Searches for heavy neutral lepton production & decays

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Outline:

1) Introduction: GeV-scale heavy neutral leptons
2) HNL production searches: NA62, E949, PIENU
3) HNL decay searches: T2K, NA62-dump, SHiP
4) Summary

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Introduction

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

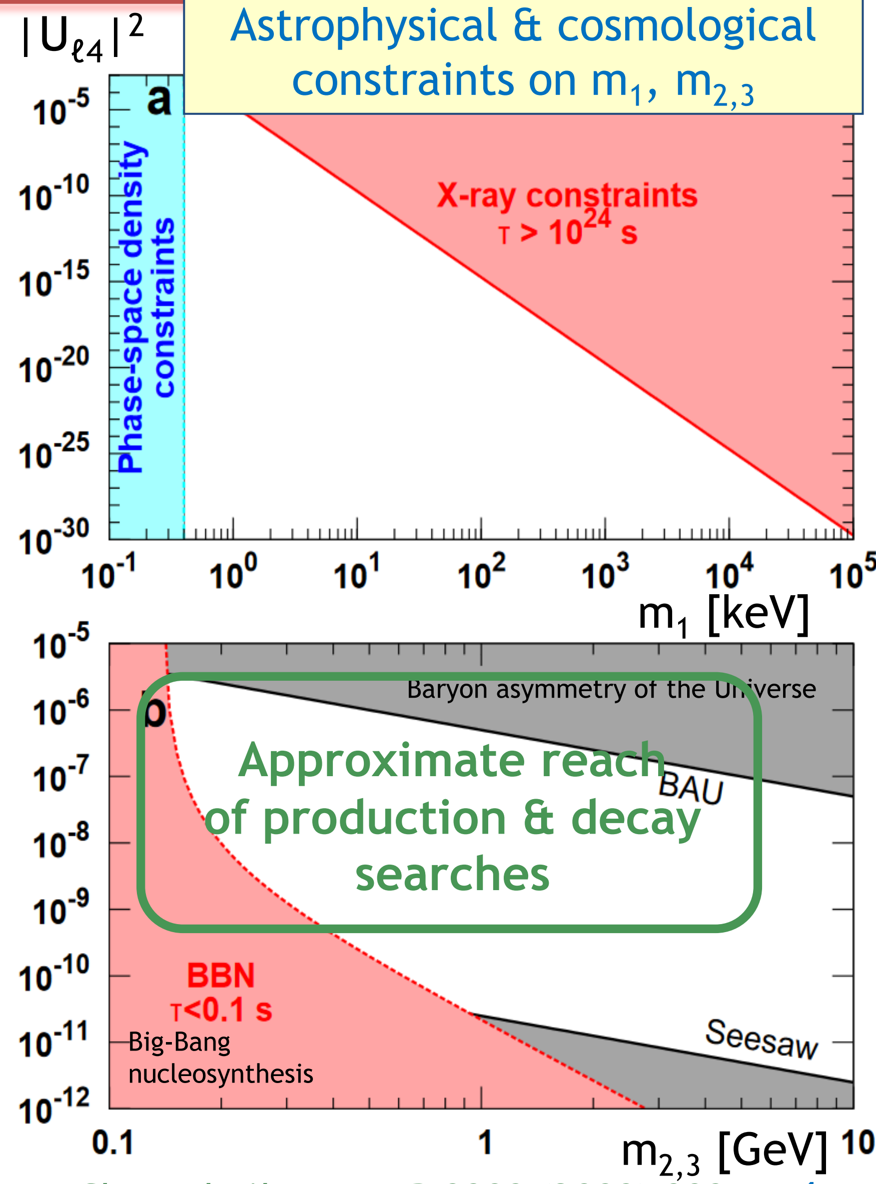
$$\nu_\alpha = \sum_{i=1}^{3+k} U_{\alpha i}\nu_i \quad (\alpha = e, \mu, \tau)$$

The νMSM: 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/c^2**.

GeV-scale HNLs observable via their **production** and **decay**.



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

Scope of this talk

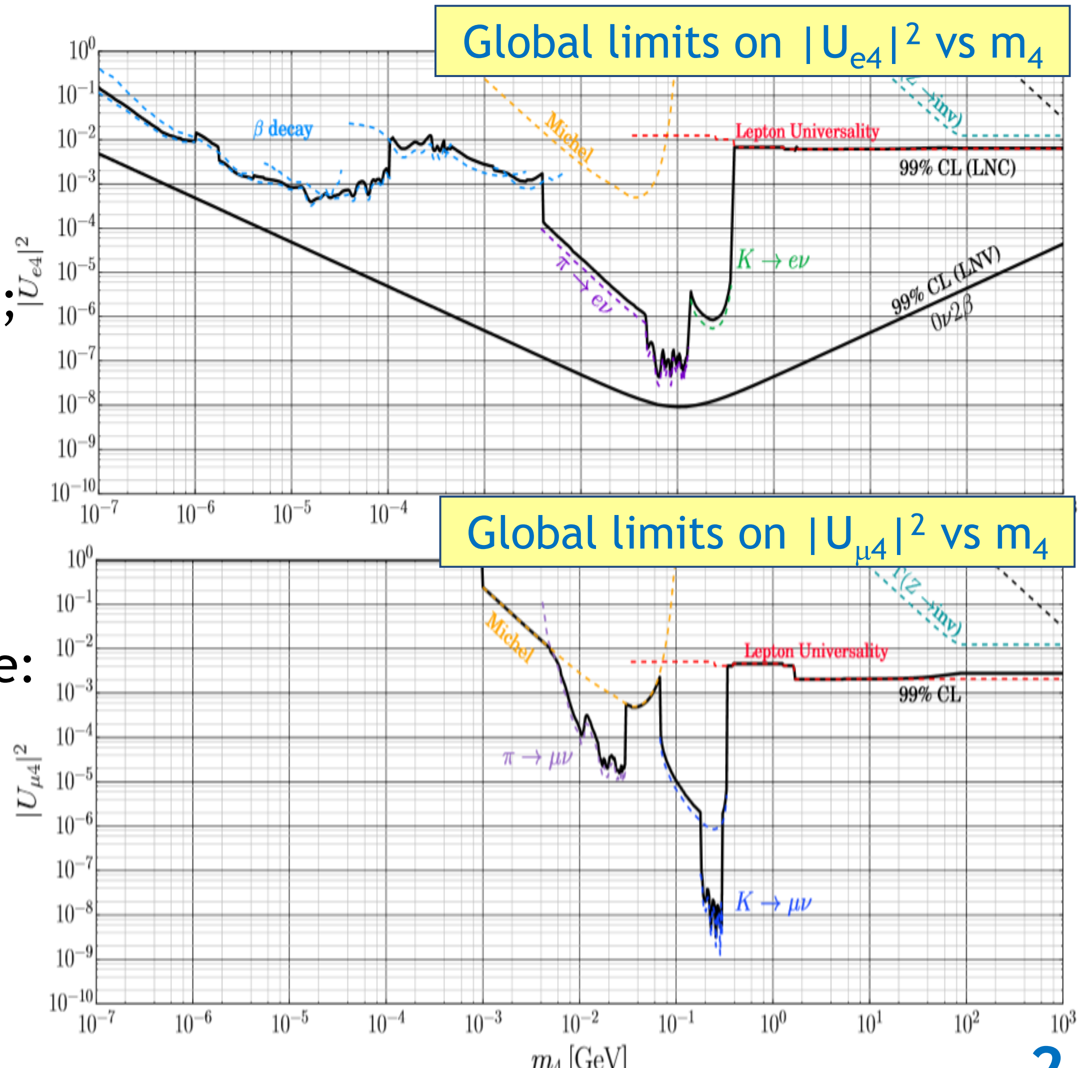
RICH phenomenology, depending on mass & couplings:

- neutrinoless double β decay;
- lepton universality tests;
- LFV decays and μ–e conversion;
- invisible Z^0 decays ($m_4 > m_Z$);
- neutrino oscillations.

This talk: constraints on HNL couplings assuming **GeV** mass scale:

- **production searches** in meson decays (e.g. $K^+ \to e^+ N$);
- **decay searches** in beam dump experiments (e.g. $N \to \pi^+ \mu^-$).

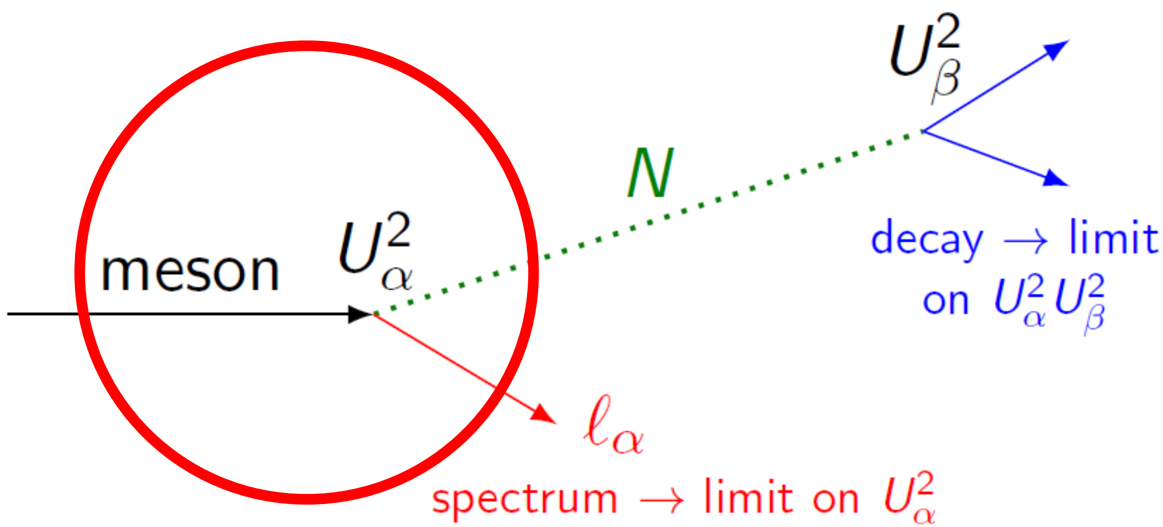
Conservative limits on couplings assuming HNL decays cannot be observed



De Gouvêa and Kobach, PRD93 (2016) 033005

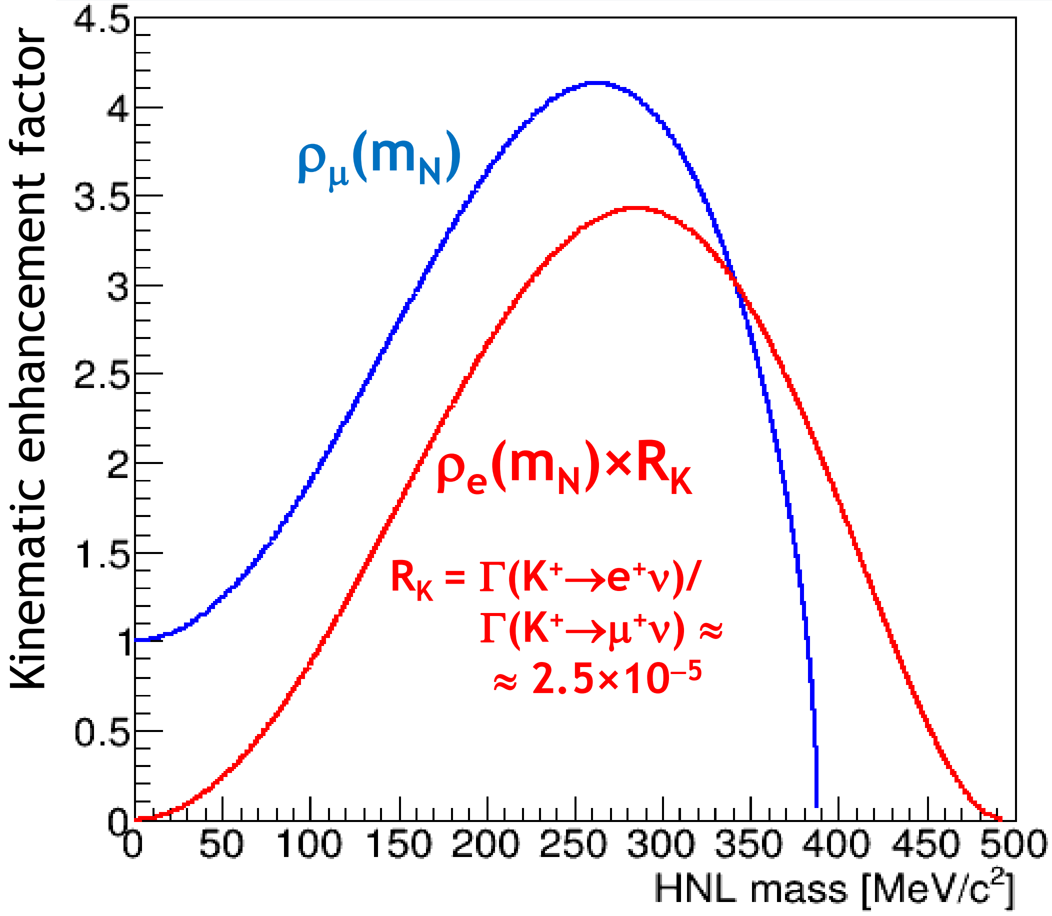
HNL production searches: NA62, E949, PIENU

PLB778 (2018) 137; PRD91 (2015) 052001; PRD97 (2018) 072012



HNL production in K^+ decays

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



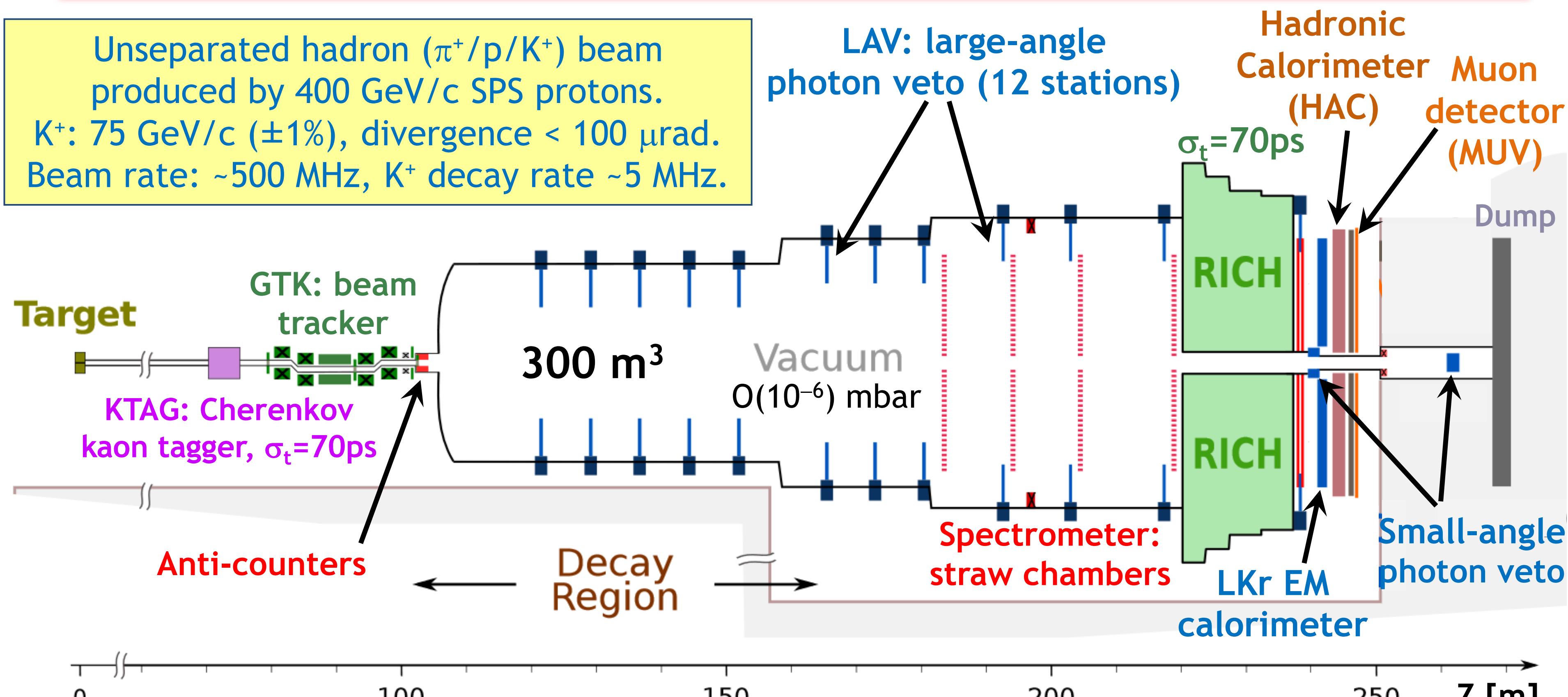
R. Shrock, PLB96 (1980) 159

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

- ❖ HNL production is enhanced kinematically wrt SM decays.
- ❖ A dramatic $f \sim 10^5$ enhancement in the $K^+ \to e^+ N$ case, as the helicity suppression is relaxed!

NA62 at CERN SPS

Unseparated hadron ($\pi^+/p/K^+$) beam produced by 400 GeV/c SPS protons.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: ~500 MHz, K^+ decay rate ~5 MHz.



- Main goal: $K^+\to\pi^+\nu\nu$ measurement to ~10% precision.
- Single event sensitivities for K^+ decays: down to BR~10^{-12}.
- Currently, 1 year of operation = 2×10^{18} protons on target; 5×10^{12} K^+ decays.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi 0}$>40 GeV) = 3×10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

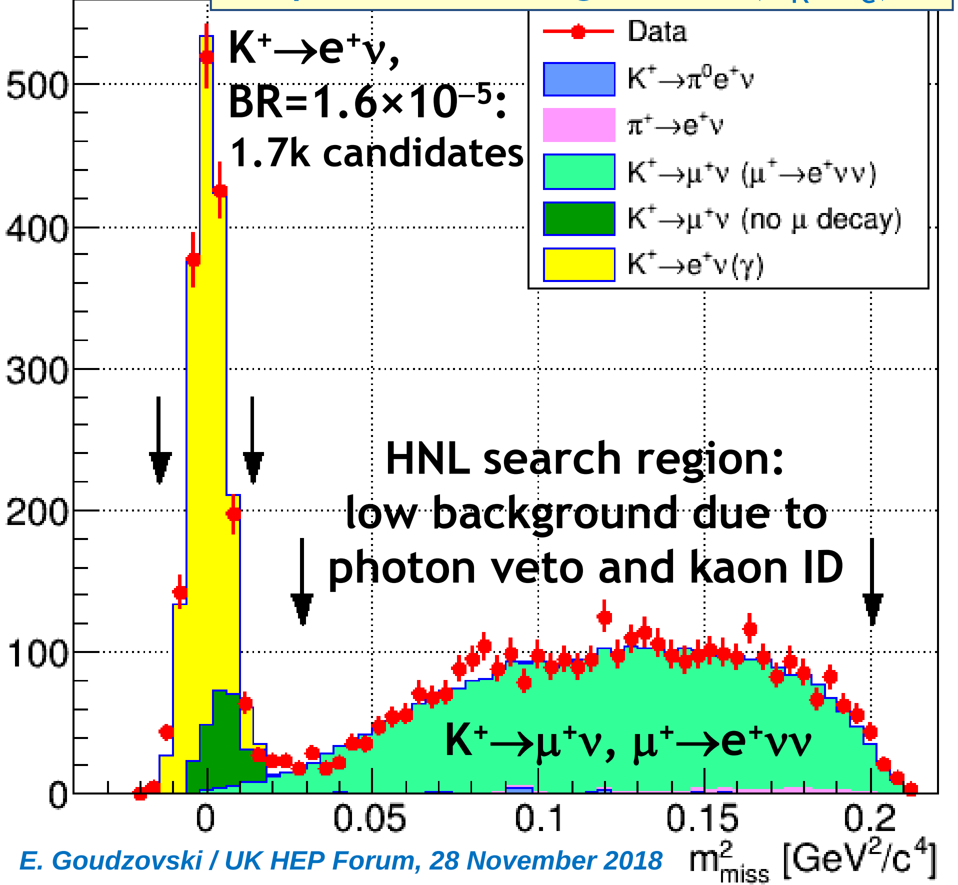
NA62 data collection

- Commissioning run **2015**: minimum bias data (~3×10^{10} protons/pulse).
- Physics run **2016** (~1.3×10^{12} ppp): 10^{11} useful K^+ decays. [arXiv:1811.08508]
- Physics run **2017** (~2.0×10^{12} ppp): ~3×10^{12} useful K^+ decays.
- Physics run **2018** (~2.3×10^{12} ppp): ~5×10^{12} useful K^+ decays.
- Restarting data taking after LS2 in **2021**.

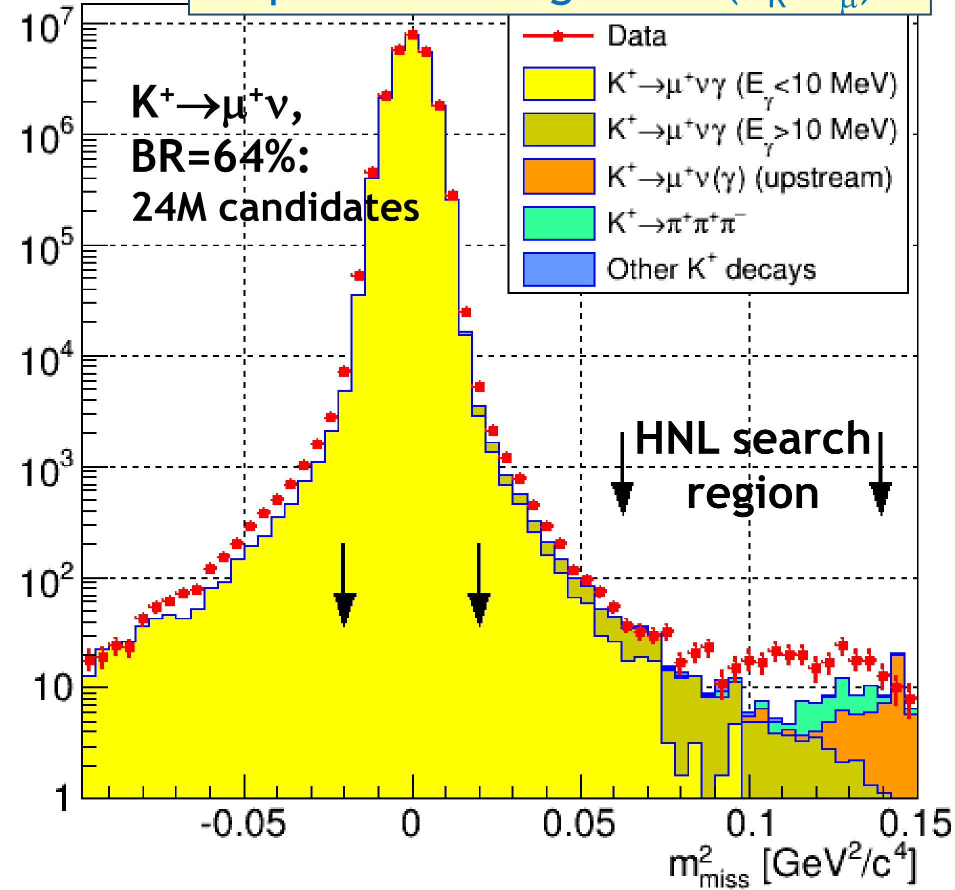
$K^+ \to \ell^+ N$ data samples

- Minimum bias data (1% intensity); 12k SPS spills (=5 days) in 2015.
- Numbers of K^+ decays in fiducial volume:
  $N_K=(3.01\pm0.11)\times10^8$ in positron case; $N_K=(1.06\pm0.12)\times10^8$ in muon case.
- Beam tracker not available: beam average kaon momentum is used.
- HNL production signal: a spike above continuous missing mass spectrum.

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

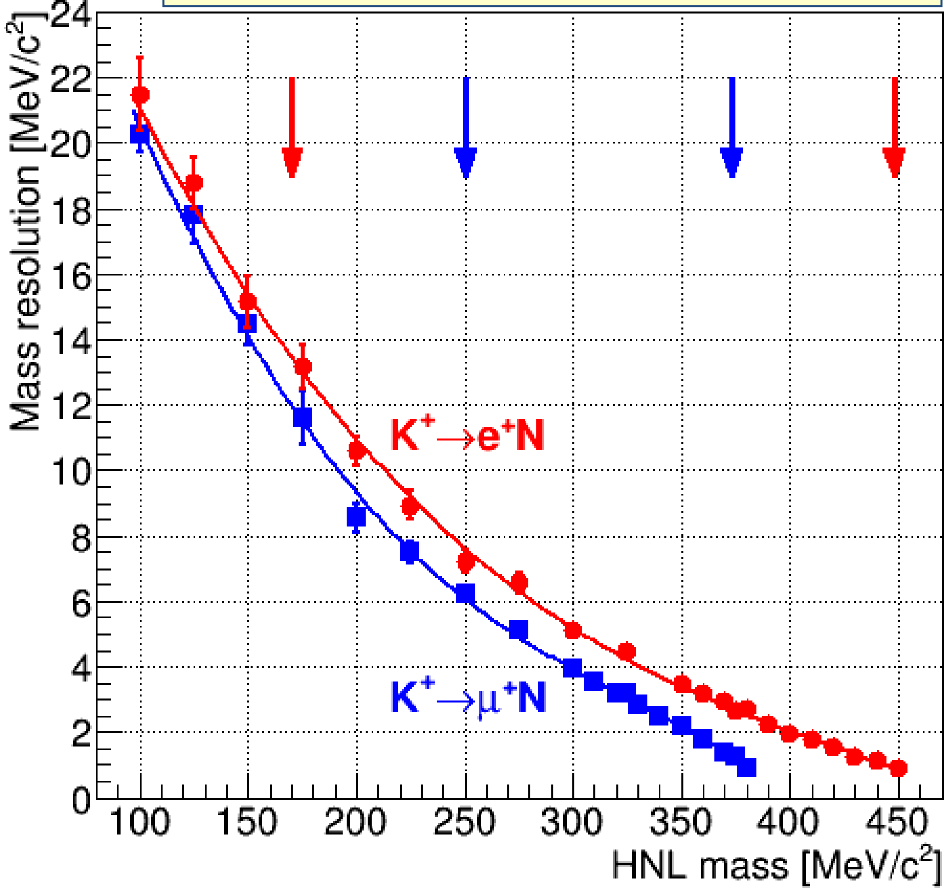


Squared missing mass: $(P_K-P_\mu)^2$

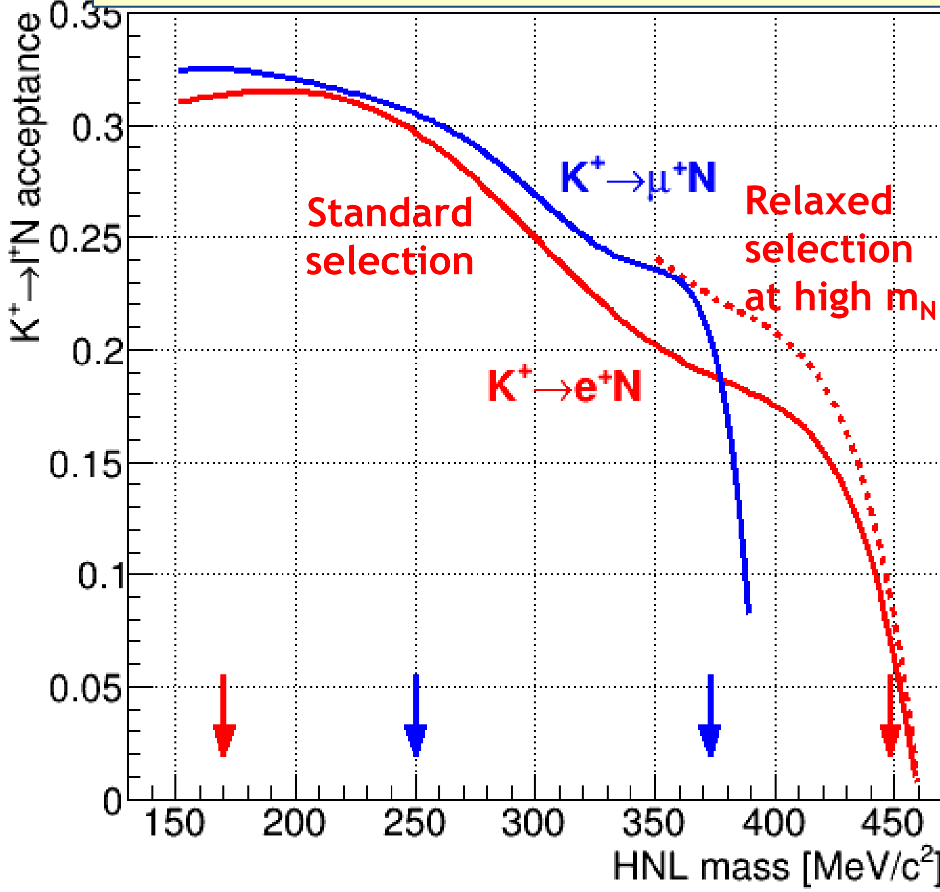


$K^+ \to \ell^+ N$: resolution & acceptance

HNL mass resolution σ_m vs mass



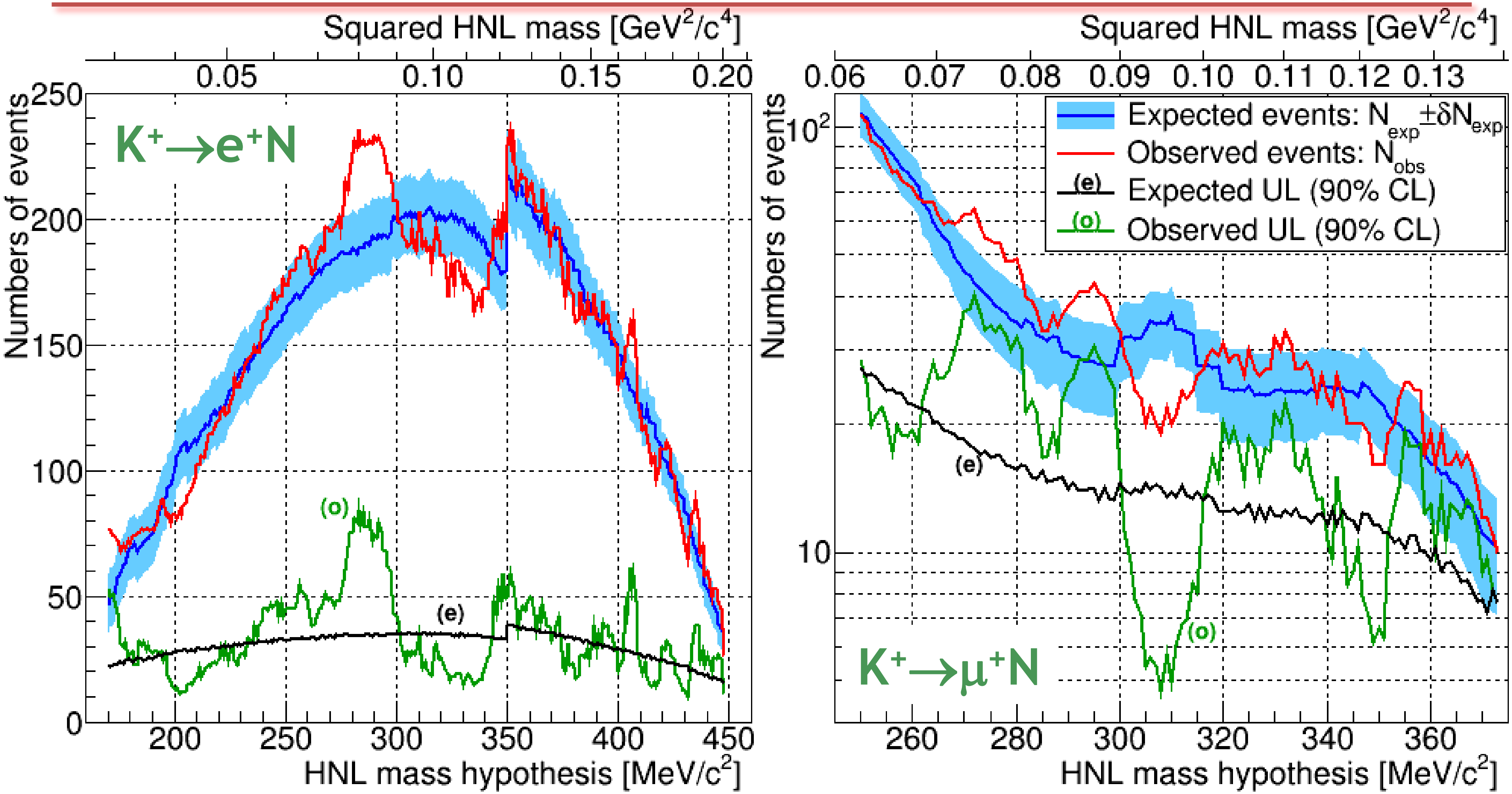
Signal selection acceptance vs mass



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

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

Statistical analysis

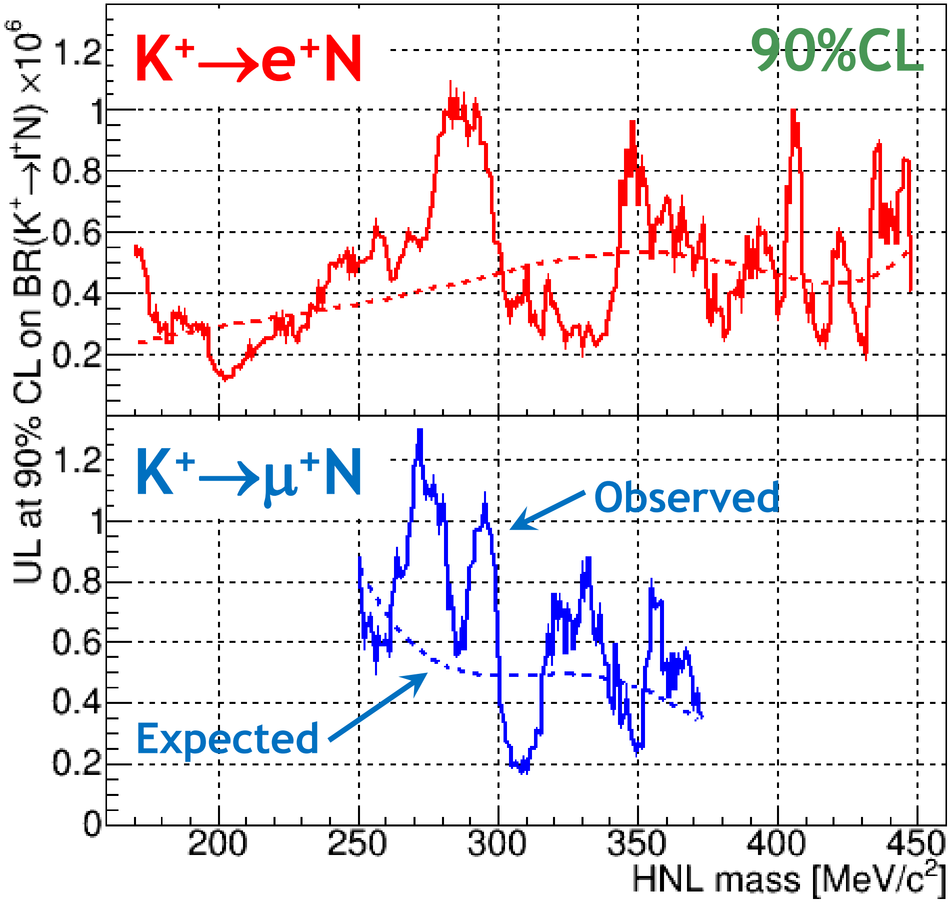


- Expected background (and stat.error) estimated from fits to the sidebands; numbers of observed and expected events converted into limits for the signal.
- Background simulations used to certify the absence of peaking structures.
- Full MC background estimate would allow **searches for $K^+ \to \ell^+ \nu\nu\nu$, $K^+ \to \ell^+ \nu X$**.

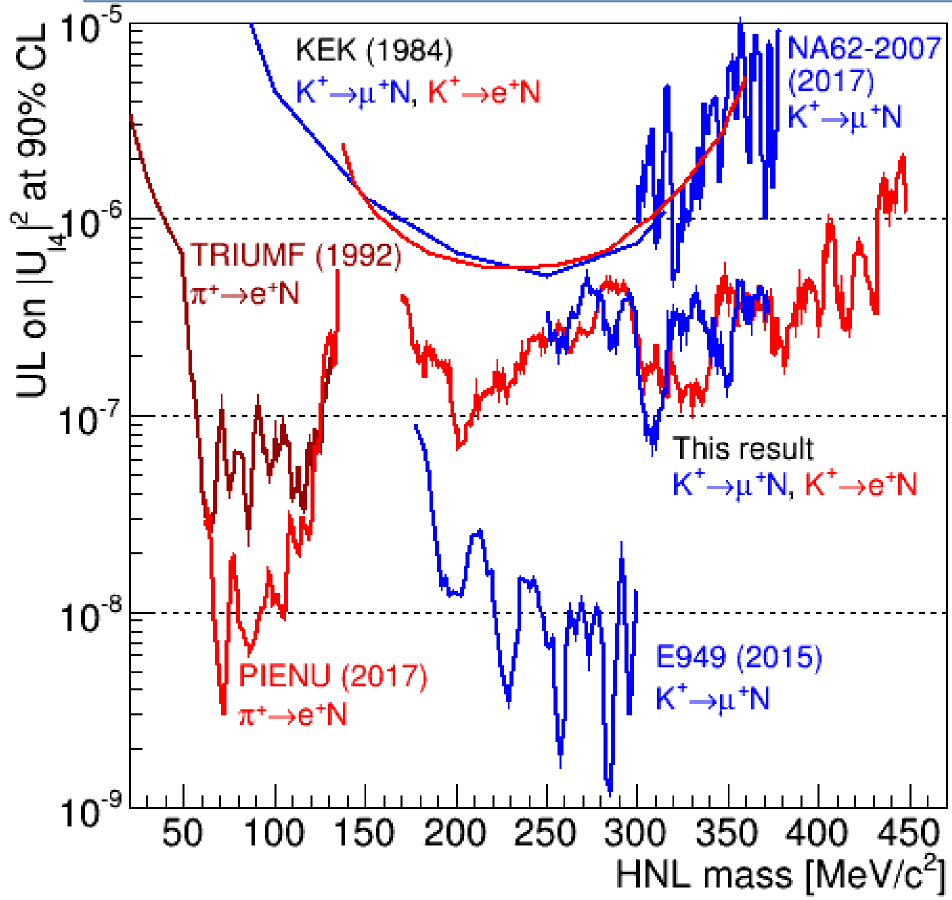
HNL production search: results

PLB778 (2018) 137

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



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



- Local signal significance never exceeds **2.2σ**: **no HNL signal** is observed.
- Reached **10^{-6}–10^{-7}** limits for **$|U_{\ell 4}|^2$** in the **170–448 MeV/c^2** mass range.

HNL production: NA62 prospects

Improvements in 2016–18 wrt 2015:

- Beam tracker (GTK) in operation:
  - ✓ HNL mass resolution σ_m improved by a factor ~2, therefore lower background and broader mass range accessible;
  - ✓ a factor ~3 lower background in the $K^+ \to e^+ N$ mode ($K^+ \to \mu^+ \nu$, $\mu^+ \to e^+ \nu\nu$: muon decays in flight rejected geometrically);
  - ✓ lower background from upstream decays in the $K^+ \to \mu^+ N$ mode.
- Much larger datasets:
  - ✓ In the $K^+ \to e^+ N$ mode, the main $K^+ \to \pi^+ \nu\nu$ trigger is used (with reduced signal acceptance: max calorimetric energy = 30 GeV): expect at $O(10^6)$ $K^+ \to e^+ \nu$ events, i.e. a factor ~1000 improvement.
  - ✓ In the $K^+ \to \mu^+ N$ mode, downscaled control trigger (D=400): expect $O(10^9)$ $K^+ \to \mu^+ \nu$ events, i.e. a factor ~100 improvement.

Expected sensitivities to $|U_{\ell 4}|^2$ with 2016–18 data:

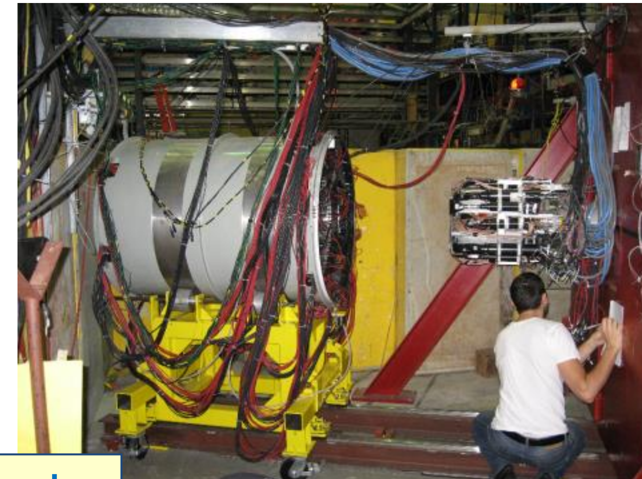
better than 10^{-8} for both $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

Analysis is in progress

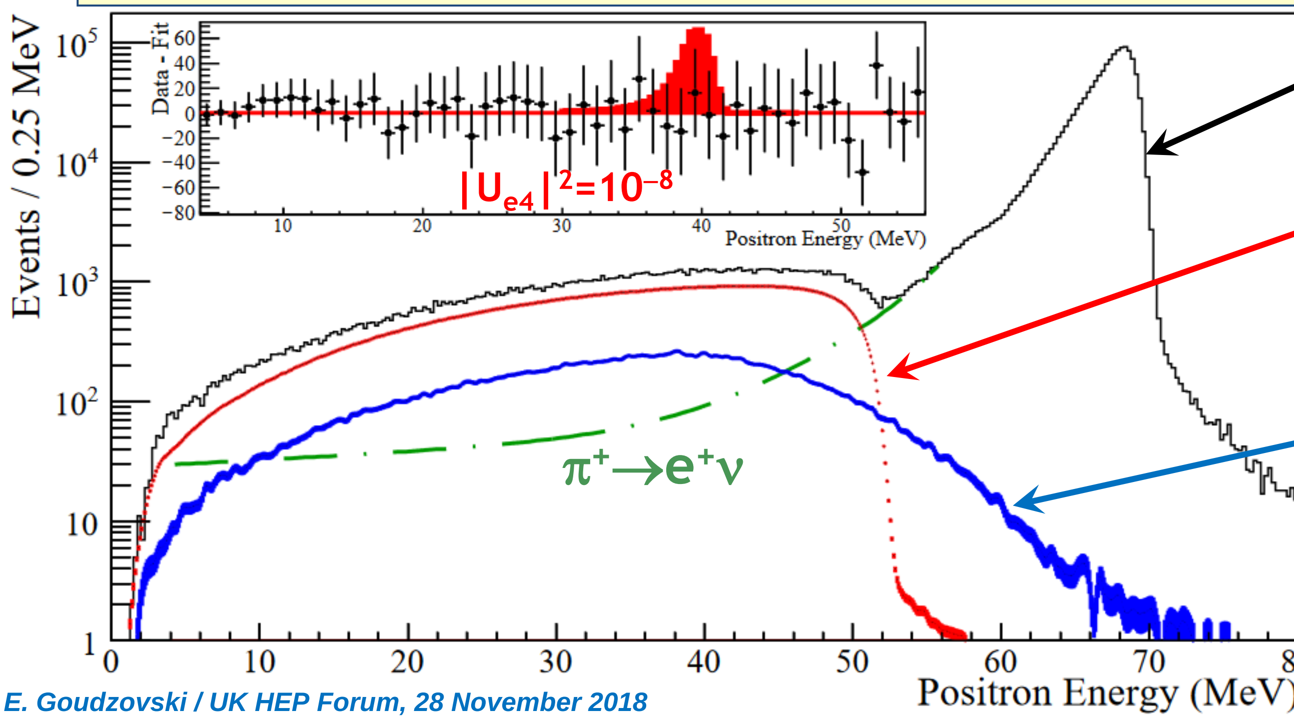
PIENU limits on $\pi^+ \to e^+ N$

- Pion decay at rest experiment at TRIUMF: collected **10M** rare decays $\pi^+ \to e^+ \nu$ in 4 years.
- Setup: active scintillator target, wire+microstrip chambers, NaI calorimeter.
- Sensitivity to $|U_{e4}|^2$ for $m_N < 130$ MeV/c^2 complementary to NA62.

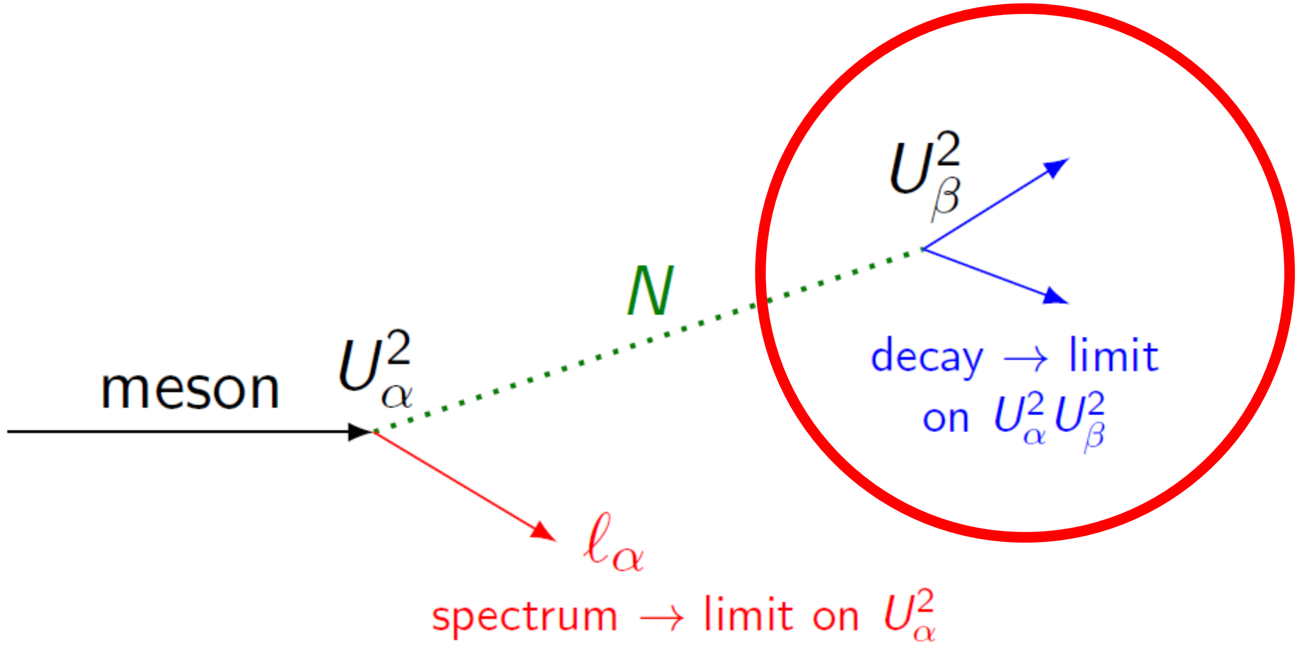
  PRD97 (2018) 072012



Positron energy spectrum and (Data–Bkg) residuals



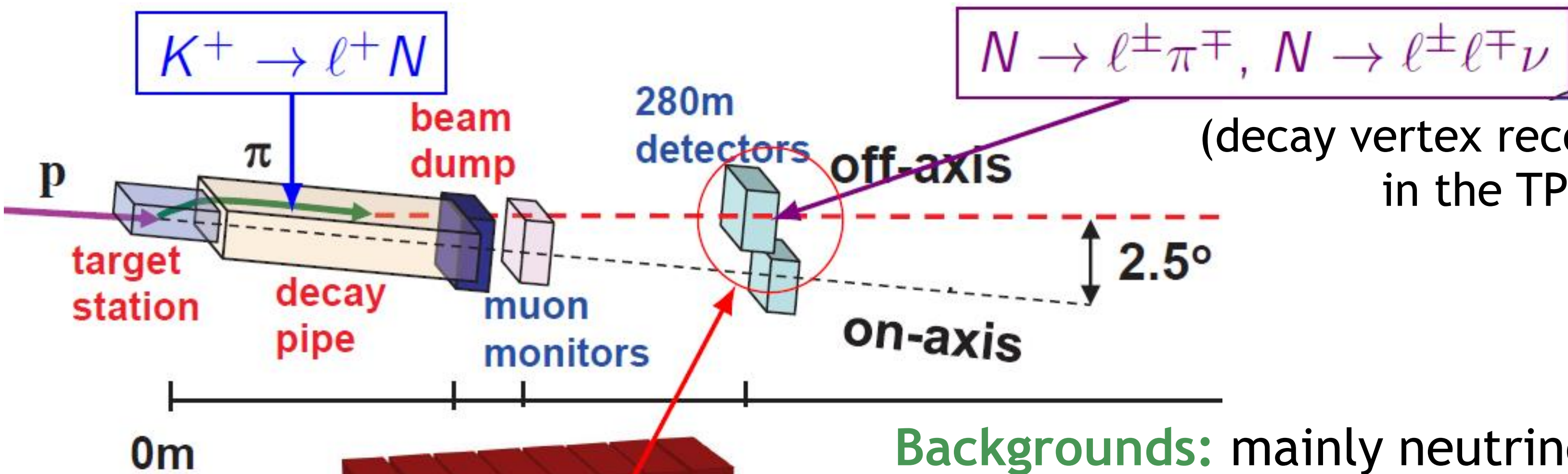
HNL decay searches: T2K, NA62-dump, SHiP



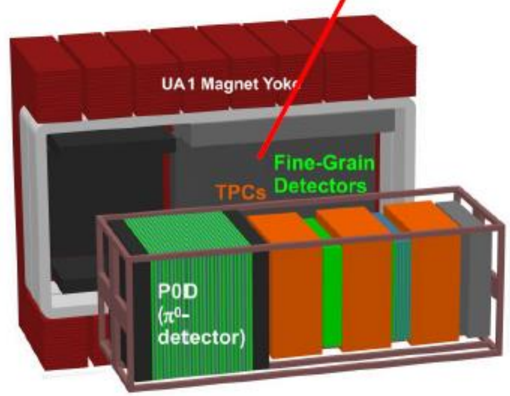
HNL decays at T2K

M. Lamoureux @ ICHP 2018

- Analysis is based on **1.8×10^{21} pot** (**30 GeV**) collected up to April 2017.
- Search for decays of HNLs produced in **$K^{\pm}$** decays.
- Mass range is complementary to that accessible in charm decays.



(decay vertex reconstruction in the TPC)

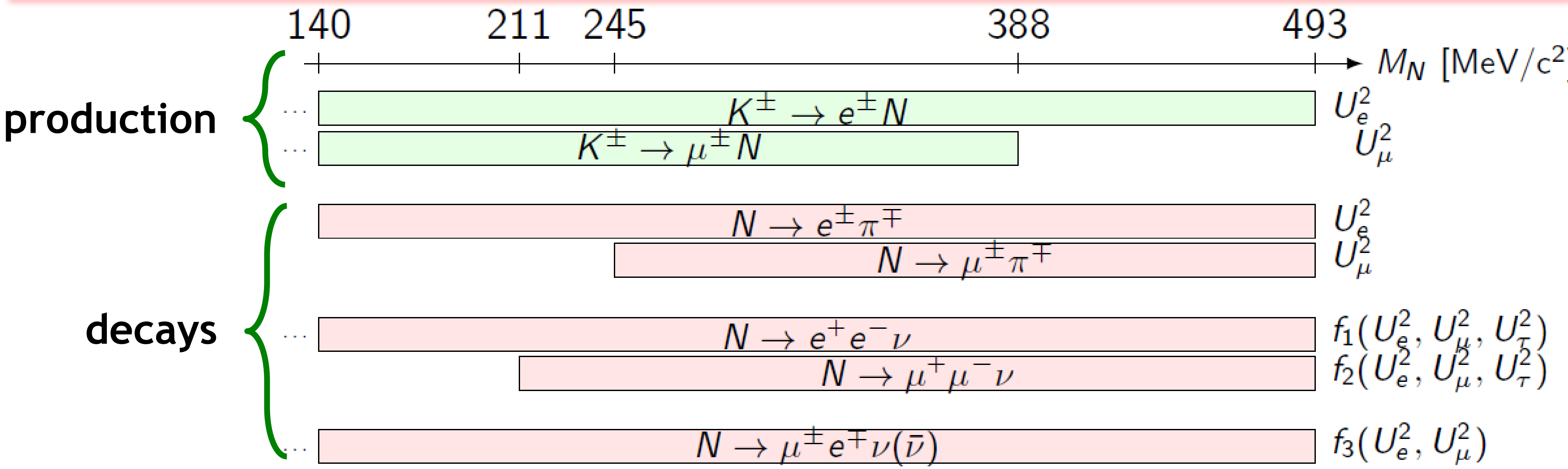


Backgrounds: mainly neutrino-induced

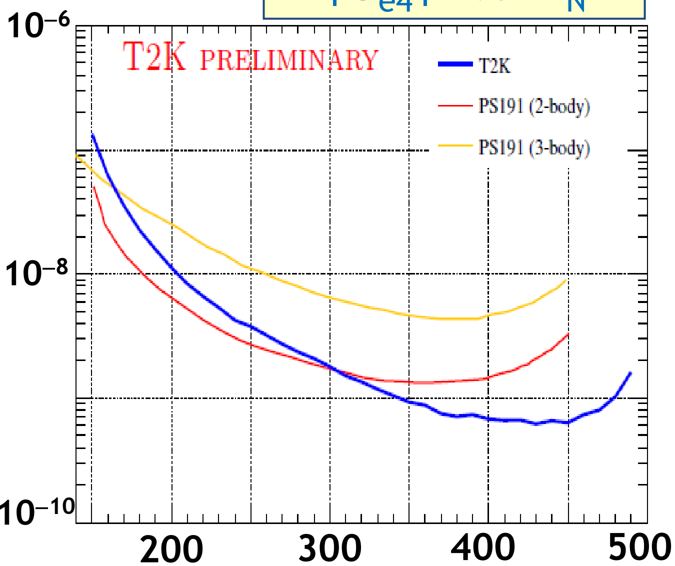
- coherent pion production in TPC: $\nu_\mu + Ar \to Ar + \mu^- + \pi^+$;
- inverse beta decay: $\nu_\mu n \to \mu^- p$.

Low expected backgrounds:
O(1) events in all decay modes.
Zero events observed in all modes.

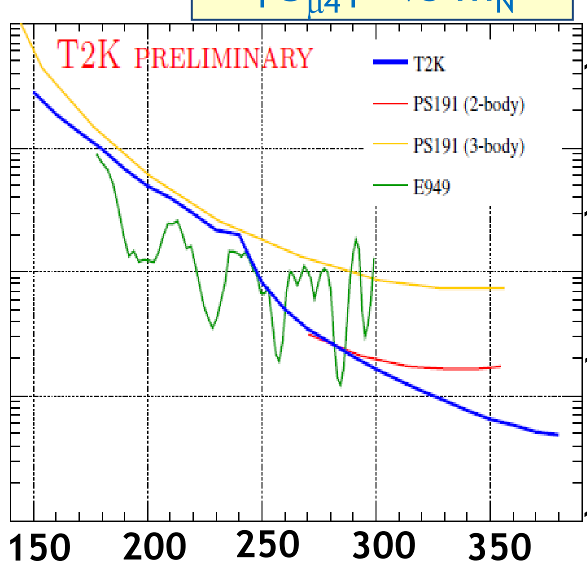
T2K: HNL exclusion (preliminary)



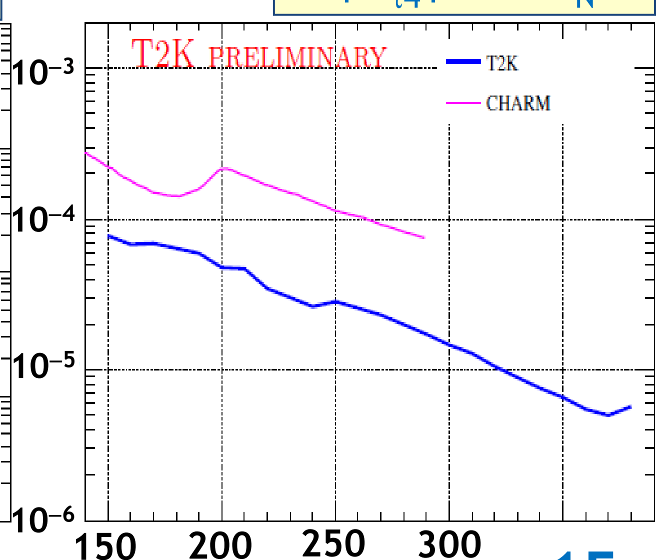
$|U_{e4}|^2$ vs m_N



$|U_{\mu4}|^2$ vs m_N



$|U_{\tau4}|^2$ vs m_N



HNL mass [MeV/c^2]

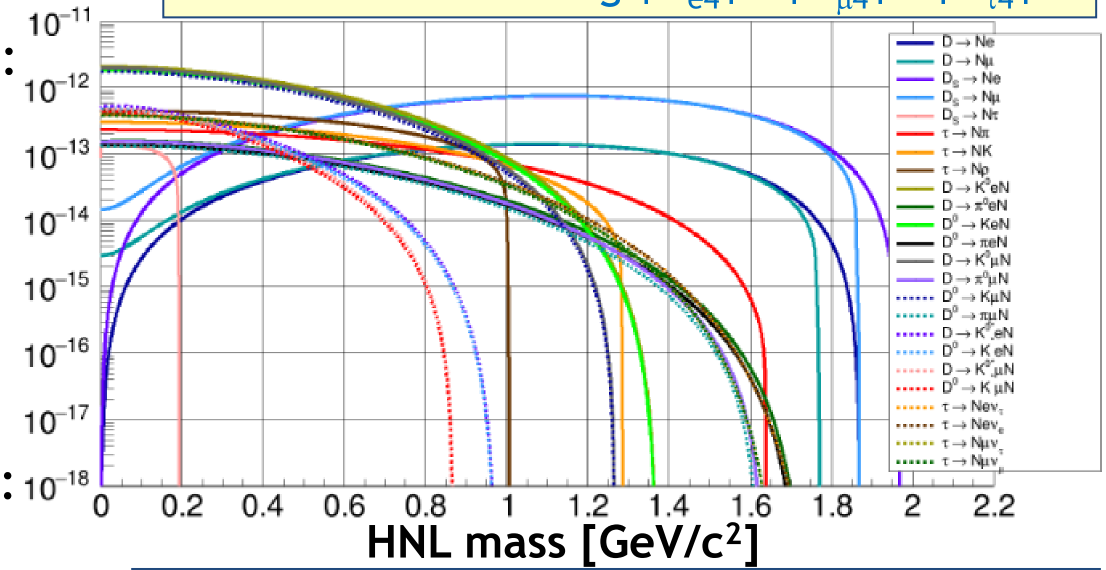
HNL production at SPS energies

Dominant HNL production mechanism by **400 GeV/c** protons: charm decays, e.g. $D_{(S)}^+ \to \ell^+ N$.

Yields for **10^{18} pot**:

- ✓ D mesons: **~2×10^{15}**;
- ✓ B mesons: **~10^{11}**.

Production assuming $|U_{e4}|^2=|U_{\mu4}|^2=|U_{\tau4}|^2$

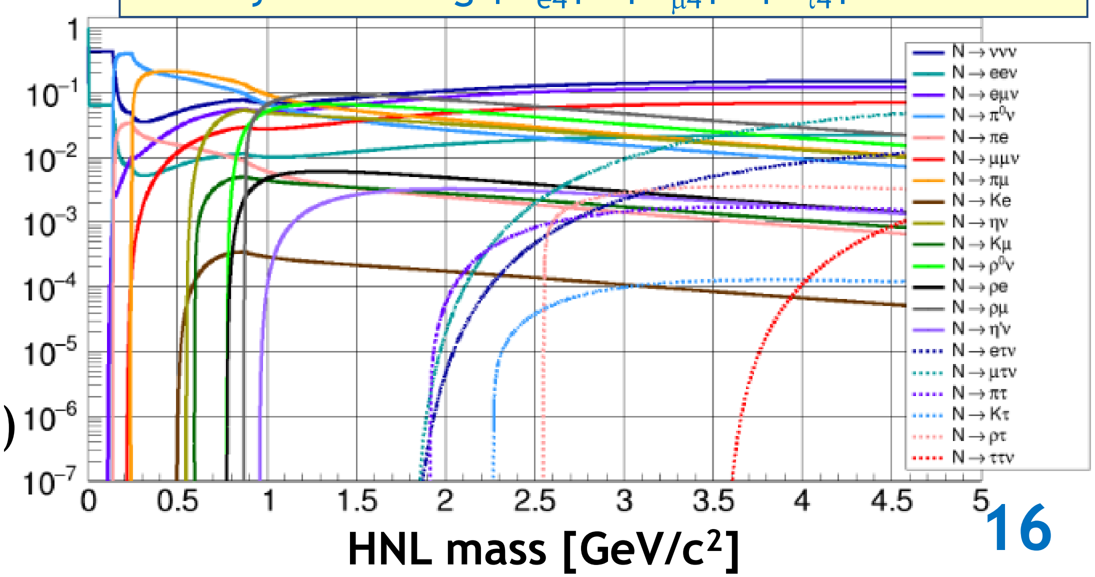


Main decay modes at m_N~1GeV/c²:

$$N_i \to 3\nu,\ \pi^0\nu,\ \pi^\pm\ell^\mp,\ \rho^0\nu,\ \rho^\pm l,\ \ell^+\ell^-\nu$$

BR

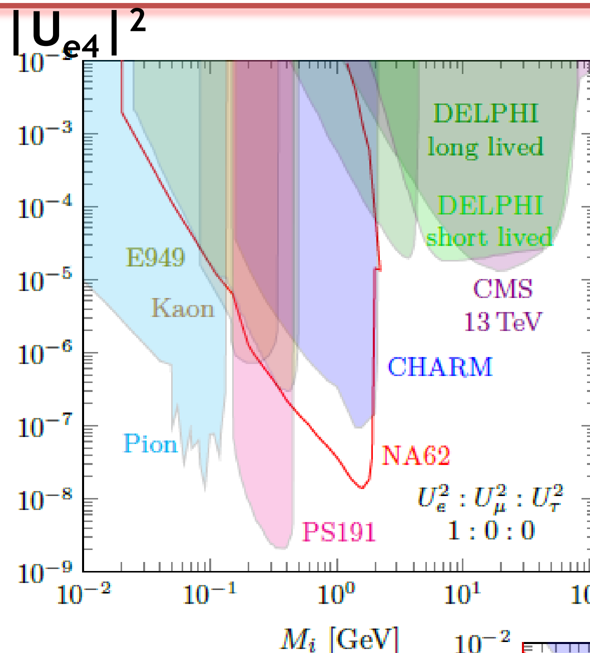
Decays assuming $|U_{e4}|^2:|U_{\mu4}|^2:|U_{\tau4}|^2=1:16:3.8$

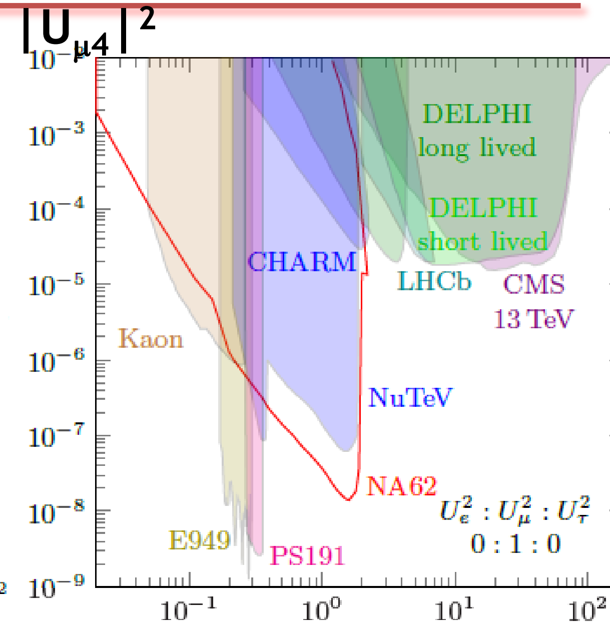


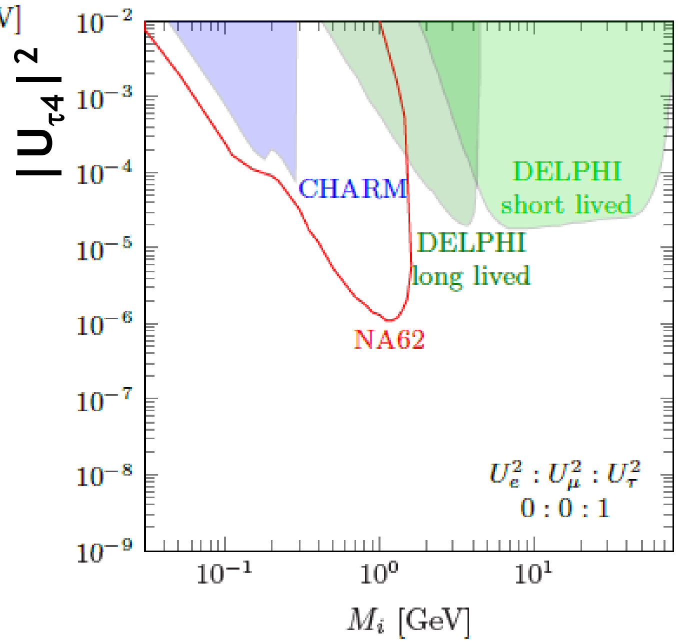
- ❖ Production & decay rates depend on mass m_N and couplings $|U_{e4}|^2$, $|U_{\mu4}|^2$, $|U_{\tau4}|^2$.
- ❖ Long NA62 decay volume (**80m**) matches the large HNL lifetimes.

NA62 sensitivity to HNL decays

Dump operation: target removed; **400 GeV** protons dumped into a **$20\lambda_I$** Fe/Cu collimator at **z≈25 m**.







- Goal: integrate **10^{18} pot** at **3×10^{12} ppp** in dump mode in **3 months** in **2021–23**.
- Existing **muon sweeping system** can be modified: factor **~4** flux reduction.
- Expected sensitivities assuming **zero background** are presented in the e, μ and τ dominated scenarios.

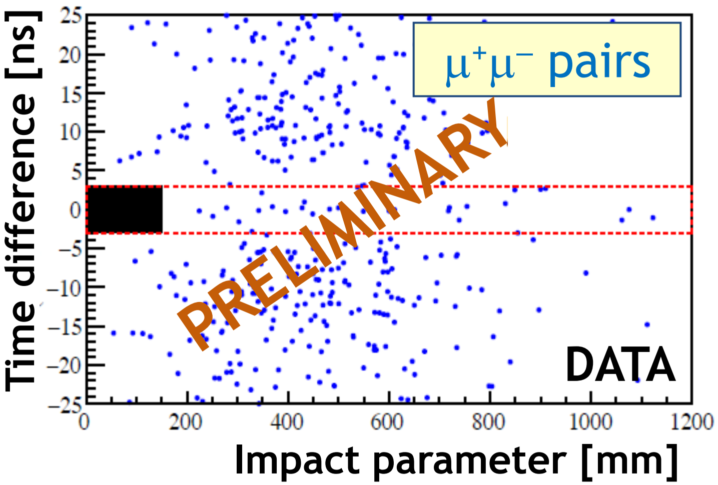
[Drewes et al., JHEP 1807 (2018) 105]

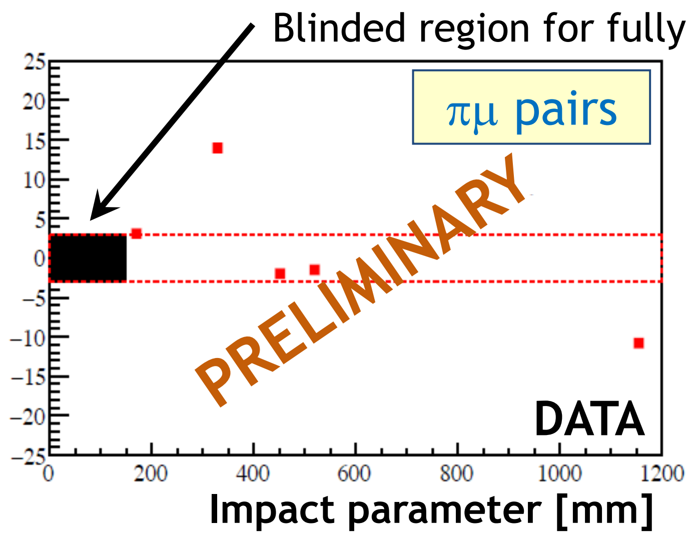
NA62: background in dump mode

Key issue: the muon halo background (~**50 kHz**).
A dedicated study with **2017+18 dump** data, **2×10^{16}** pot

NB: also ~10^{17} pot collected along with K^+ data taking

Two-track vertices:





ANTI0 location

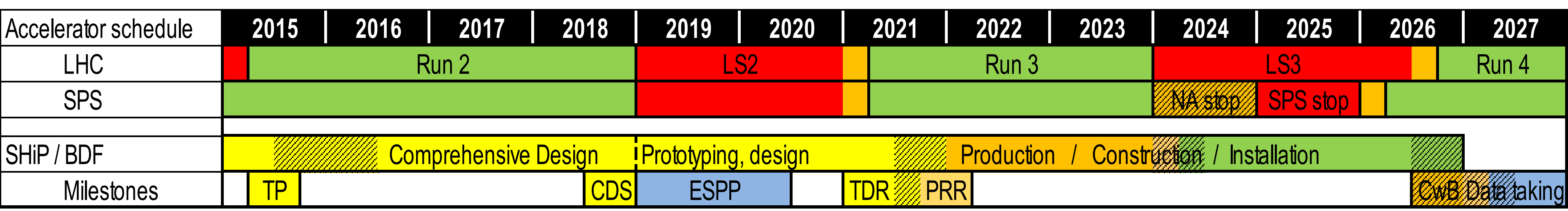
- Background demonstrated to be negligible for fully reconstructed final states (e.g. $N\to\pi^+\mu^-$).
- For open channels (e.g. $N\to\ell^+\ell^-\nu$), an **ANTI0** veto hodoscope required for background suppression.
- **ANTI0** installation by **2021** has been approved.

SHiP project at CERN

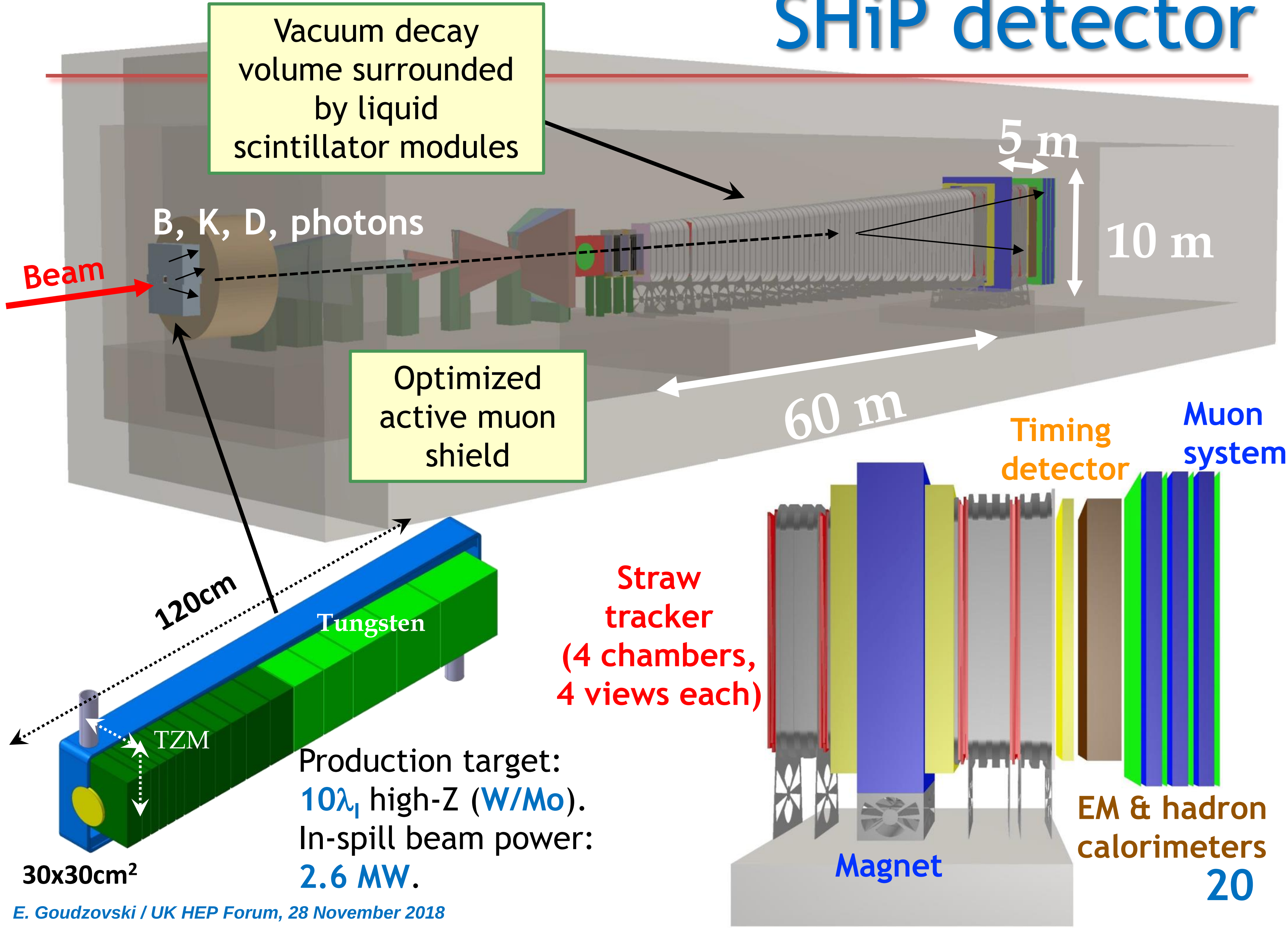
SHiP experiment at the Beam Dump Facility at CERN SPS North Area:
ultimate sensitivity to HNL decays

- High intensity **400 GeV/c** proton beam: **4×10^{13} ppp** (NA62-dump ×10).
- Up to **4×10^{19} pot/year**, and **2×10^{20} pot** in **5** years (NA62-dump ×200).
- Heavy flavour yields: **$N_D \approx 1.6\times10^{18}$**, **$N_B \approx 1\times10^{14}$** (including cascade enhancement factors **~2**).
- Compatible with current and planned SPS experiments.
- Currently, major engineering design and prototyping work.

Current schedule: commissioning at the start of LHC Run 4 (assuming approval in 2020–21)

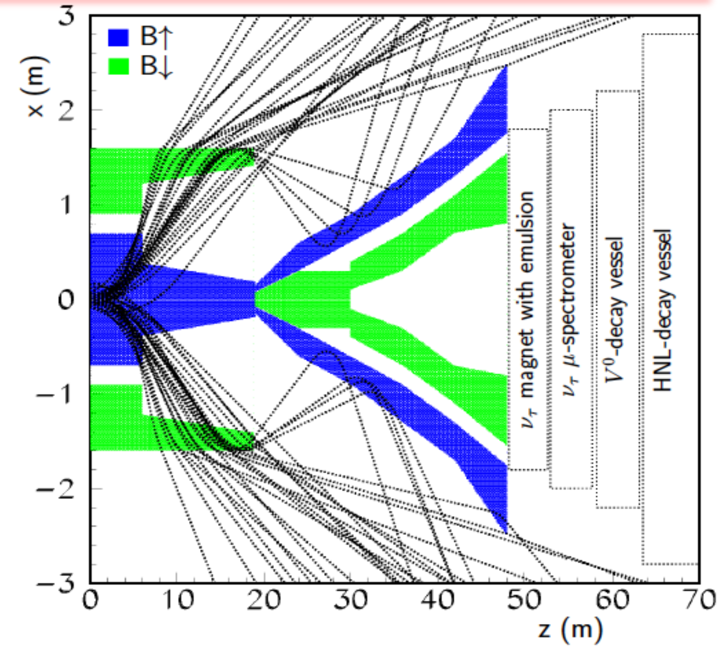


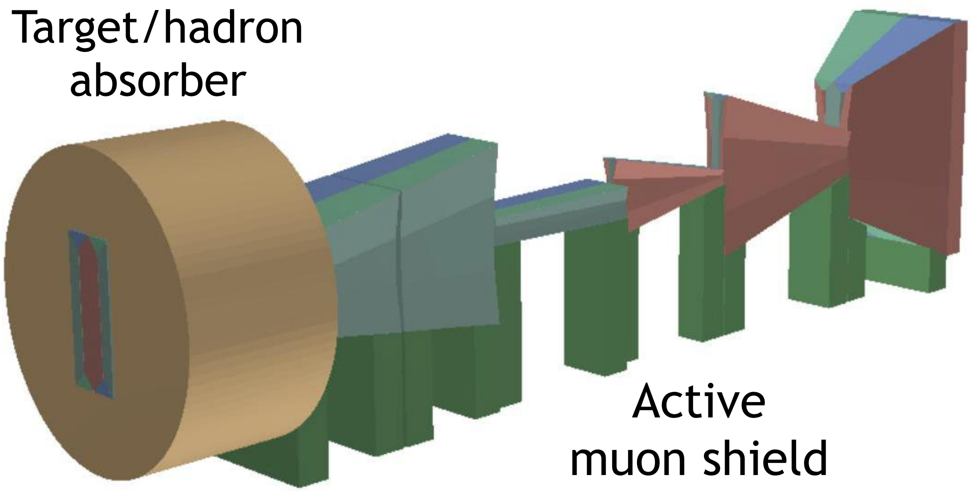
SHiP detector

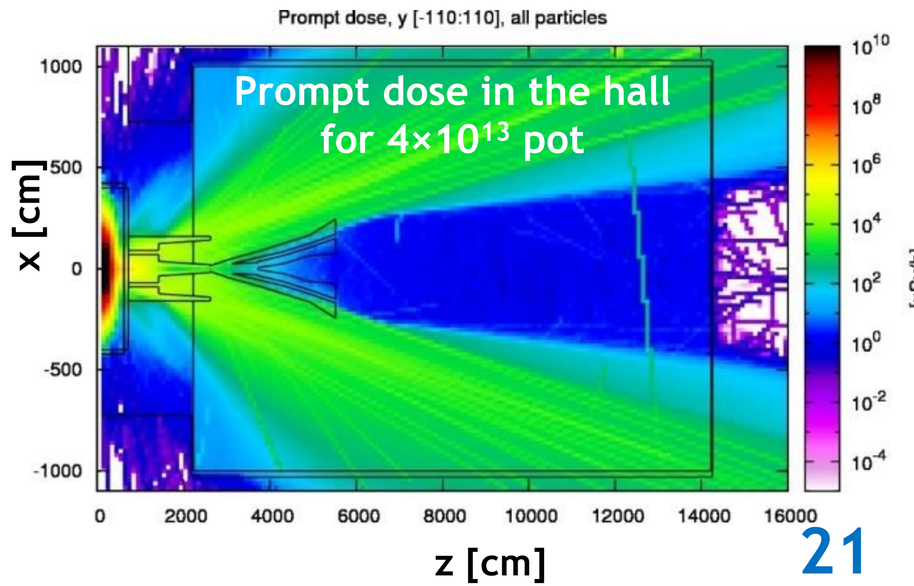


Muon background

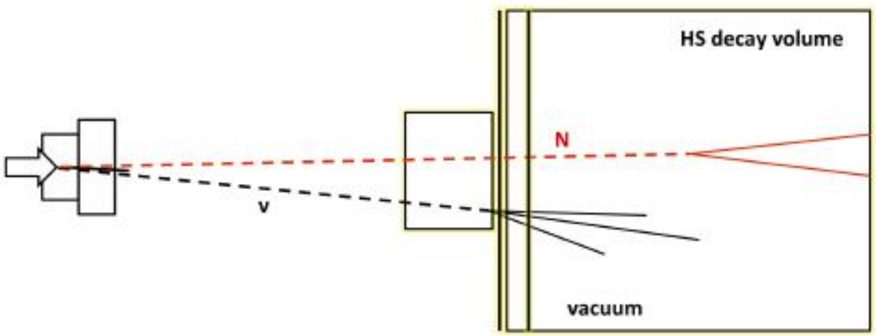
- Pions, kaon and short-lived resonance decays in the production target: **O(10 GHz) muon and neutrino flux**.
- Muon shield is based on magnetic sweeping.
- Expect **O(10 kHz)** muon flux on detector.
- Combinatorial background suppressed by **100ps** timing.



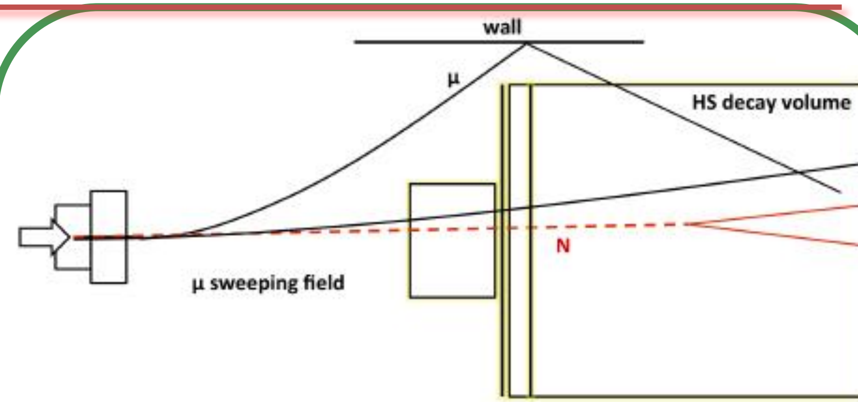




SHiP: backgrounds



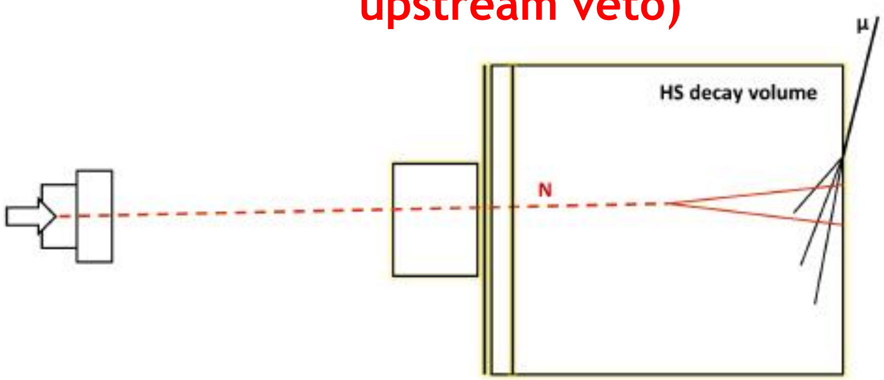
Neutrino interactions



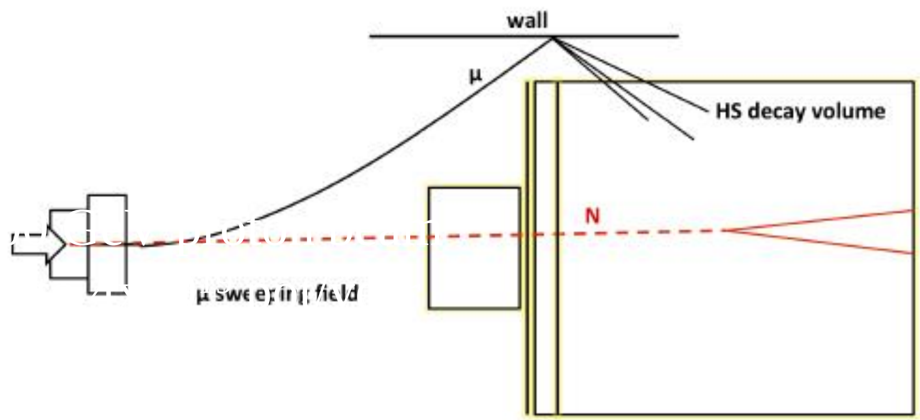
Muon combinatorial

In-time tracks, not pointing to the target.
Suppressed by VETO detectors
(surrounding background tagger,
upstream veto)

Mostly out-of-time tracks,
not pointing to the target.
Suppressed by ~100ps timing.



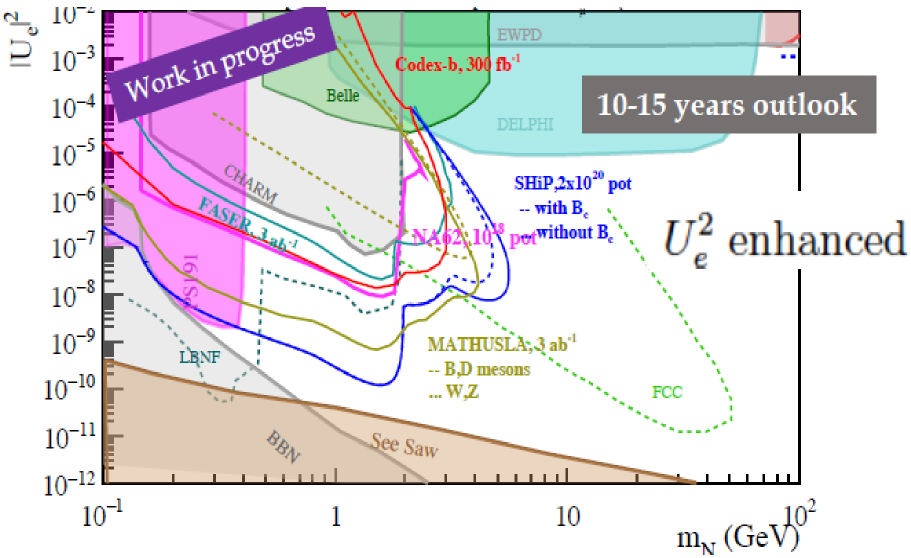
Cosmic muons

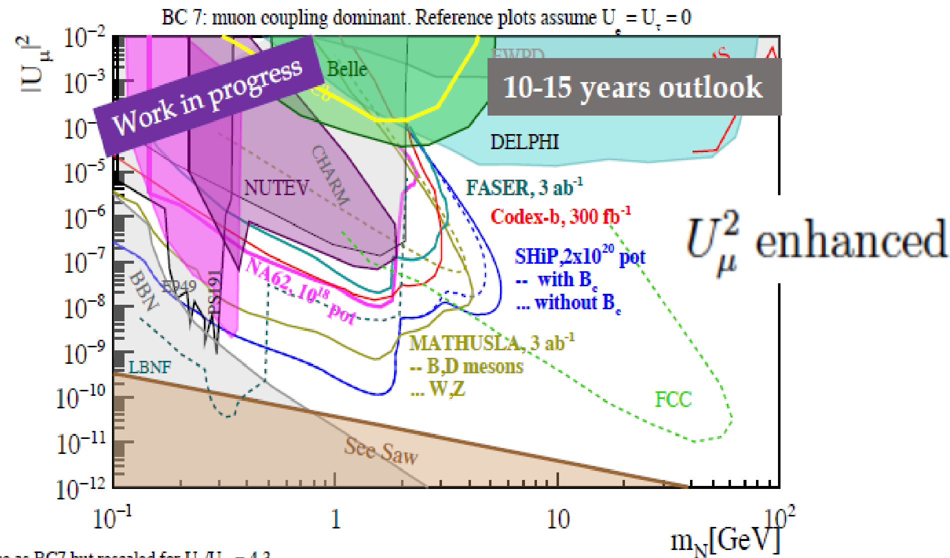


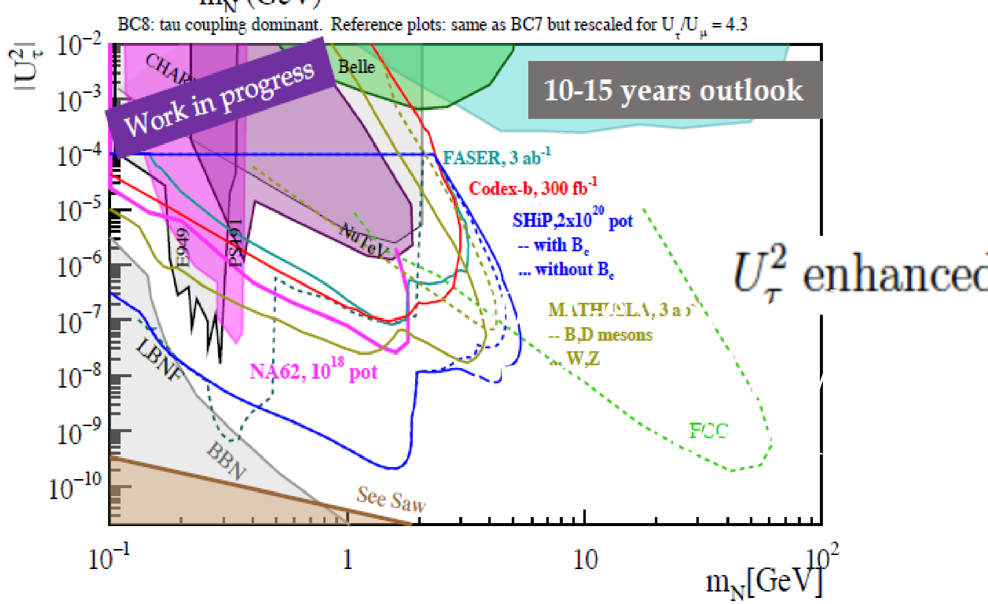
Deep inelastic

Equivalent of the full SHiP dataset has been simulated.
Residual background compatible with 0 events.

HNL decays: 15 years from now







(G. Lanfranchi, PBC workshop, CERN, June 2018)

Summary

- **HNL production searches in K/π decays**
  - ✓ No assumptions on HNL nature and HNL decays.
  - ✓ HNL mass range accessible: **50–450 MeV/c²**.
  - ✓ Sensitivity to $|U_{\ell 4}|^2$ ~ **1/Luminosity**. [limited by bkg systematics]
  - ✓ Major progress in the last few years as secondary goals: BNL E949, CERN NA62, PIENU@TRIUMF.
  - ✓ Powerful constraints on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ (below 10^{-8}).
  - ✓ Further progress foreseen soon at NA62.

- **HNL decay searches in beam dump experiments**
  - ✓ HNL mass range accessible: up to the **B**-meson (**~5 GeV/c²**) scale.
  - ✓ Sensitivity to $|U_{\ell 4}|^2$ ~ $(1/\text{Luminosity})^{1/2}$.
  - ✓ Expect **~10^{-9}** sensitivity on **all** $|U_{\ell 4}|^2$ in **15 years time**.