

Exploring neutrino masses and dark matter at particle colliders

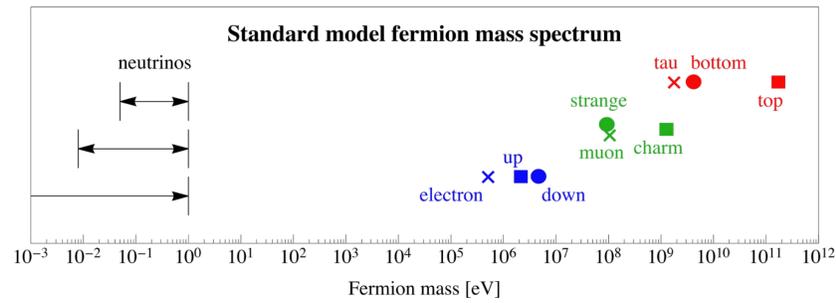
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On behalf of the ATLAS and the RD_FCC University of Pavia and INFN groups

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The discovery of **neutrino oscillations** proved that neutrinos have a non-zero mass, several orders of magnitude smaller than the mass of any other fundamental particle. One proposed model for motivating these small masses is the **Type-I see-saw mechanism**: for each light neutrino, a heavier "sterile" counterpart is introduced to the Standard Model, with a mass inversely proportional to the neutrino one. Neutrinos are described as **Majorana** particles.

In this model, new particles, the **heavy neutral leptons (HNLs)**, are introduced. They have zero electric and colour charges, and their weak interactions are heavily suppressed. They can be produced, and decay, through their mixings with neutrinos. With $N=3$ families of HNLs, a total of 18 new parameters have to be added to the Standard Model¹.

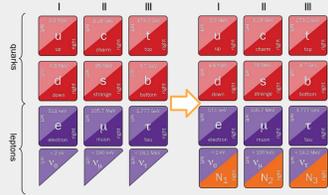


With an appropriate set of parameters (HNL masses, mixing angles with neutrinos), several currently open problems of particle physics might be solved:

- Neutrino masses
- Dark matter
- Matter/antimatter asymmetry

To address these problems, we need three HNLs:

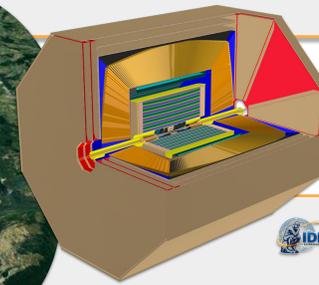
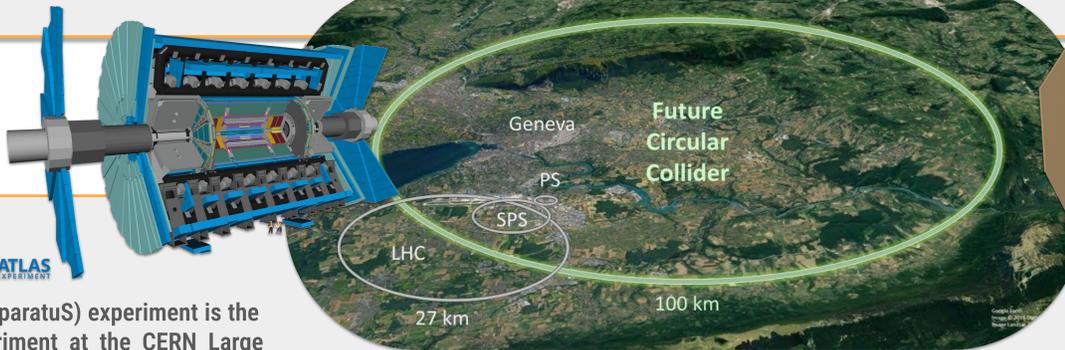
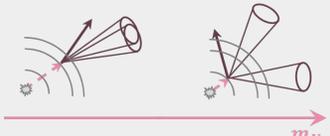
- N_1 - stable, DM candidate, $m_{N_1} \sim \mathcal{O}(\text{KeV})$
- $N_{2/3}$ - CP violations through oscillations, $m_{N_{2/3}} > \mathcal{O}(\text{GeV})$



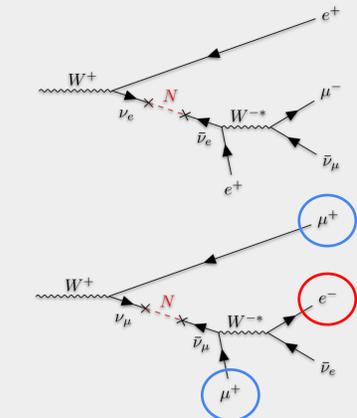
Broad phenomenology to be experimentally investigated:

The HNL mass, lifetime and mixing with neutrinos are related. For lighter HNLs, the lifetime increases and it travels for longer distances (**long-lived particle, LLP**). For heavier HNLs, the particle decays immediately after its production (**prompt decays**).

Being Majorana particles, HNL may violate the lepton number symmetry in up to 50% of its decay channels, giving rise to Lepton Number Conserving (LNC) or Violating (LNV) topologies.



The ATLAS (A Toroidal LHC ApparatuS) experiment is the largest general-purpose experiment at the CERN Large Hadron Collider (LHC)

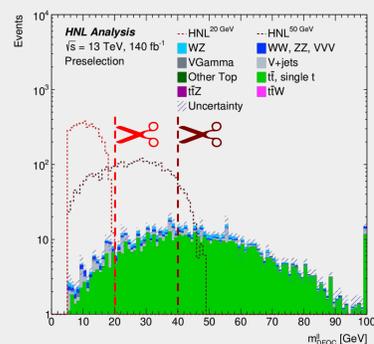


HNLs are searched through final states originated by decays of on-shell W bosons ($m_W = 80 \text{ GeV}$) into one charged lepton (electrons or muons) and one HNL. The HNL then decays promptly into two charged leptons and one escaping neutrino.

HNLs are searched in the mass range [8 - 65] GeV by exploiting LNV signatures, consisting of two Same-Flavour, Same Charge leptons, and a third Different Flavour, Opposite Charge lepton. This requirement allows to drastically reduce backgrounds arising from other Standard Model processes.

Given the specific final state targeted in this analysis, the largest sources of background are fake/non-prompt leptons from incorrect object reconstruction.

Remaining backgrounds are multiboson final states with decays to τ leptons.

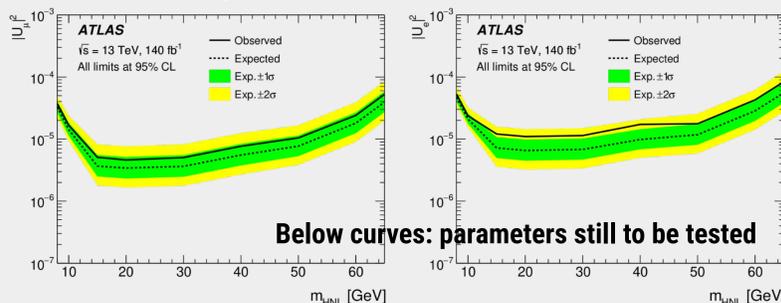


Dedicated Signal Regions (SRs) are built by applying cuts on kinematic and high-level variables. They are designed to maximise the statistical significance obtained from Monte Carlo simulations and data-driven estimates.

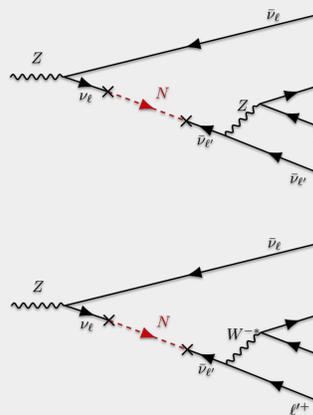
Largest deviation from predicted background of 1.7σ , for 40 GeV HNLs coupling to electron neutrinos².

Further investigation has started with the additional dataset of LHC Run 3 and more sophisticated ML tools.

Above curves: parameters excluded



Below curves: parameters still to be tested



The IDEA (Innovative Detector for Electron-positron Accelerators) is one of the experiments proposed at the FCC-ee, with INFN being the leading institute.

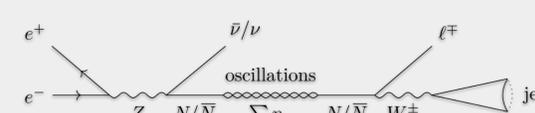
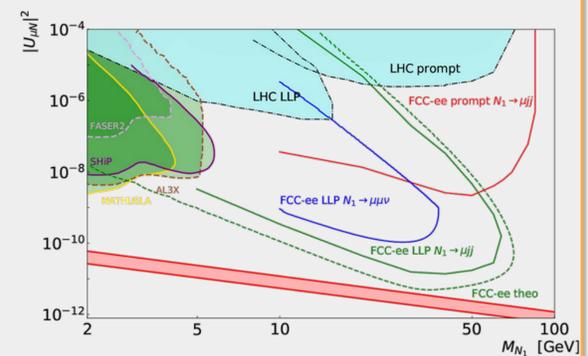
Very high luminosity and clean environment make searches for feebly interacting particles easier than at the LHC. At the "Z-pole" (centre-of-mass energy of 90 GeV), 6×10^{12} Z bosons will be produced.

HNLs are produced from decays of Z bosons in association with a neutrino. Two possible decays are considered, with **leptonic and semileptonic final states**.

Fast-simulations are used to parametrise the response of the IDEA detector and estimate the range of search sensitivity.

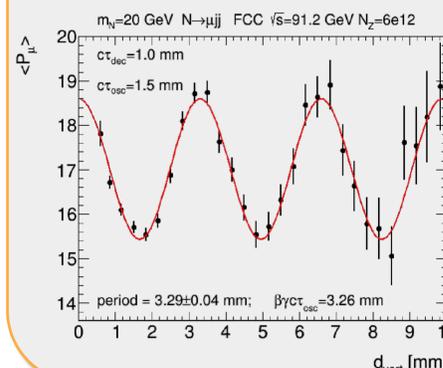
Prompt HNL decays: the excellent performances of the IDEA dual-readout calorimeter allow to define search regions for final states including jets.

Long-lived HNLs: requirement for displaced decay vertices rejects SM backgrounds, enhancing the sensitivity to extremely small mixings.



More specific HNL scenarios can be considered, with more than one active mixing between HNLs and neutrinos, and quasi-degenerate HNL masses⁴.

For small HNL mass differences, **oscillations between neutrino and antineutrino states** appear as the HNL travels inside the detector. The presence of oscillations correspond to LNV decays.



The nature of the recoiling neutrino is unknown; oscillations can be measured through dedicated variables dependent on the HNL and Z boson polarisations.

High precision on the HNL pair mass splitting is reachable in a portion of the accessible parameter space.

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[1] T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. B 631 (2005) 151
[2] ATLAS Collaboration, arXiv:2508.20929 (accepted by Eur. Phys. J. C)
[3] L. Bellagamba, G. Polesello & N. Valle, Eur. Phys. J. C(2025) 85:1069
[4] G. Polesello & N. Valle, Measuring the parameters of an HNL model at FCC-ee. CERN. <https://doi.org/10.17181/hd9nb-zmq24>

