Snowmass2021 - Letter of Interest

Opportunities and signatures of non-minimal Heavy Neutral Leptons

Thematic Areas:

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (CF1) Dark Matter: Particle-like
■ (TF8) BSM model building
■ (TF11) Theory of neutrino physics
■ (RF4) Baryon and Lepton Number Violating Processes
■ (RF6) Dark Sector Studies at High Intensities
■ (EF9) BSM: More general explorations

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Abstract: Heavy neutral leptons (HNLs) are one of the most motivated extensions of the Standard Model. Beyond providing a natural explanation to light neutrino masses, these states offer several new portals to dark sectors in non-minimal models. Their "dark" interactions can have important consequences for neutrino masses, the dark matter puzzle, and lead to several experimental signatures yet to be explored. Recently, non-minimal HNLs have been discussed in the context of the MiniBooNE and LSND anomalies as one of the few explanations that is not currently excluded by data. In this letter, we highlight the great discovery potential of such non-minimal HNLs at a variety of experimental facilities, including neutrino detectors, colliders, and kaon experiments.

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Introduction.– Heavy neutral leptons (HNL) constitute one of the most well-motivated particles to be added to the Standard Model (SM). Their existence can explain non-zero small neutrino masses via the Type-I seesaw mechanism[1–9] and its variants, and the origin of the baryon asymmetry of the universe via the leptogenesis mechanism. Two main approaches have been considered: a minimal one in which they are the only particles added to the SM, as in the νMSM[10;11], and one in which they are a key part of a broader extension. In the latter approach they can act as portal to a dark sector pointing to a new fundamental scale in Nature. An intriguing and generic possibility is that HNLs partake in "secret" or "dark" interactions, possibly as a result of hidden symmetries in Nature, allowing for new decay and production channels thanks to hidden mediators. If the new physics scale is low, from sub-eV up to the TeV scale, this inevitably leads to a variety of novel experimental signatures, typically involving fast decays and missing energy, and requires new dedicated search strategies.

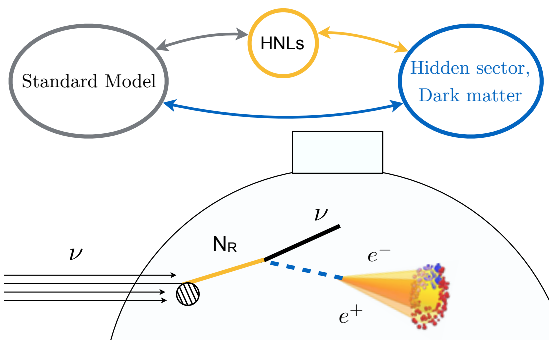

Figure 1: HNLs as a portal to hidden sectors and a potential new signature at MiniBooNE.

A richer structure of the dark sector, together with the presence of HNLs, could explain some of the observed low-energy anomalies present in particle physics. The LSND and MiniBooNE experiments observed significant excesses of electron-like events. These short-baseline (SBL) anomalies are some of the most significant deviations from the νSM, the SM with added massive neutrinos, and have evaded an explanation for decades. These anomalies have been studied mostly within the framework of eV sterile neutrinos[12–15], where the excesses are explained with of muon-to-electron-neutrino oscillations. However, as we would like to emphasize in this letter, the tension between these minimal models and the global neutrino oscillation data set is remedied in non-minimal scenarios. For instance, it is possible that these two experiments have observed two distinct phenomena, either entirely due to new physics, or with an admixture of SM backgrounds. In light of this, non-minimal HNLs have been put forward as a new solution in several proposals from the eV to MeV scale[16–25;25–33], which, depending on the specific mass scale and added interaction, are currently allowed.

Theoretical landscape.– Sterile neutrinos[34], fermions that are singlets of the SM gauge interactions, couple to the leptonic and Higgs doublets via Yukawa couplings and, unless lepton number is imposed as a conserved symmetry, have Majorana mass terms. After electroweak symmetry breaking, the massive nearly-sterile HNLs can participate in charged- and neutral-current interactions through mixing. Their mass scale is theoretically unconstrained and can range from eV-scale to the scale of grand unification. While the heaviest HNLs are easily incorporated in GUT theories, *e.g.* in $SO(10)$ models, naturalness arguments prefer a lower mass scale[35], though still not necessarily below the TeV scale.

Since HNLs are not charged under any SM symmetries, they could be seen as a natural portal to novel interactions and dark sectors. More than a generic possibility, the dark interactions can also help explain light neutrino masses[36–38], solve the dark matter puzzle[39–47], and even provide new mechanisms for baryogenesis, leptogenesis, and inflation[43;48;49]. Popular avenues that allow for modifications to the HNL interactions include the promotion of accidental SM symmetries to local gauge symmetries, such as $U(1)_{B-L}$ or $U(1)_{L_\mu - L_\tau}$ models; the addition of secluded $U(1)'$ symmetries in a dark sector; singlet or doublet scalar SM extensions; and large transition magnetic moments[17;23;50–53].

The scales at which these interactions have been invoked are varied, ranging from: eV steriles in oscillations[54;55], keV sterile neutrino dark matter candidates[56–59]), in the MeV to GeV scale under the lamppost of intensity frontier experiments[26;33;60], as well as in theories with enlarged electroweak sectors (e.g. two-Higgs-doublet models)[22;61]. In the latter case, one can probe the scalar sector at high-energy colliders, while simultaneously obtain a rich low-energy phenomenology. In all scales above, the new HNL interactions also play an important role in cosmology[62], where they may impact BBN, relax cosmological bounds on neutrino masses[63], or explain the Hubble tension[61]. In astrophysics, they could affect the evolution of supernovae and modify the high-energy neutrino spectrum[64–66].

Current hints of non-minimal HNLs.– The LSND experiment observed an excess of inverse-beta decay (IBD) events from a pion decay-at-rest source at a significance of 3.8σ[67]. IBD is a well-understood and low-background signature that allows the excess to be interpreted as a $\overline{\nu_e}$ observation. Later, MiniBooNE observed a 4.8σ excess of electron-like events[68–71], which, unlike LSND, can be induced by either electrons or photons[72–76]. When interpreted under the eV-sterile oscillation hypothesis, these two anomalies are consistent[14], but lead to strong tensions with muon-neutrino datasets; in particular MINOS/MINOS+[77;78], IceCube[79–81], MiniBooNE-SciBooNE[82], and CDHS[83]. Moreover, the minimal models are also disfavored by cosmological observations[84–90], unless their cosmological history is modified by secret interactions[54;91–100].

The difficulties with the sterile-neutrino oscillation explanation to the SBL anomalies begs one to go beyond this minimal paradigm. More complex models with neutrino upscattering into HNLs that decay to e^+e^- pairs, HNL decay-in-flight to visible or invisible ν, and new long-range neutrino forces have been proposed. In these setups, non-minimal HNLs have additional predictions that can be connected with other anomalies such as: the anomalous $(g-2)_\mu$ measurement[101]; other electron-like excesses in muon-neutrino beams in PS-191 at CERN[102] and E-816 at BNL[103]; and double vertex events at CCFR[104–107].

Opportunities.– Since the experimental landscape does not point to any one overarching solution, a broad search strategy must be pursued to discover such non-minimal HNL, be they solutions to the SBL anomalies, and to the long-standing mysteries of the origin of neutrino masses, dark matter and/or baryon asymmetry in the universe. Different scenarios can be tested with a variety of current and future neutrino experiments. More generically, a common feature of all the aforementioned cases is that the additional particles in the dark sector can also interact with the SM via portal couplings, and allow for novel production and decay channels for HNLs when compared to the minimal models.

Searches in the laboratory can be performed at very-large-volume neutrino detectors such as the IceCube Neutrino Observatory in the South Pole, which can search for non-minimal HNLs by either studying cascade distributions[108–111] or searching for displaced vertexes[112]. Liquid-argon detectors, such as μBooNE, SBND, and ICARUS[113;114], are expected to have unprecedented particle identification capabilities, and could differentiate between electron, photon, and e^+e^- signatures for the SBL. In general, near detectors of long-baseline experiments such as T2K[115], NOνA[116] and DUNE[117] can search for HNL-induced e^-e^+ pairs or photons[24], be it in scattering or via decay-in-flight searches[118]. Coherent neutrino-nucleus scattering is also sensitive to HNLs below the GeV scale[119–122]. Proton fixed-target experiments with high-energy beams (~ 100 GeV), including CHARM, NuCal, SeaQuest (and extensions DarkQuest/LongQuest), and in the future SHiP, can also probe these models[43;123–125]. More broadly, HNLs with visible decays via dark photon, dark scalar, or dipole interactions can be probed at other intensity frontier experiments like NA64[126] and LDMX[127], as well as B-factories like Belle-II[128], if these experiments adapt their searches to look for semi-visible final states. Kaon factories such as NA62[129] would also play a pivotal role in finding new visible or semi-visible resonances below the kaon mass[26].

At the energy frontier, the LHC is able to search for GeV scale HNLs. For instance, it can test the effects of transition magnetic moments and direct couplings to the Higgs generated via higher dimensional operators[130–134], as well as new gauged interactions[135–138], where in some models, the HNL decays could reveal the nature of neutrinos[139]. Recent efforts from collaboration-spanning working groups also aim at testing signatures connected to finite lifetimes[140]. HNL with masses on the TeV scale can be tested at all kinds of future colliders[141;142]. Finally, HNL scales of up to $10^8 - 10^9$ GeV could be tested with gravitational waves from the phase transition of a new symmetry[143].

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