IOP joint HEPP and APP meeting
Bristol, March 2018

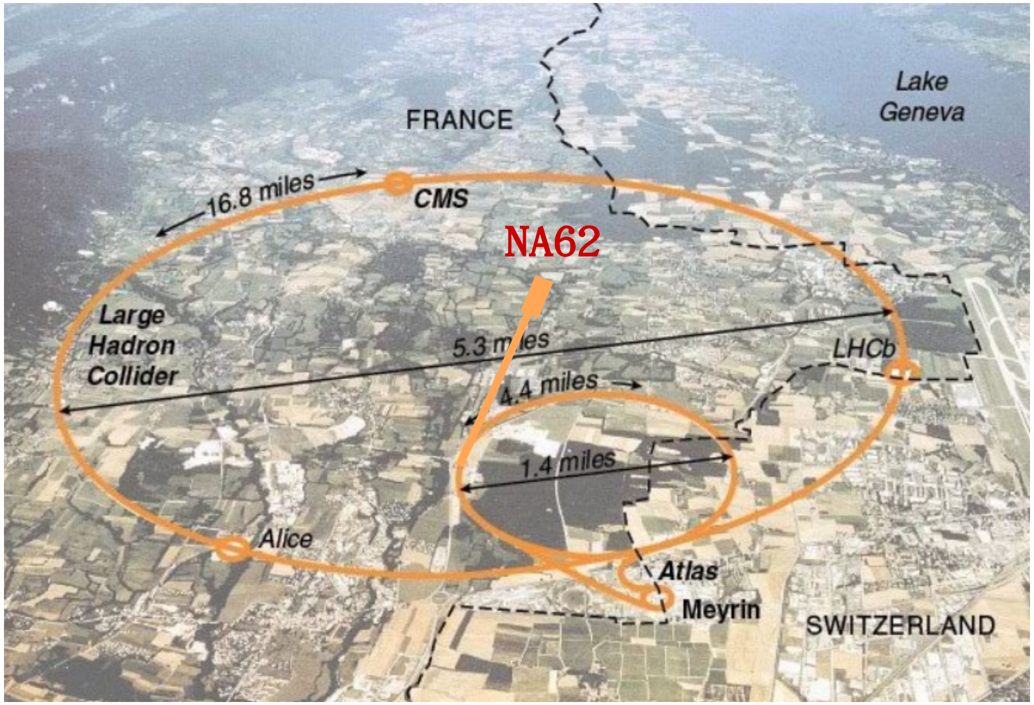
Heavy neutral lepton searches at NA62

Lorenza Iacobuzio
University of Birmingham

- The NA62 experiment at CERN
- Theoretical motivations for HNL searches
- HNL decay searches at NA62
- Conclusions and further work

The NA62 experiment at CERN SPS

- Fixed-target experiment at CERN SPS
- Run I (2016-2018): *[see talk by A. Romano]*
  - Measure BR($K^+ \to \pi^+ \nu \bar{\nu}$) with 20% precision
  - Related to CKM matrix element V_{td}
  - $K^+ \to \pi^+ \nu \bar{\nu}$: strongly suppressed FCNC and sensitive to New Physics
  - Besides $K^+ \to \pi^+ \nu \bar{\nu}$, broad physics programme performed in presence of K^+ beam:
    - LFV/LNV processes
    - Hidden sector searches: axions, dark photons, heavy neutral leptons (HNLs) *[this talk]*
- Run II (2021++):
  - Possible continuation of $K^+ \to \pi^+ \nu \bar{\nu}$ data-taking
  - Opportunity to run in "beam-dump" mode to collect 10^{18} protons on target (POT) for hidden sector searches

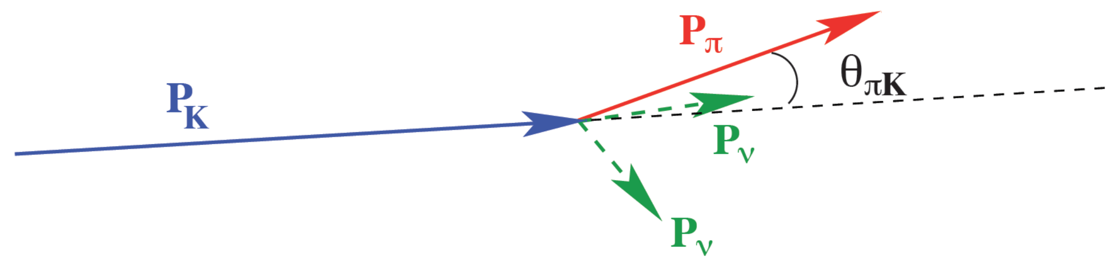


The NA62 experiment at CERN SPS.
The NA62 collaboration (about 200 participants): Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Merced, Moskow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

The NA62 beam and experimental setup

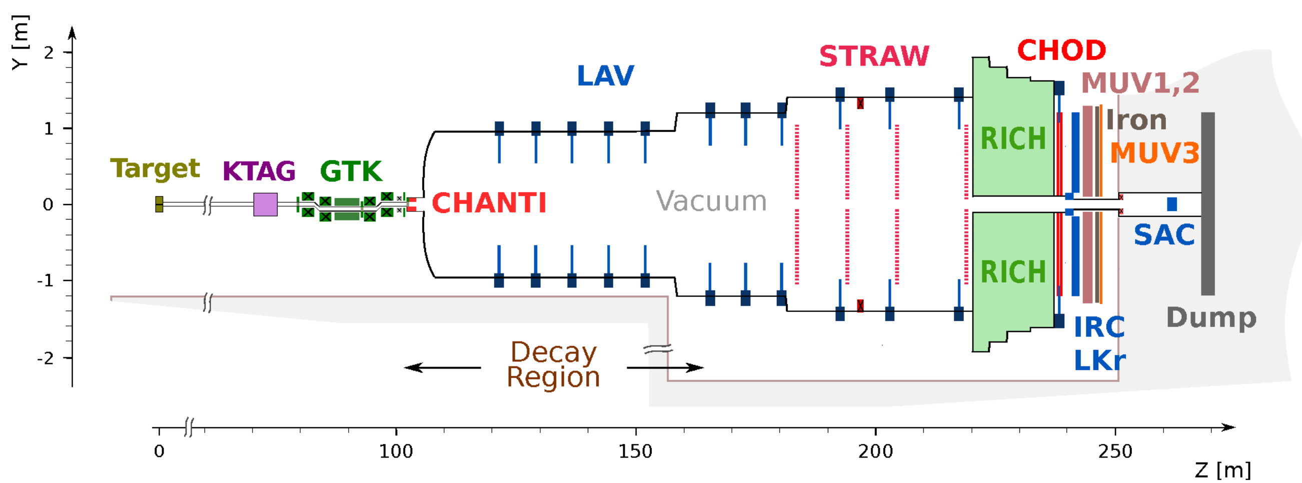
- SPS 400 GeV/c protons on target (POT)

  to produce secondary beam:
  - 6% K^+, 70% π^+, 24% p
  - 75 GeV/c momentum
  - 750 MHz of particles
  - In-flight-decay technique in fiducial volume (FV)
  - 5 MHz of K^+ decays in FV (105 m - 180 m)



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ event topology

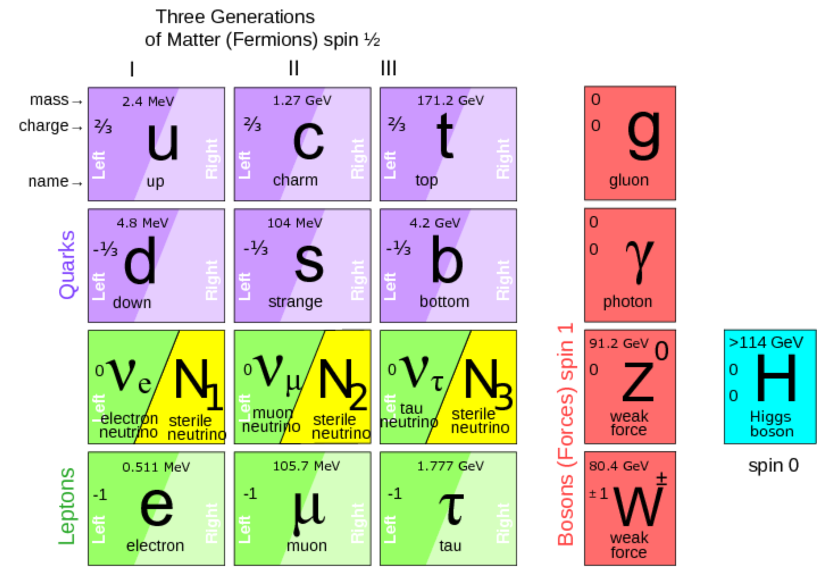
- Detectors:
  - Particle ID and tracking systems for upstream K^+ and downstream π^+
  - Veto systems for charged particles, photons and muons



NA62 schematic layout. All detectors are visible

Theoretical framework for HNL searches

- νMSM:
  - SM extension accounting for baryon asymmetry of the universe (BAU), dark matter (DM), neutrino masses and oscillations
  - 3 additional right-handed, singlet, Majorana HNLs (not observed yet)
  - See-saw mechanism to explain light SM neutrinos
  - Lightest HNL (about 10 keV) is good candidate for DM
  - Production and decay modes same as SM ones, scaled by coupling factor (U^2)
- Constrained νMSM scenarios by Shaposhnikov *[JHEP, 0710 (2007)]*:
  - 4 free parameters: 1 active HNL mass (0.1-1 GeV) and 3 squared matrix elements (U_e^2, U_μ^2, U_τ^2)
  - $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$
  - U^2 in range (10^{-9}, 10^{-5})



νMSM particle zoology

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS mixing matrix between HNL flavour and mass eigenstates

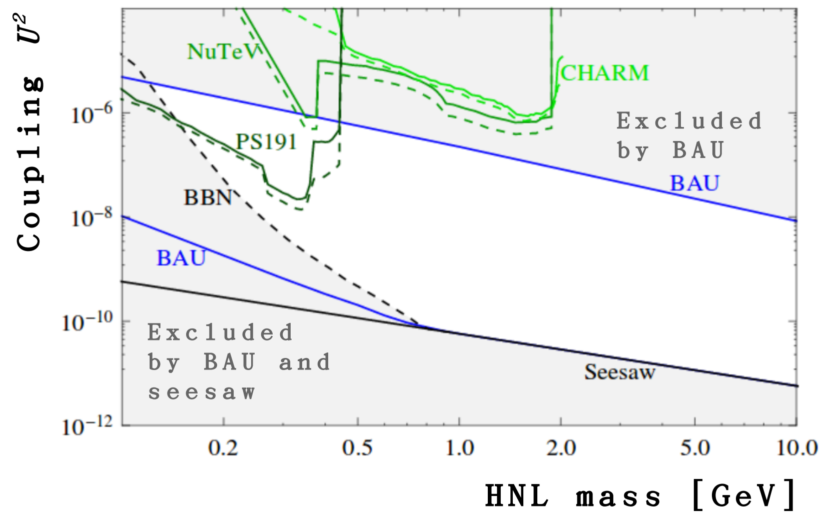
$$U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1 \, (I)$$
$$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8 \, (II)$$
$$U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3 \, (III)$$

Constrained scenarios of the νMSM by Shaposhnikov

Experimental techniques

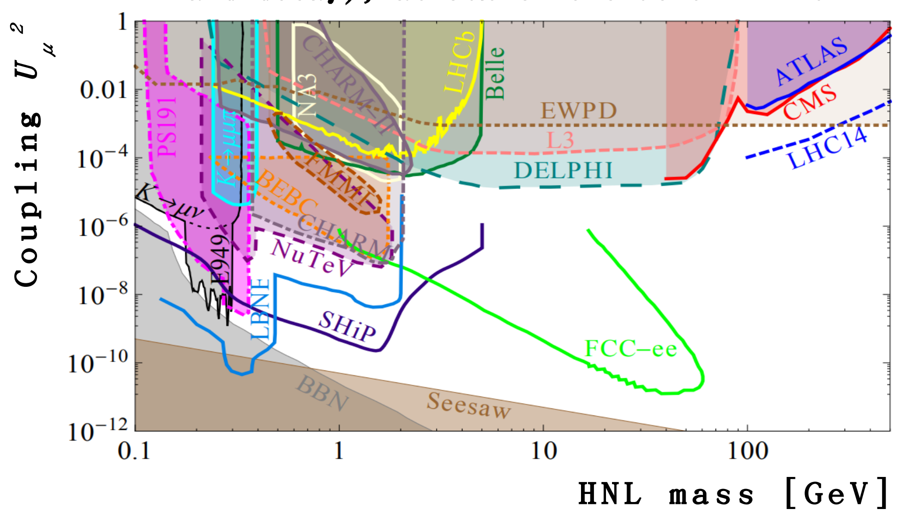
- Production searches:
  - Look for peaks in squared missing mass distribution
  - Decay-model independent → sensitive to long-lived HNLs
  - $\pi^+ \to e^+ \nu_e$ (TRIUMF): $m^2 = (P_\pi - P_e)^2$
  - $K^+ \to \mu^+ \nu_\mu$ (NA62, KEK, E949): $m^2 = (P_K - P_\mu)^2$
  - No HNLs observed → upper limits (UL) on U^2 as $f(m_N)$
- Decay searches:
  - Coupling- and decay-model dependent → sensitive to short-lived HNLs
  - $N \to e\mu\nu_e$ (PS191), $N \to l^+ l^- \nu_l$, $N \to l^- l'^+ \nu_l$ (CHARM)
  - PS191 excluded region allowed by BAU

Allowed region of HNL parameters for decay searches, for normal mass hierarchy



[Gninenko, Gorbunov, Shaposhnikov: 10.1155:718259 (2012)]

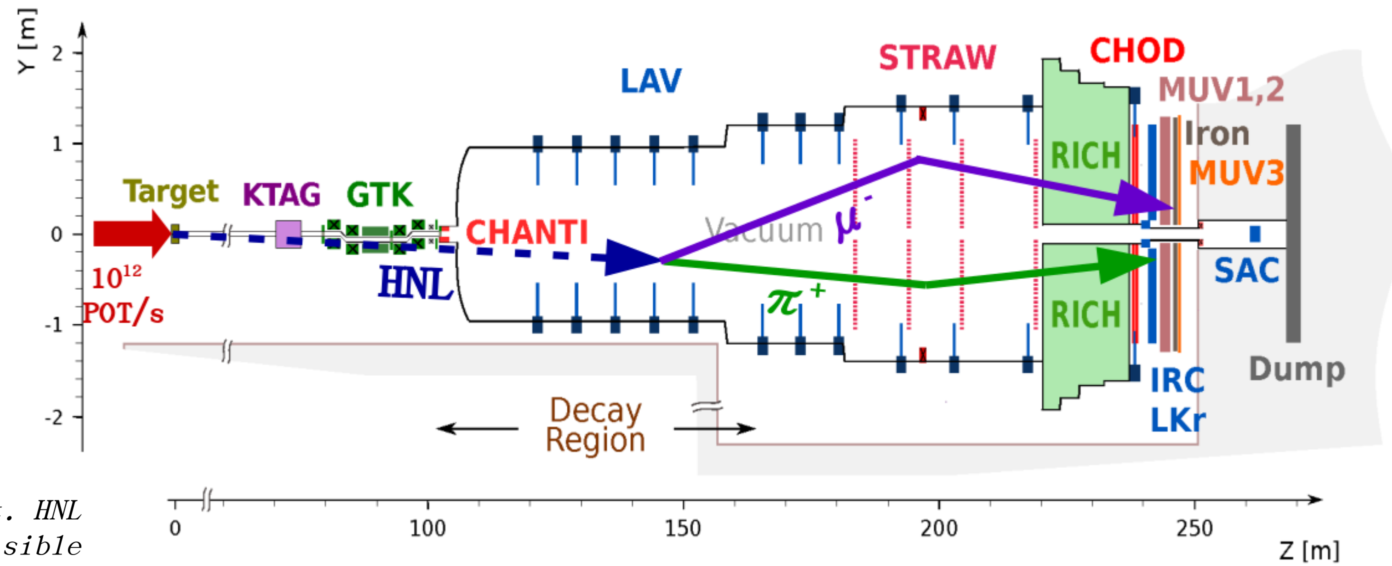
Past and future HNL searches (production and decay), at 90% CL exclusion limit



[Alekhin et al., Rept. Prog. Phys. 79 (2016) no.12, 124201]

HNL searches and prospects at NA62

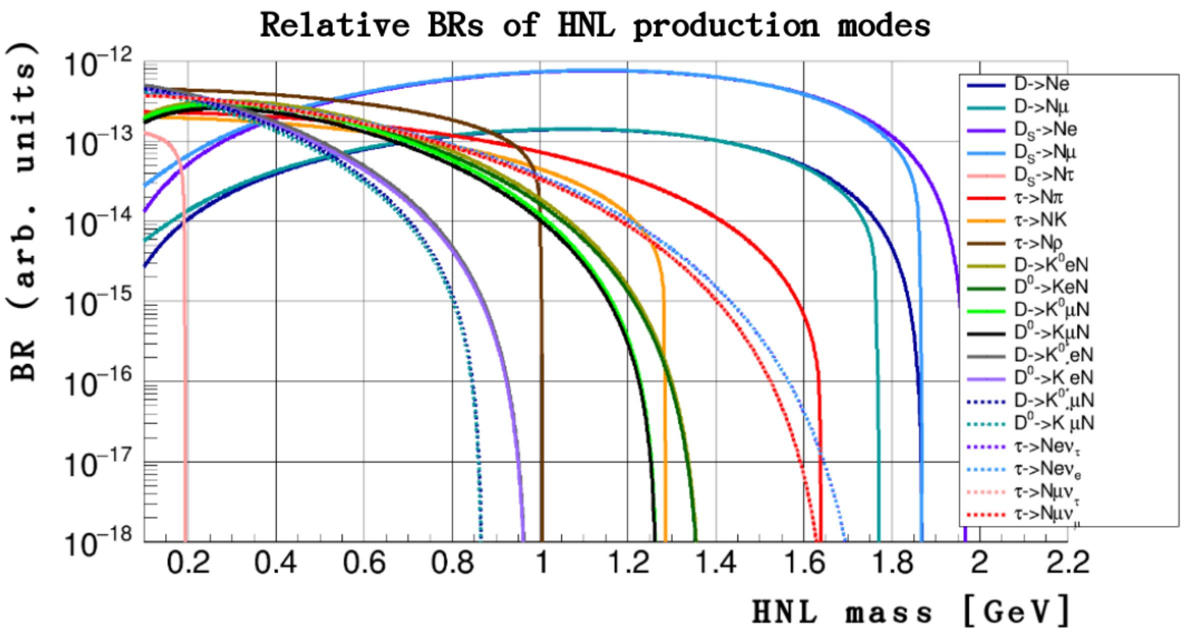
- First NA62 physics result on search for HNL production in $K^+ \to l^+ \nu_l$ decays *[Phys. Lett. B 778 (2018) 137-145] [see talk by V. Duk]*
- Sensitivity study in view of NA62 "beam-dump" mode (2021++)
- Study $p + Be \to D \to N \to \pi\,\mu$
- Dominant production/decay contribution → explore mass range (0.25, 1.9) GeV
- Signal signature:
  - Displaced 2-track vertex, mother trajectory pointing to target, 1 track in muon detector
- Set UL on U^2 in range $(10^{-9}, 10^{-5})$ as $f(m_N)$

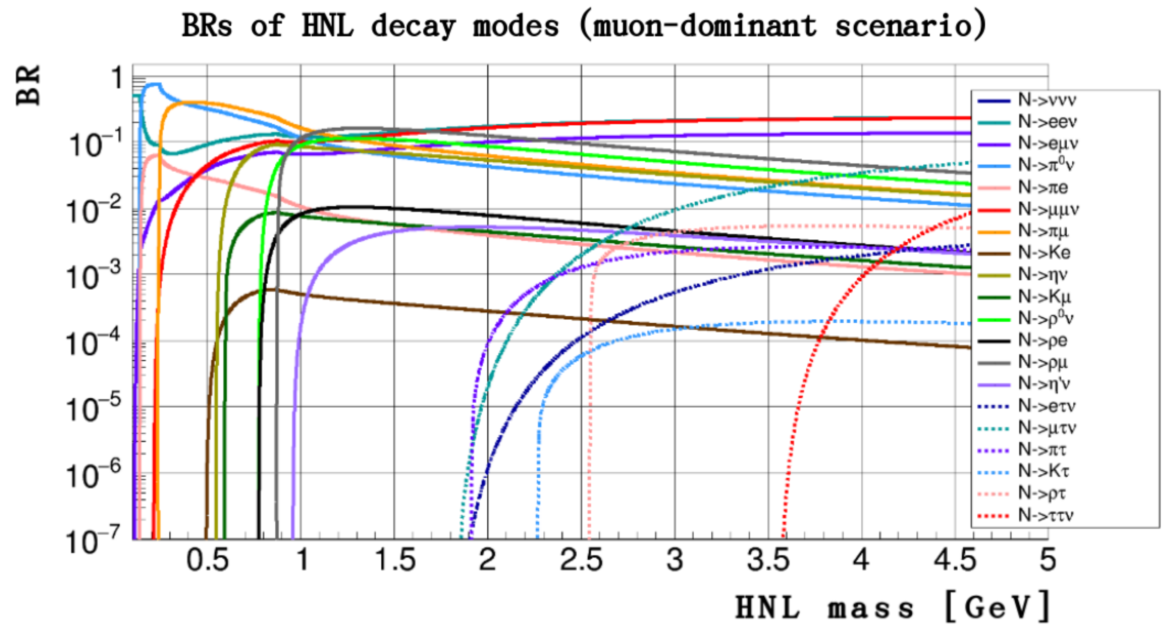


NA62 schematic layout. HNL signal topology is visible

HNL production and decay

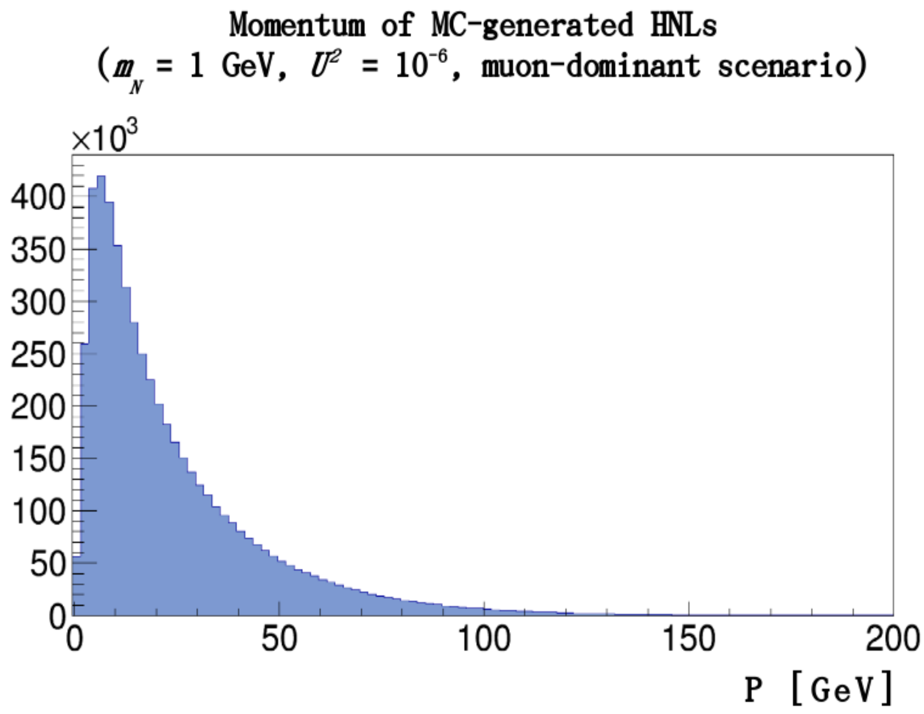
- Complete phenomenology study of HNL production and decay modes
- Fully integrated in NA62 MC
- Coupling-independent MC simulation allows to study scenarios and expected UL on U^2 as $f(m_N)$
- BRs shown depend on U^2 assumptions

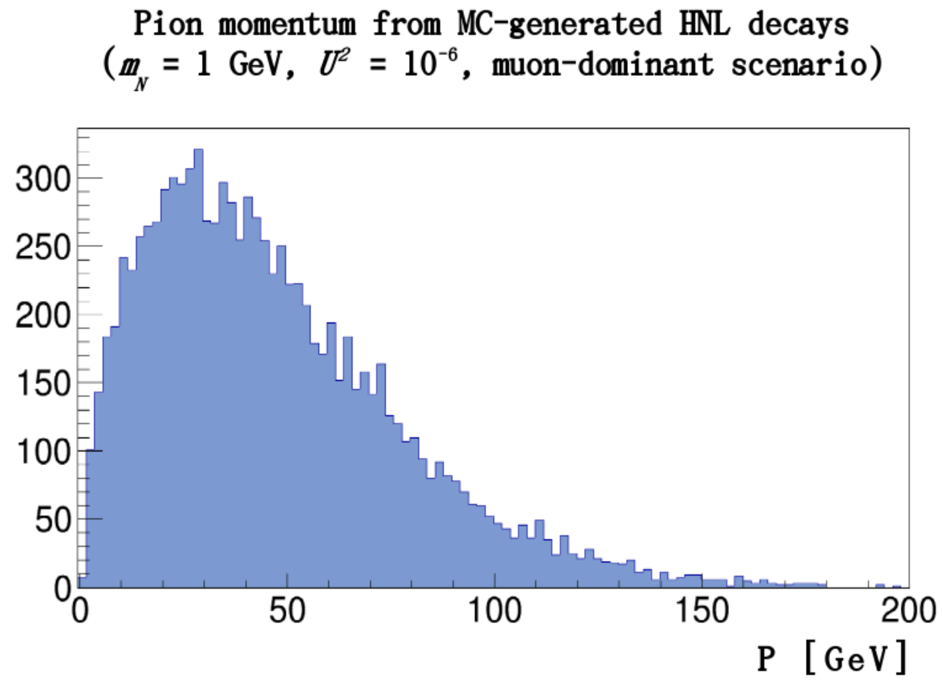




MonteCarlo simulation - I

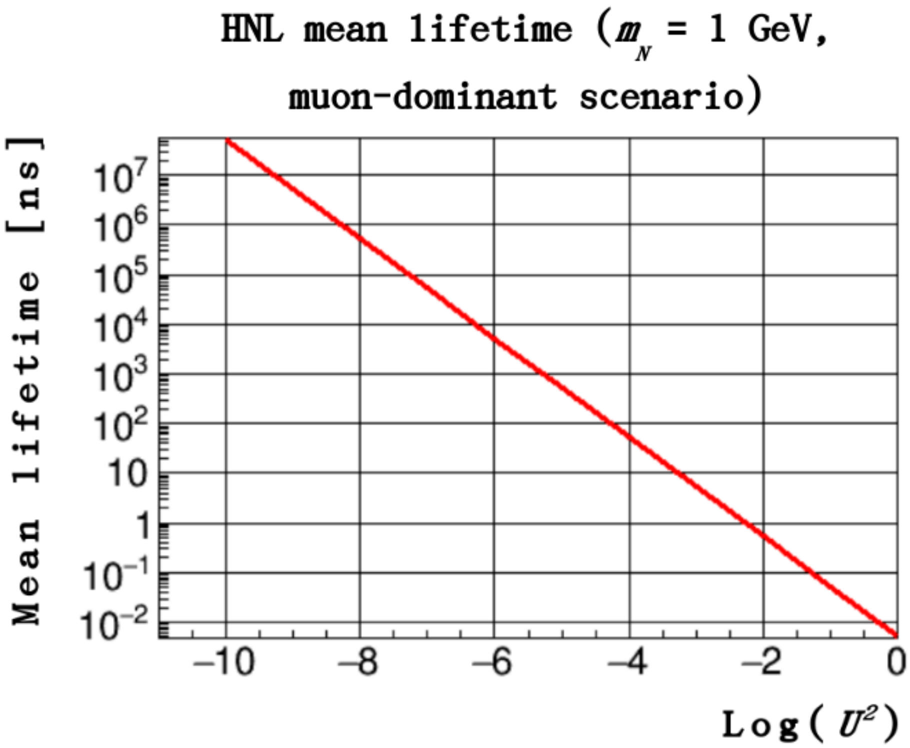
- Signal acceptance boosted through regeneration process:
  - If $\pi\mu$ final state not in charged hodoscope geometric acceptance → HNL regenerated from scratch, all HNL info stored for analysis purposes, $\pi\mu$ final state discarded
  - Regeneration proccess occurs about 10^3 times for each MC event

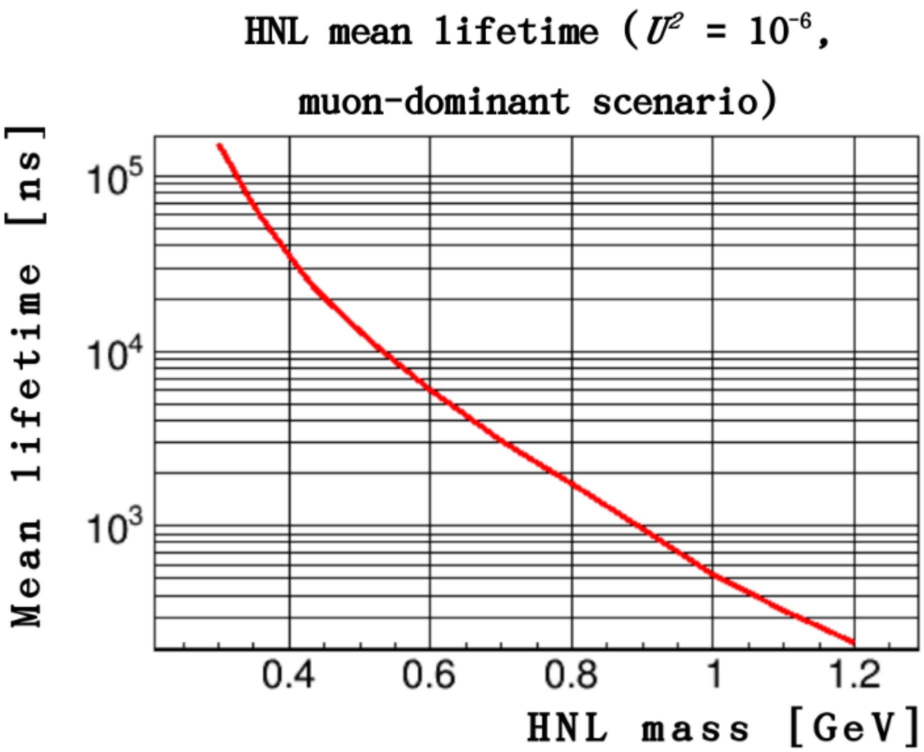




MonteCarlo simulation - II

- Probability for HNL to reach and decay in FV (ε)
    - m_N = 1 GeV $\rightarrow$ $\tau_{mean} \approx 10^{-6}$ s $\rightarrow$ $\tau_{lab} \approx 10^{-5}$ s $\rightarrow$ $\varepsilon \approx 10^{-2}$

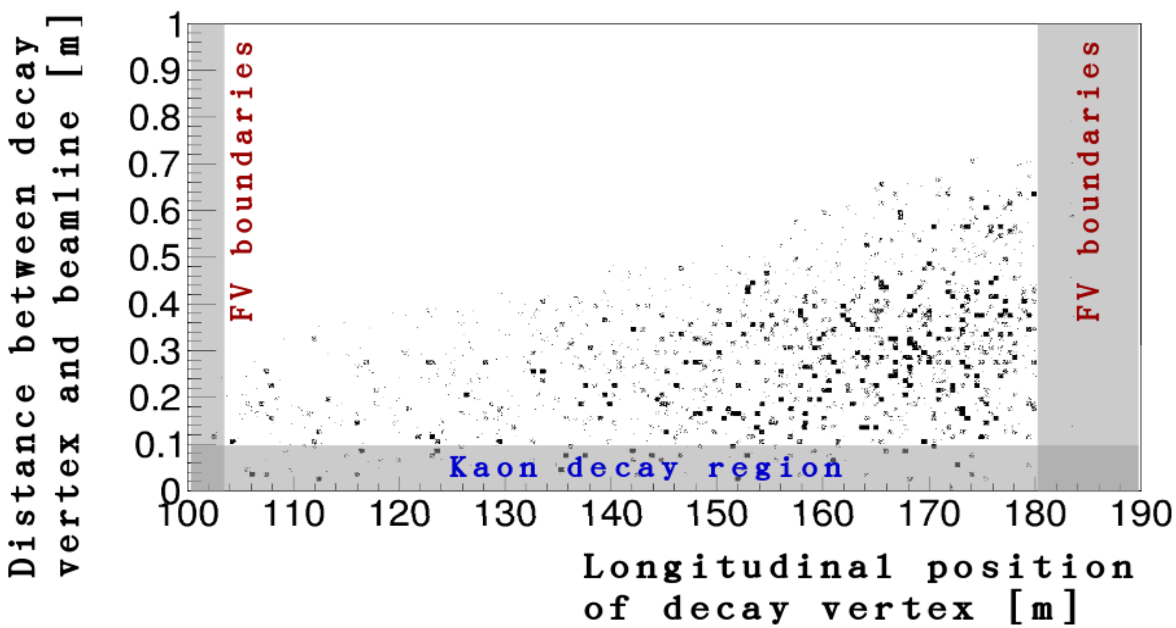




Analysis strategy - I

- Select $\pi\mu$ reconstructed final states in presence of K^+ beam:
  - 2-track events, geometric acceptance from tracker to muon detector
  - Opposite-charged tracks forming a decay vertex
  - Used closest distance of approach method (CDA < 1 cm)
  - Vertex in FV, displaced from K^+ beamline (> 10 cm)
  - Mother trajectory pointing back to target (remove combinatorial background)
  - Expect to keep background under control

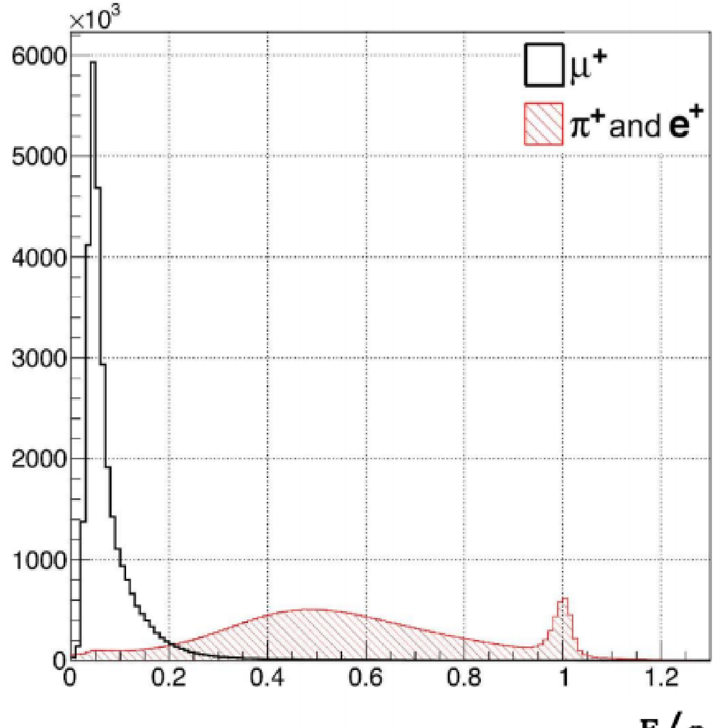
Reconstructed MC tracks (m_N = 1 GeV, U^2 = 10^{-6}, muon-dominant scenario)



Analysis strategy - II

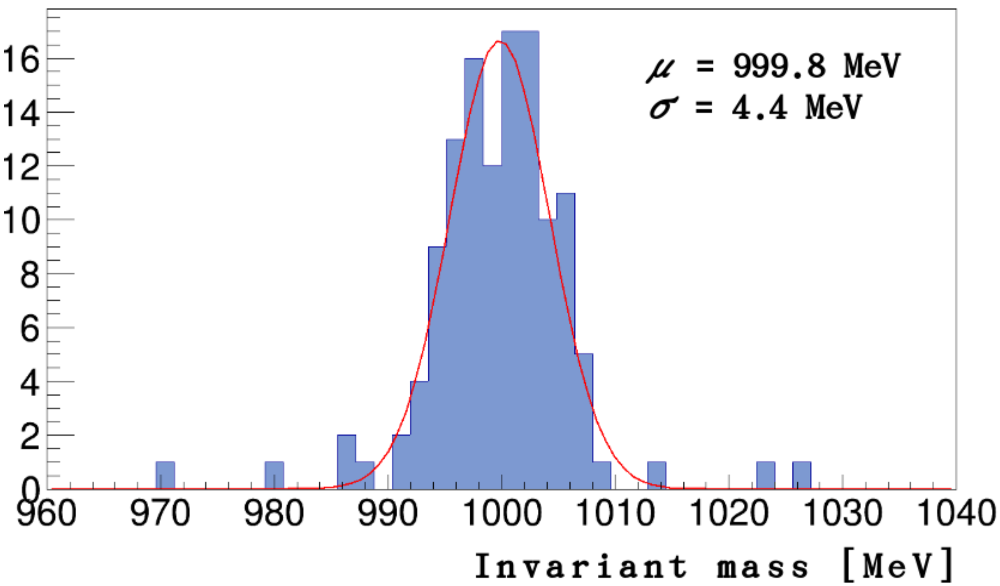
- Select $\pi\,\mu$ reconstructed final states in presence of K^+ beam:
  - Particle ID through E/p in EM calorimeter
  - 1 track associated to muon
  - No additional activity in photon/charged-particle veto detectors

E/p distribution for muons, pions and electrons in the NA62 electromagnetic calorimeter



[JINST 12 P05025 (2017)]

Reconstructed invariant mass for MC events (m_N = 1 GeV, U^2 = 10^{-6}, muon-dominant scenario)



Goals and expected sensitivity

- Goals:
  - Compute NA62 expected sensitivity to $N \rightarrow \pi\mu$ decays as $f(U^2, m_N)$
  - Set upper limits on U^2 as $f(m_N)$
  - Expected to be competitive with 10^{18} POT

- First results:
  - Leptonic, two-body D decays considered
  - m_N = 1 GeV and $U^2 = 10^{-6}$, muon-dominant scenario by Shaposhnikov
  - Assuming 10^{18} POT: **0.56 ± 0.12** expected signal events
  - Conservative: number of expected signal events 3-5 times higher when considering all HNL production modes and additional production in final collimator

Conclusions and further work

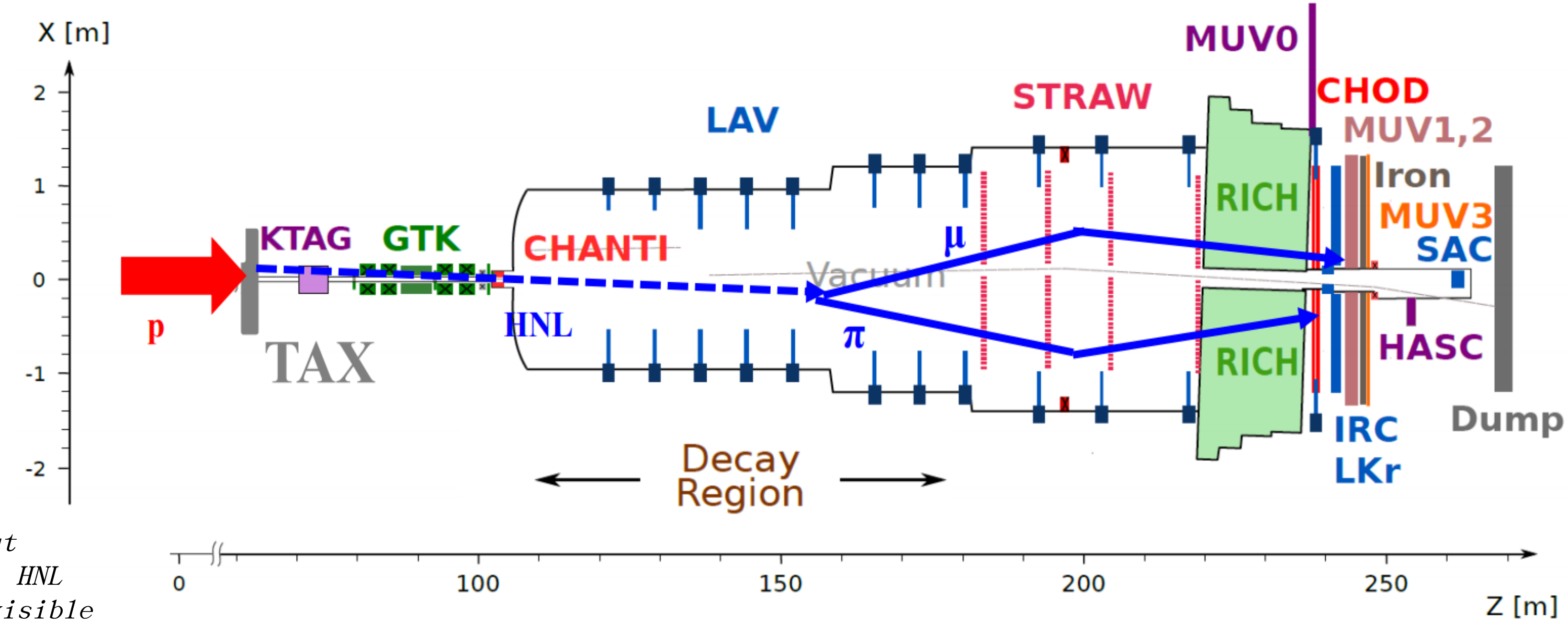
- Conclusions:
  - NA62 suited for hidden sector searches in presence of K^+ beam
  - HNL decay searches to $\pi\mu$ final states being performed in view of NA62 “beam-dump” mode (2021++)
  - Set upper limits on HNL coupling to SM leptons as function of HNL mass

- Further work:
  - Consider all HNL production modes
  - Thorough background studies to $N \rightarrow \pi\mu$ decays
  - Analysis of 2016-2018 data collected in presence of K^+ beam

Spares

NA62 in “beam-dump” mode

- Target can be moved away from beam
- Beam let impinging on Cu final collimator (TAXs), acting as dump
- HNLs, dark photons, and axions originated from D, B, γ produced in p interactions with dump
- Already in beam mode about 40% of p do not interact with target and are dumped onto TAXs

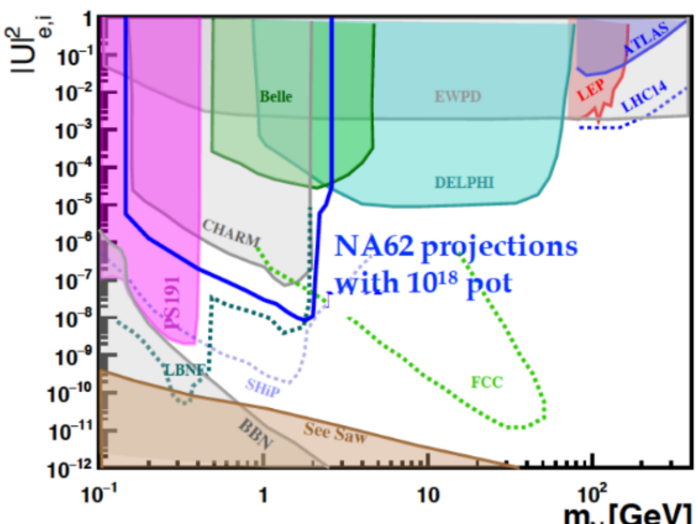


NA62 schematic layout in “beam-dump” mode. HNL signal topology is visible

Expected sensitivity in "beam-dump" mode

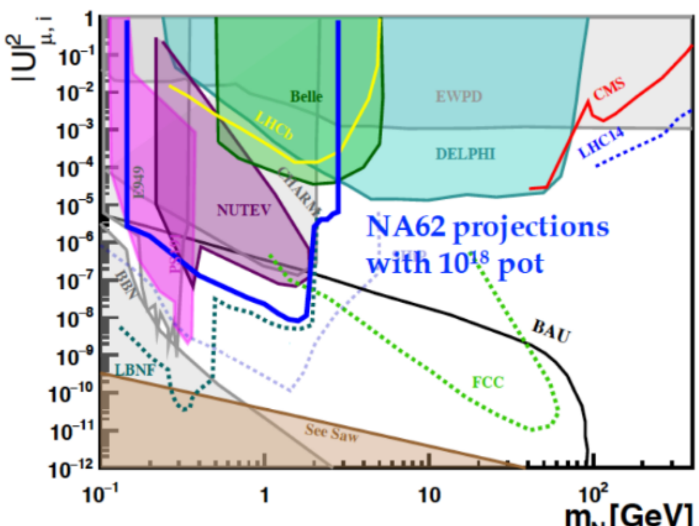
- Assuming 10^{18} POT
- Fully reconstructed 2-track final states
- All HNL decays, close and open channels
- Assume zero-background
- Evaluate expected 90% CL exclusion plots

Scenario 1



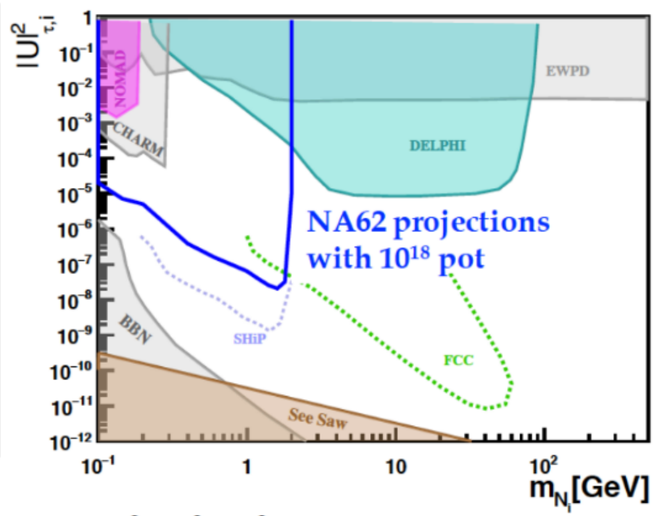
$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active **ν** masses

Scenario 2



$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active **ν** masses

Scenario 3



$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active **ν** masses