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Searches for long-lived particles and Heavy Neutral Leptons: Theory perspective

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I briefly summarize on the theoretical motivations for having long-lived particle signatures from models predicting Heavy Neutral Leptons, making special emphasis on the associated (displaced) collider phenomenology at the Large Hadron Collider.

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1. Introduction

Long-lived particles (LLP) can travel macroscopic distances before decaying inside a detector. Depending on the detector capabilities, distances can range from order microns to several meters. There are generally theoretical arguments as to why one would expect LLPs in a theory: conserved or approximately conserved symmetries, small couplings between the LLP and lighter states, or heavy mediators which would lead to a suppressed phase space available for decays [1, 2]. Several examples can be found in our world. For instance, our Standard Model (SM) muon is long-lived due to a heavy propagator mediating its decay, the W boson. In ref. [2], theories beyond the SM with such properties were classified in five broad categories. One of the categories contains models with fermionic-portal mediators or Heavy Neutral Leptons (HNL), which are right-handed singlets.[1] Long-lived particles are predicted in HNL models and can be searched for at the *lifetime* frontier, which has become a transversal line of exploration for new physics within several experiments.

2. Theoretical motivations for Heavy Neutral Leptons as long-lived particles

Theoretical motivations to search for HNLs are aligned with as to why we look for new physics in general: the understanding of neutrino masses in the Standard Model [3], the baryon asymmetry [4] or the nature of dark matter [4–6]. The motivation I would like to address in this talk is neutrino masses. HNLs are predicted in several models that are able to explain why neutrinos in the SM have mass. We know neutrino oscillations happen and therefore, neutrinos must be massive [7]. The precise mechanism behind their mass, the HNL mass, their Dirac or Majorana nature are still unknown.

Neutrino masses can be explained by the seesaw mechanism [8–10], introducing the existence of massive HNLs. There is a mixing between the HNL, N, and the neutrinos in the SM, ν_l, with $l = e, \mu, \tau$. The relative size of the Majorana mass M_N and Dirac mass m_D (meaning in their eigenvalues), allows to distinguish different scenarios. In the so-called minimal type-I seesaw limit, where $M_N \gg m_D$, the mixing V_{lN}, is given by $V_{lN}^2 \approx \frac{m_\nu}{m_N}$, the ratio of the neutrino mass and the HNL mass $m_N \approx M_N$. In the case of inverse seesaw [11], an additional singlet with a μ mass term is added. Contrary to the minimal seesaw, where the smallness of the neutrino masses is related to a large mass scale, in the inverse seesaw it is linked to the smallness of μ. This can lead to HNL masses much closer to the electroweak scale. The mixing in this case is given by $V_{lN}^2 \approx \frac{m_\nu}{\mu}$, which is expected to be larger than in the case of the minimal type-I seesaw (as $\mu \ll M_N$). Such HNLs are automatically long-lived for small mixings.

As the relation between HNL masses and mixings depends on the specific seesaw model, a phenomenological approach is to consider m_N and V_{lN}^2 as independent parameters when studying HNLs as LLPs (see reviews in [12–14] for HNL phenomenology at colliders). In general, for small enough mixings and HNL masses in the GeV scale, HNLs will have macroscopic lifetimes as $\Gamma_N \propto G_F^2 m_N^5 V_{lN}^2$ [15]. HNL decays could happen inside inner tracker regions of main LHC detectors all the way to the muon systems and beyond (when considering detection prospects at far-detectors such as FASER [16] or MATHUSLA [1]). This makes it possible to discover them with dedicated displaced searches at the LHC.

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[1] They may also be called sterile or Heavy neutrinos in the literature.

3. HNL-LLP phenomenology at the LHC

In the minimal type-I seesaw, the dominant HNL production mode for masses below the W mass (and roughly above the B meson mass) is through W bosons, $pp \to W^{\pm} \to Nl^{\pm}$. The HNL can have a macroscopic lifetime due to an off-shell gauge boson mediating its decay to leptons and quarks. HNL decays can happen inside main LHC detectors. Several proposed strategies were developed in the past years, usually inspired by ongoing LHC-LLP searches not particularly designed for HNLs with masses of $O(10)$ GeV. These can be grouped as follows:

Displaced vertex searches: The HNL decays leptonically and/or semileptonically. Searches consider prompt lepton triggers (from the W decay). When decays are constrained within the inner trackers (IT), high-mass and displaced track multiplicity cuts are useful to suppress hadronic backgrounds [17–19]. When the HNL decays in the muon systems (MS), larger displacements can be accessed allowing to constrain lower HNL masses [18, 21].

Displaced lepton searches: The HNL decays leptonically. Searches consider prompt lepton triggers, and at least one displaced track from the HNL to be a non-isolated lepton. Can do an explicit vertex reconstruction of displaced di-muon/di-electron or $e\mu$ vertices in the IT or in the MS [18, 20]. No explicit vertex requirement leads to additional sources of SM backgrounds [22]. The ATLAS collaboration sets the first LHC limits on a long-lived HNL decaying in the IT when mixing to muon neutrinos, reaching mixings as low as $V_{\mu N}^2 \sim 10^{-6}$ for HNL masses in the range $\sim 4.5 - 15$ GeV [23].

Displaced lepton-jets searches: The HNL decays leptonically. A boosted HNL decay reconstructed as a single collimated displaced lepton-jet object, with more than one leptonic displaced track concentrated within a cone of certain radius [24, 25].

Beyond the minimal type-I seesaw, similar strategies were proposed in which one could have either 1 or 2 displaced vertices from HNL decays. For instance, in left-right symmetric models, where the long HNL lifetime comes from the off-shell decays of a right-handed W boson, can be probed with searches for displaced vertices [26, 27] or a displaced HNL jet [28]. Other models as $U(1)_{B-L}$ predicts long-lived HNLs produced in pairs from Higgs [29] or Z' decays [30–32]. These HNLs can be produced without prompt objects, highlighting the need of dedicated experimental displaced triggers at the LHC.

A systematic way to study such non-minimal models is to apply Effective Field Theory (EFT), with non-renormalizable operators suppressed by a new physics scale, Λ. For recent works on long-lived HNLs in EFT at the LHC, see refs. [33–35]. As an example, I would like to comment on ref. [35], where we considered HNL pair operators with quarks, up to dimension 6. In this case, the mixing is only important for the HNL decays, as HNL production is dominated by the effective operators. As a result, the sensitivity to the mixing grows substantially compared to the minimal type-I seesaw due the much enhanced production rates of the HNLs, reaching mixings squared of the order $O(10^{-20})$ or smaller, which are even below type-I seesaw expectations. Figure 1 shows the 95% CL exclusion limits for one single operator, $\mathcal{O}_{uN}$ with fixed coefficient $c_{uN}/\Lambda^2 = 1/(2\ \text{TeV})^2$, with displaced vertex searches under the assumption of zero background, for LHC current and future lifetime frontier experiments.

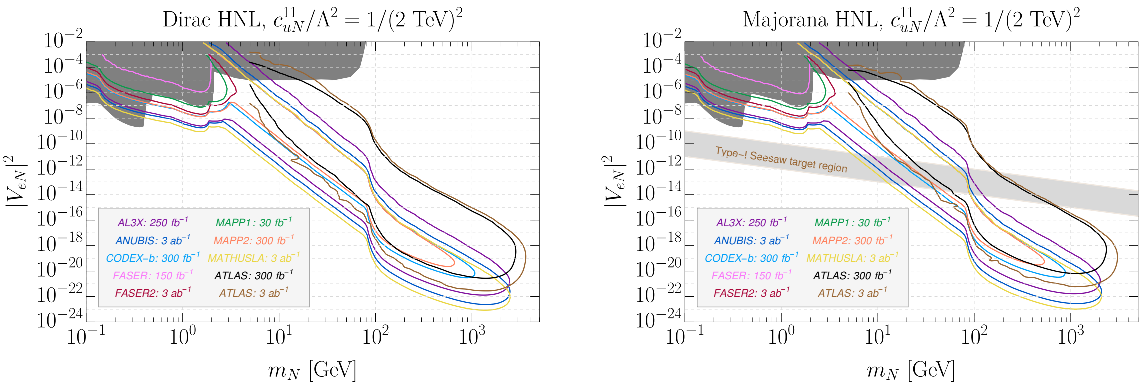

Figure 1: Experimental sensitivity reach for $|V_{eN}|^2$ as a function of HNL mass m_N. Limits obtained for Dirac (left) and Majorana (right) HNLs. Figure from ref. [35].

4. Summary

HNLs are predicted in (seesaw) mechanisms able to explain the origin of small neutrino masses in the SM, and they can be automatically long-lived particles. In the high-luminosity phase of the LHC, LHCb, ATLAS and CMS can extend existing limits for (or provide discovery of) HNLs using displaced searches. Dedicated far-detectors as AL3X, ANUBIS, CODEX-b, FASER, MATHUSLA, and MoEDAL-MAPP, can cover complementary regions in HNL mass and mixing space.

Experimental searches with different HNL decay signatures (i.e. $N \to ejj$, $N \to \tau jj$), are desirable to complement existing LHC analyses (as ref. [23], which considers mixing in the muon sector only for long-lived HNLs) for the minimal type-I seesaw and beyond. HNL production in non-minimal models can lead to enhanced cross-sections (which are not suppressed by the small mixing of the HNLs with the SM neutrinos) leading to a larger sensitivity reach at the high-luminosity-LHC. Several phenomenological works cited through this document demonstrate that displaced signatures at the LHC can provide a clear test of many theoretical scenarios for neutrino mass generation that predict long-lived HNLs.

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