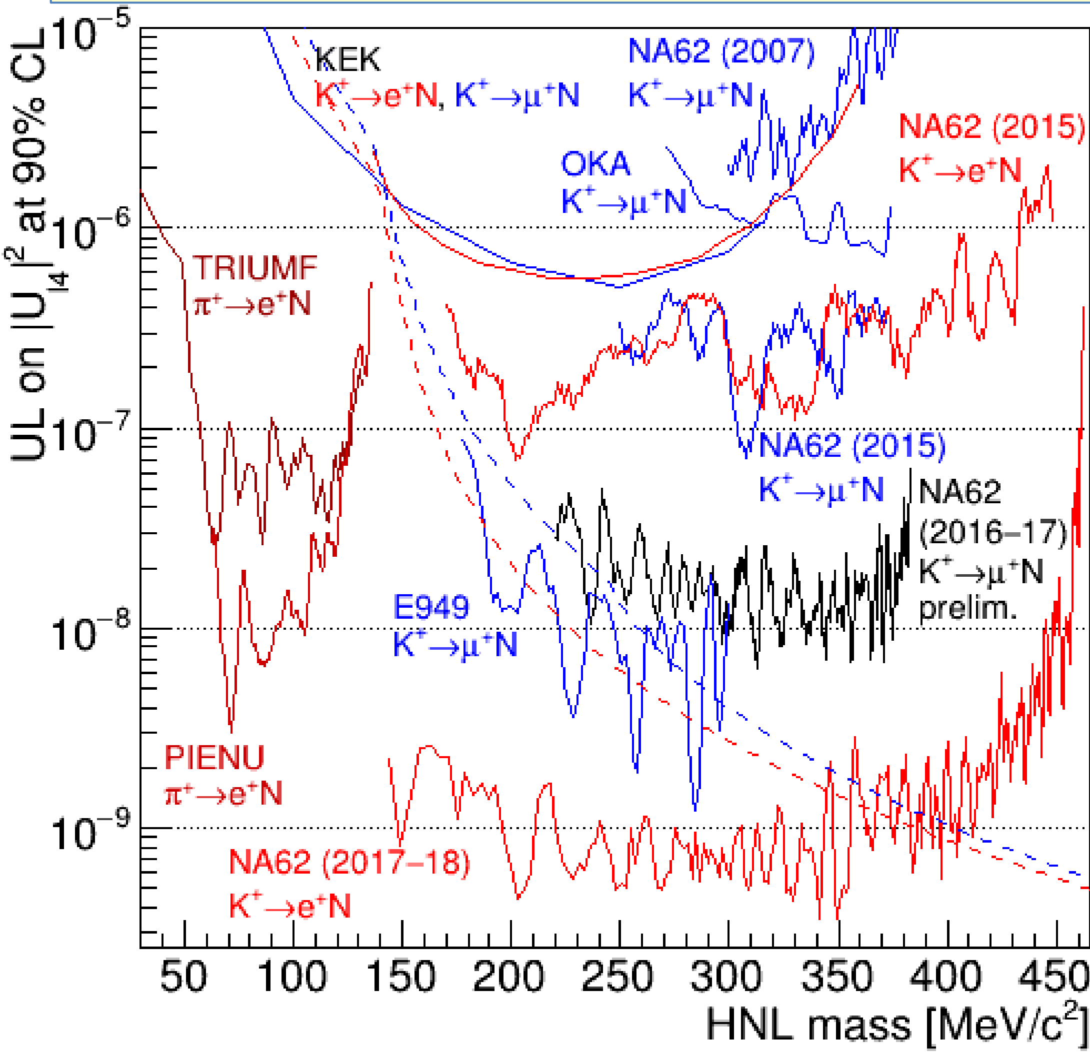




- In the e^+ case, maximum local significance of 3.6 for m_N=346 MeV/c^2.
- Accounting for look-elsewhere effect, global significance = 2.2.

HNL production searches: summary

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production searches

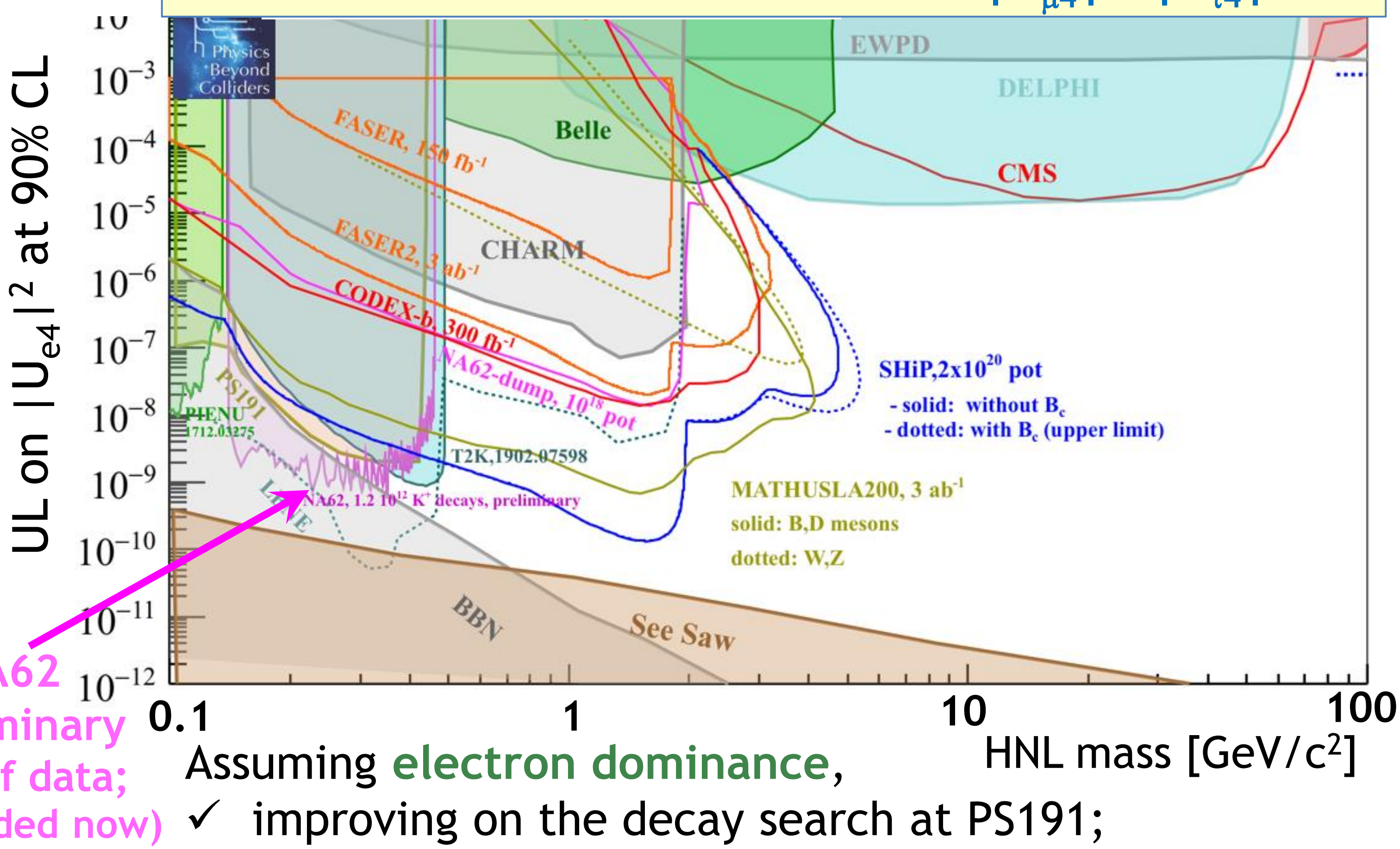


- Full 2016–18 data set for $|U_{e4}|^2$, ~1/3 of the data set for $|U_{\mu4}|^2$.
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range is excluded up to **340 MeV**.
- For $|U_{\mu4}|^2$, the sensitivity approaches the E949 one; the search extends to **383 MeV**.

Comparison to decay searches

(CERN-PBC-REPORT-2018-007; update: Gaia Lanfranchi, PBC meeting, 6 Nov 2019)

Summary of $|U_{e4}|^2$ limits vs m_{HNL}
in the electron dominance scenario: $|U_{\mu4}|^2=|U_{\tau4}|^2=0$

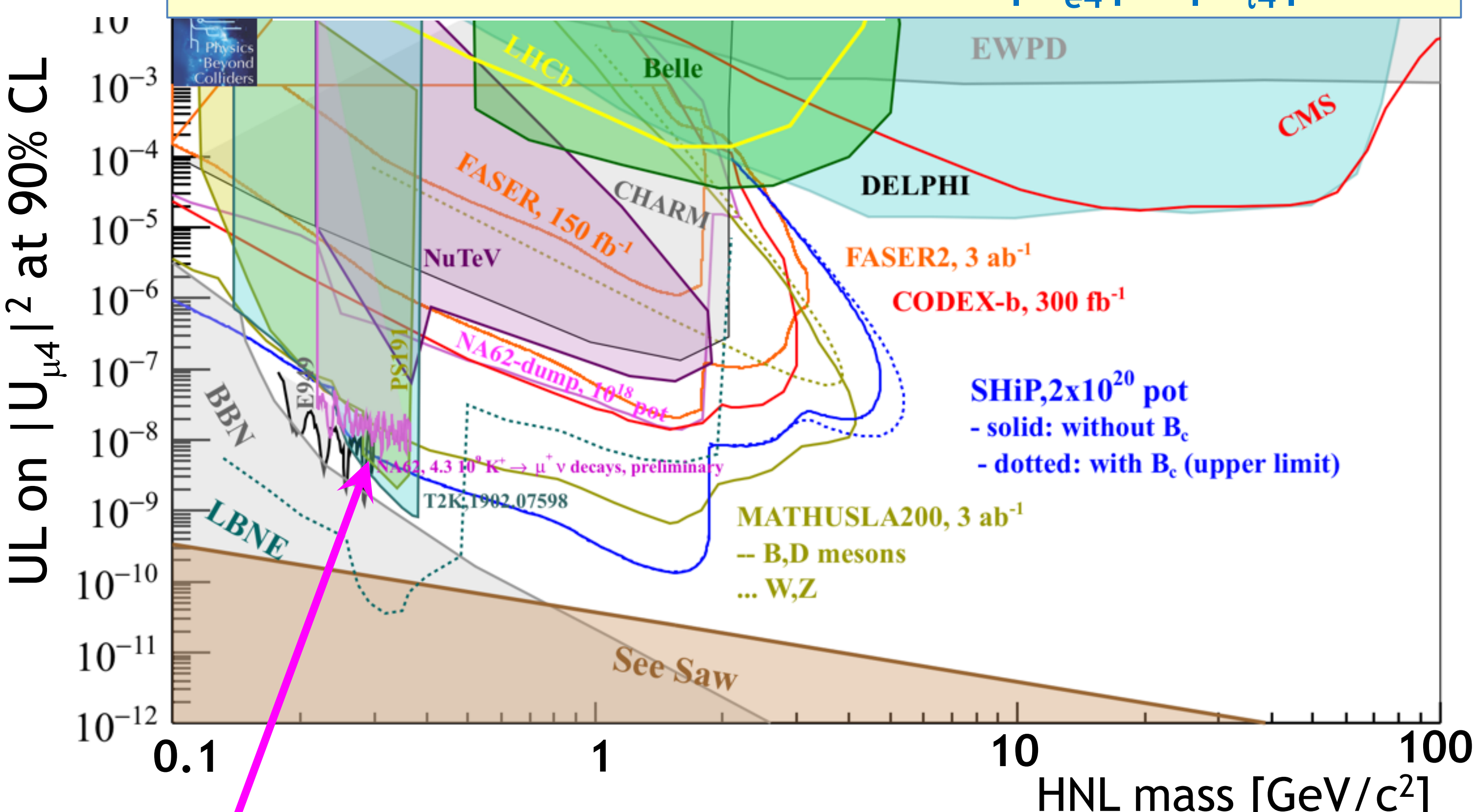


Assuming **electron dominance**,
- ✓ improving on the decay search at PS191;
- ✓ complementary to the decay search at T2K;
- ✓ BBN-allowed range is excluded up to $m_N \approx 340$ MeV/c².

Comparison to decay searches

(CERN-PBC-REPORT-2018-007; update: Gaia Lanfranchi, PBC meeting, 6 Nov 2019)

Summary of $|U_{\mu4}|^2$ limits vs m_{HNL}
in the muon dominance scenario: $|U_{e4}|^2=|U_{\tau4}|^2=0$



NA62 preliminary: approaching the E949 (production) and T2K (decay) limits

Summary

- NA62 experiment at CERN collected a sample of **~6×10^{12} K^+** decays in flight during Run 1 in **2016–18**.
- HNL production (**$K^+\to\ell^+N$**) with the **2016–18** data set:
  - ✓ **$O(10^{-9})$** limits on $|U_{e4}|^2$ *[full data set – PLB 807 (2020) 135599]*;
  - ✓ **$O(10^{-8})$** limits on $|U_{\mu4}|^2$ *[1/3 data set – preliminary]*.
- Limits on $|U_{e4}|^2$ improve over the PS191 production searches, and saturate the BBN-allowed range up to **340 MeV/c^2** mass.
- NA62 sensitivity to $|U_{\ell4}|^2$: to be improved with larger data sets.