# Heavy Neutral Leptons Search in a Realistic Neutrino Oscillation Model at FCC-ee

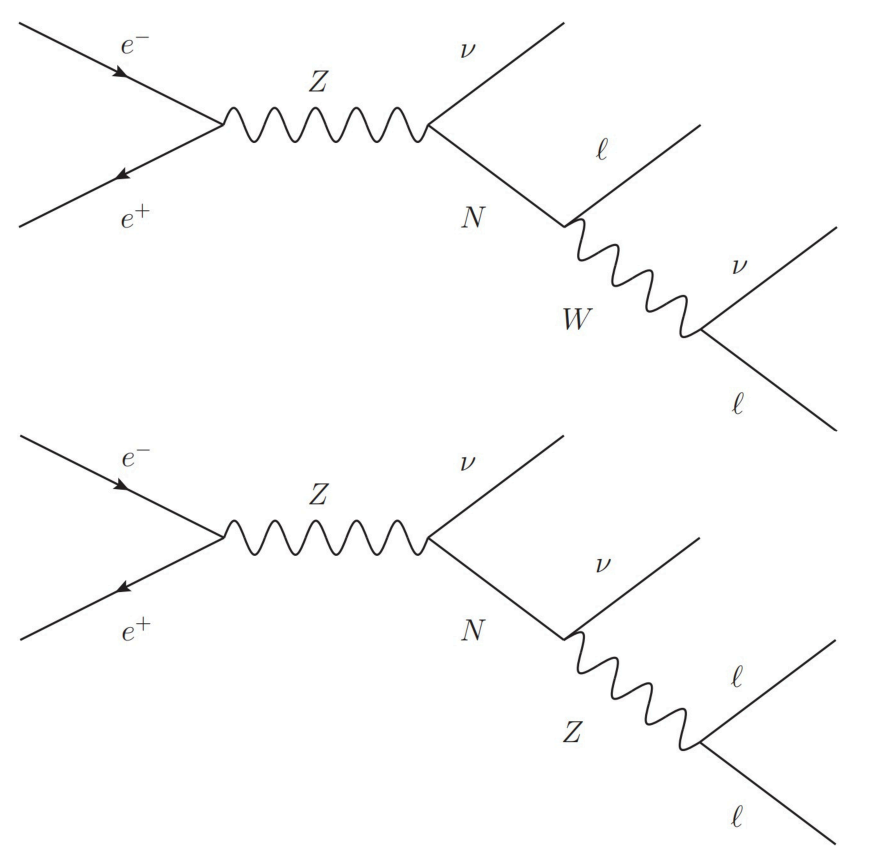
Sehar Ajmal (a), Patrizia Azzi (b), Sofia Giappichini (c), Orlando Panella (a), Matteo Presilla (c), Markus Klute (c), Xunwu Zuo (c)

## 1. Motivation

Introducing multiple sterile heavy neutrinos (also referred to as heavy neutral leptons, HNLs) to generate neutrino masses in the **type I see-saw mechanism** proposes a **realistic model** that can explain neutrino flavor oscillations and leads to the generation of the baryon asymmetry of the Universe through leptogenesis, besides proposing a suitable dark matter candidate [1]. The relevant Lagrangian is:

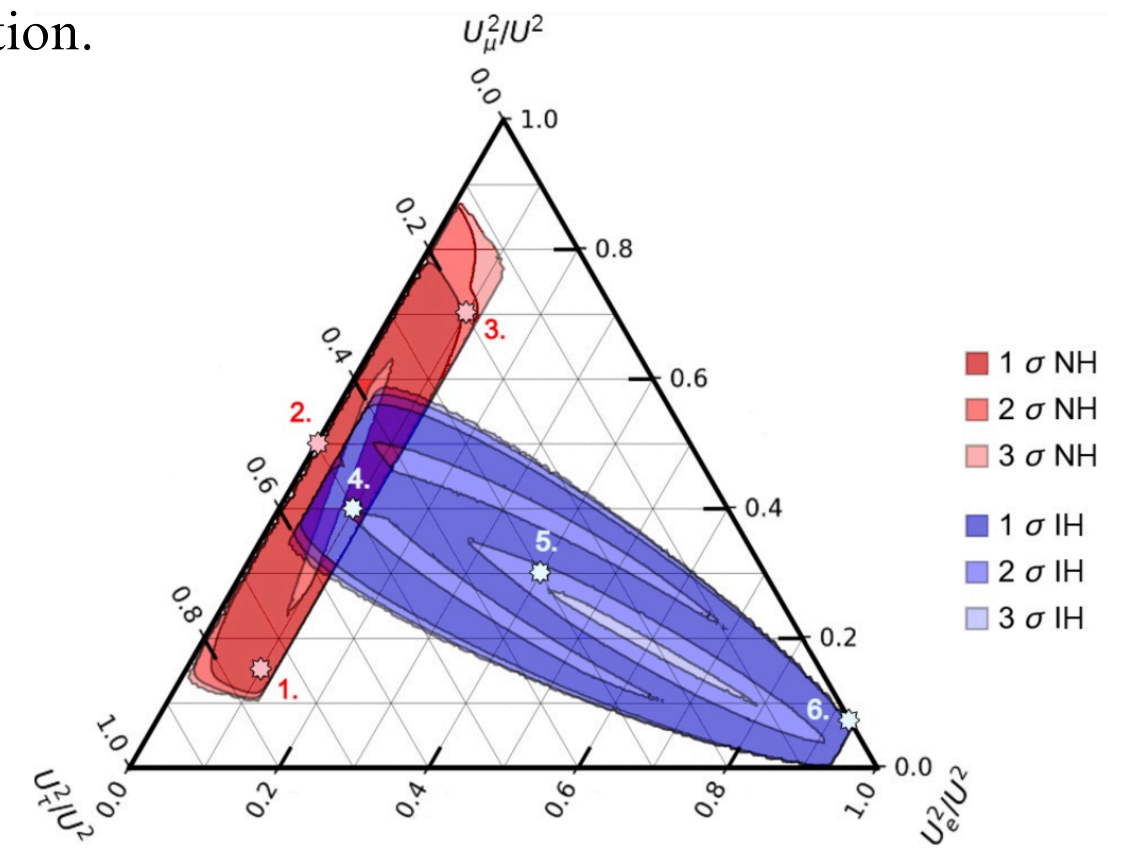
$$\mathcal{L}_{type\ I} = \frac{1}{2}\sum_{i=1}^{n}\bar{N}_i(i\partial\!\!\!/ - m_i)N_i - \frac{g_W}{\sqrt{2}}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau}\bar{N}_i U^*_{\ell i} W^+_\mu \gamma^\mu \ell^-_L - \frac{g_W}{2\cos\theta_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau}\bar{N}_i U^*_{\ell i} Z_\mu \gamma^\mu \nu_{L,\ell} - \frac{g_W H m_i}{2M_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau}\bar{N}_i U^*_{\ell i}\nu_{L,\ell} + H.c.$$

The search for HNLs in this work will be focused on the opportunities given by the $e^+e^-$ collider FCC-ee. We studied **two HNLs in the fully leptonic decay channel** (diagrams on the right) at $\sqrt{s}$=91 GeV, focusing only on the leptonic decays of tau. The visible final state is then given by two leptons (electrons or muons).



## 2. Simulation

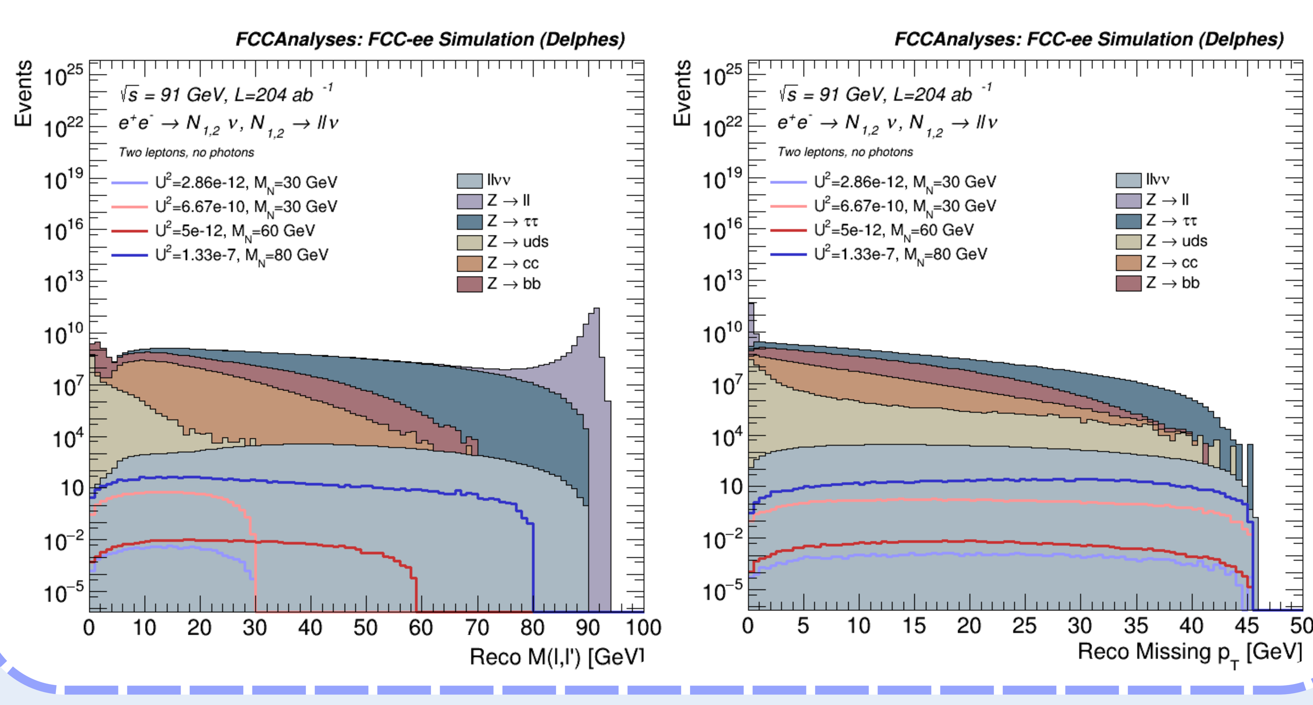
The HNL mixings are chosen to be compatible with neutrino oscillation data, see figure below. A scan on HNLs masses was performed, setting $\Delta M=10^{-5}$ GeV. This induces a symmetry in the model [2] that reduces the number of free parameters and maximizes the cross-section.




Simulation procedure:

- **MadGraph5_aMC** v. 3.5.3 integrated with the model HeavyN at Leading Order for the HNL samples
- **Pythia** 8.306 to shower the events
- **Delphes** v. 3.5.1pre05 for a fast simulation of the IDEA detector
- **FCCAnalyses** to analyze the output in EDM4Hep format

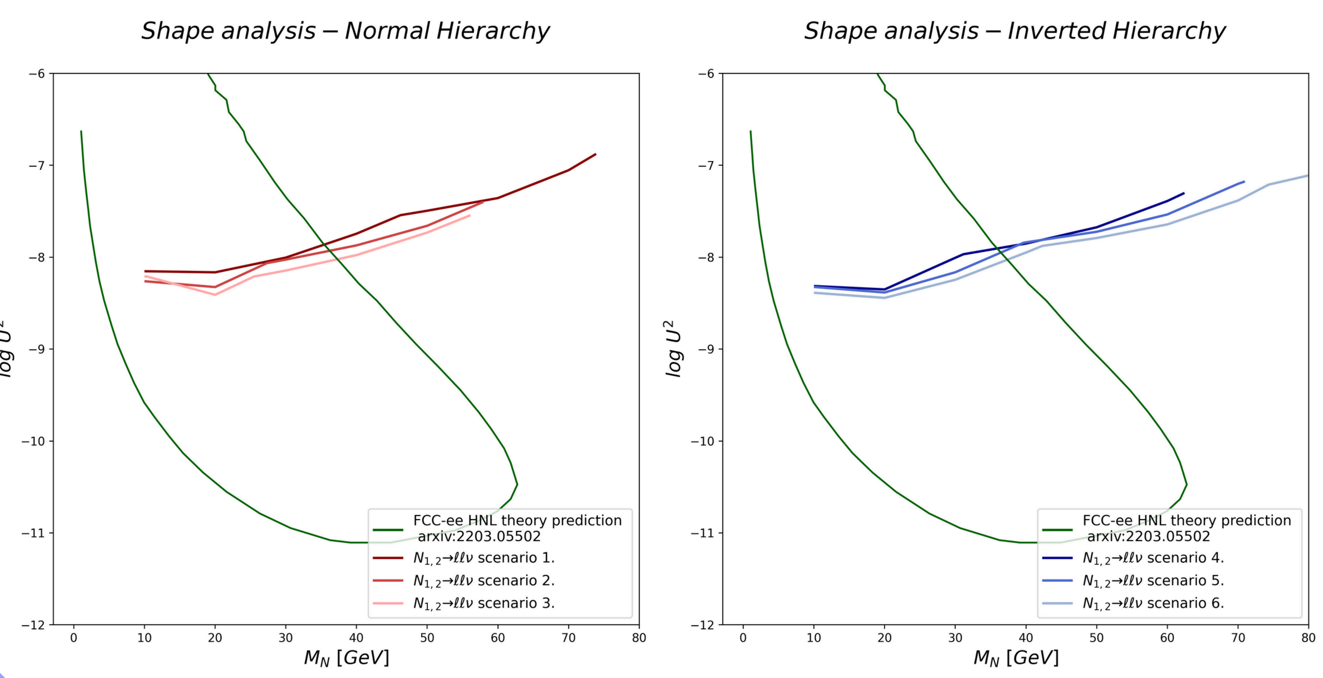
The data cards are the same as the official FCC-ee "Winter 2023" campaign from where we took our background events. All simulated events have been scaled to $\mathscr{L}$=204 ab$^{-1}$.




## 3. Shape analysis

The significance of HNL samples has been evaluated using the CMS tool **Combine** in a shape-based analysis on the distribution of the angular distance between the final state leptons, after applying the cuts listed in the table below.

| | |
|---|---|
| 1. Selection | Two leptons with opposite charges, no photons |
| 2. Reconstructed tracks | No other tracks |
| 3. Jets | No jets |
| 4. Invariant mass | $M(\ell,\ell') < 80$ GeV |
| 5. Missing transverse momentum | $\not{p}_T > 10$ GeV |
| 6. Cosine between the leptons | $\cos\theta > -0.8$ |




The systematical uncertainty on the cross-section has been taken into account for each process. Statistical uncertainties are handled automatically by the software using the technique Barlow-Beeston-lite [3].

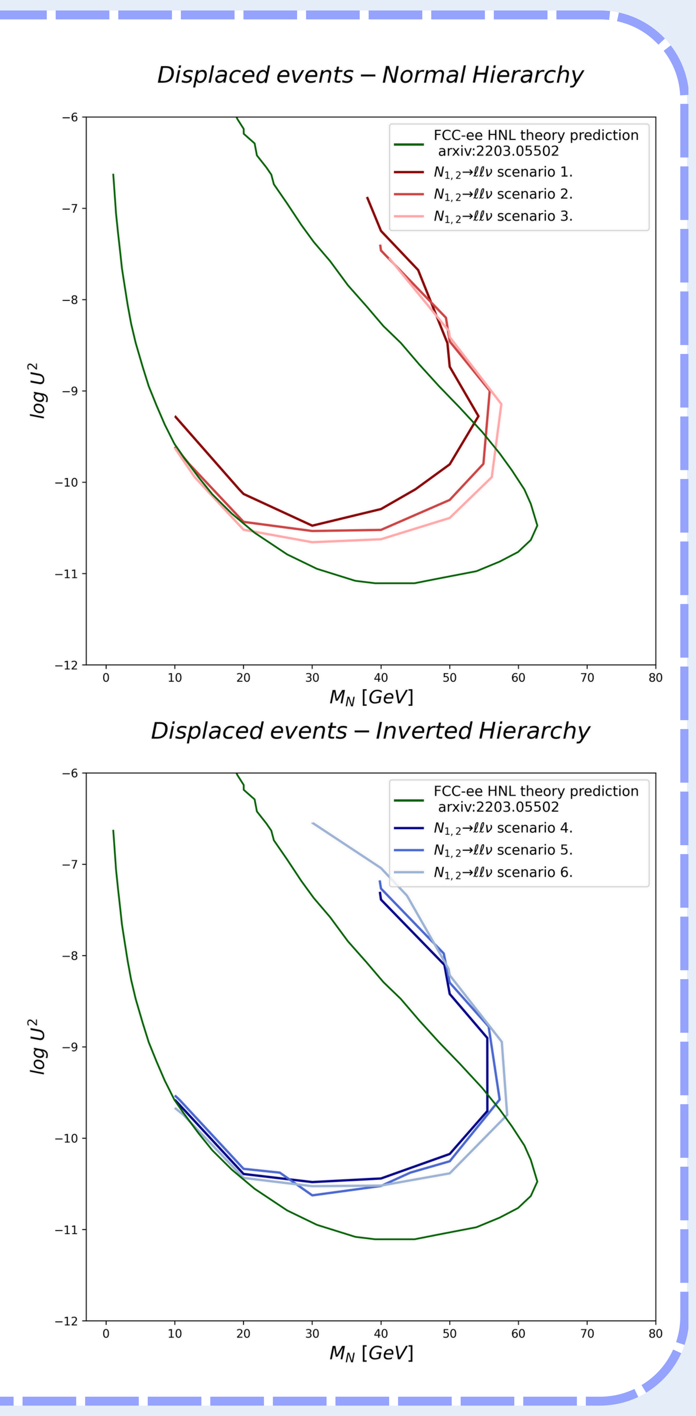
We found a region where HNL events could be distinguished from the background at σ=5. The plots on the left show this region for the different mixing assumptions.

## 4. Displaced HNLs

The reconstruction of the vertex from the two final state leptons corresponds to the HNL decay vertex and can then be directly used to differentiate between the prompt and displaced decays. Further cuts have been added to the previous ones to achieve a background-free scenario, see the table below.

| | |
|---|---|
| 7. Vertex $\chi^2$ | $\chi^2 < 10$ |
| 8. Tracker dimensions | $L_{xy} < 2000$ mm |
| | $\lvert z\rvert < 2000$ mm |
| 9. Lepton impact parameter | $\lvert d_0\rvert > 0.57$ mm |

The plots on the right correspond to 4 signal events, in the different mixing scenarios. FCC-ee will explore the region of parameter space where HNLs are long-lived particles and SM processes can be extremely suppressed.




(a) INFN Sezione di Perugia, Perugia, Italy
(b) INFN Sezione di Padova, Padova, Italy
(c) Institute for Experimental Particle Physics (ETP), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

[1] T. Asaka, S. Blanchet, and M. Shaposhnikov. "The nuMSM, dark matter and neutrino masses". In: Phys. Lett. B 631 (2005), pp. 151–156.
[2] K. Moffat, S. Pascoli, and C. Weiland. "Equivalence between massless neutrinos and lepton number conservation in fermionic singlet extensions of the Standard Model".
[3] R. J. Barlow and C. Beeston. "Fitting using finite Monte Carlo samples". In: Comput. Phys. Commun. 77 (1993), pp. 219–228.