Snowmass2021 - Letter of Interest

Physics Opportunities for detection and study of Heavy Neutral Leptons at Accelerator Neutrino Experiments

NF Topical Groups: (check all that apply ☐/■)

☐ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors

RF Topical Groups: (check all that apply ☐/■)

☐ (RF1) Weak decays of b and c quarks
☐ (RF2) Weak decays of strange and light quarks
☐ (RF3) Fundamental Physics in Small Experiments
☐ (RF4) Baryon and Lepton Number Violating Processes
☐ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
■ (RF6) Dark Sector Studies at High Intensities
☐ (RF7) Hadron Spectroscopy

Contact Information:
Athanasios Hatzikoutelis [athanasios.hatzikoutelis@sjsu.edu]

Authors:

Georgios Christodoulou[1], Pilar Coloma[2], Albert De Roeck[1], Enrique Fernandez-Martinez[2], Zahra Gh. Moghaddam[3], Manuel Gonzalez Lopez[2], Athanasios Hatzikoutelis[4], Josu Hernández-Garcia[5], Matheus Hostert[6], Kevin Kelly[7], Zarko Pavlovic[7], Silvia Pascoli[8], Haifa Rejeb Sfar[9], Alexander Sousa[10], Yu-Dai Tsai[7], Yun-Tse Tsai[11], Jaehoon Yu[12]

(1)CERN, CH-1211 Geneva 23 Switzerland, (2)Instituto de Fisica Teorica UAM/CSIC, Madrid, Spain, (3)Department of Physics University of Perugia and INFN Genova, Italy, (4)San Jose State University, San Jose, CA, USA, (5)Institute for Theoretical Physics, ELTE Eötvös Loránd University, H-1117 Budapest, Hungary, (6)University of Minnesota, USA, (7)Fermi National Accelerator Laboratory, Batavia, IL, USA, (8)Durham University, UK, (9)Universiteit Antwerpen, Antwerpen, Belgium, (10)University of Cincinnati, Cincinnati, Ohio, USA, (11)SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA, (12)University of Texas at Arlington, USA

Abstract: This Letter of Interest discusses the search for Heavy Neutral Leptons with future neutrino detectors. These detectors, either near detectors of long-baseline experiments or main detectors of short-baseline ones, are situated near intense proton beams and offer unique sensitivity to discover Heavy Neutral Leptons of many varieties.

Executive summary: We intend to study, in detail, the sensitivity for the search of Heavy Neutral Lepton (HNLs) with masses in the few hundred MeV to a few GeV range, with planned detectors for neutrino physics experiments, located within a few hundred meters of a proton beam target. Examples are the planned DUNE near detector, as well as the SBND and ICARUS experiments at the Short-Baseline Neutrino facility at Fermilab. Initial studies have demonstrated the huge potential of the DUNE Near Detector (DUNE-ND) complex for such a search. We plan for realistic detector studies for experimental set-ups like the ones above, including background, with up-to-date configuration of the detectors and with most recent plans for beam conditions and expected amount of protons on target (POT), using state-of-the-art tools for the simulation of production and decay of HNLs.

Introduction: As an example, in the νMSM scenario, HNLs are the almost-sterile, right-handed, partners of the active neutrino flavors[1]. This model aims to address, within one consistent framework, several of the present problems in the Standard Model (SM) such as the smallness of the neutrino masses and the baryon asymmetry observed in the Universe, see e.g. Ref.[2] for a recent review on this topic. The lightest HNL is also a potential dark matter candidate. HNLs *complete* the SM particle list by providing right-handed partners, which are singlets under the electroweak and strong interactions, to Standard Model left-handed neutrinos. Thanks to mixing with the SM neutrinos, they undergo a tiny fraction of weak interaction.

HNL searches: Over the last ten years, a new region of phase space of couplings and masses of HNLs is gaining interest. It is consistent with cosmological and astrophysical bounds, and is becoming accessible with the new generation of beam dump experiments at the Intensity Frontier. Next-generation neutrino experiments offer a broader search for HNL in this region of parameter space[3].

A prominent beam dump proposal is the SHiP experiment[4] at the CERN SPS, which, according to the originally proposed time plan, would be contemporary with DUNE and the Short-Baseline Neutrino detectors operations at FNAL. In the meantime, results from searches have been presented by the T2K[5] and MicroBooNE[6] collaborations, and are expected for NOvA and MiniBooNE. Discovering HNLs would be a true game changer in the field of particle physics.

The primary assumption in the planned studies is that HNLs are the lightest new particles in the hidden sector (which a priori could contain several new states) and these HNLs, couple very weakly to SM particles. We also plan to consider searches based on non-standard decays of HNLs e.g including decays through a dark Z'[7–9], dipole moments[10–13], or a $B - L$ gauge boson[14].

HNL production: We consider HNLs that originate from decays of mesons and leptons produced at the target, when hit by the proton beam. Mesons of any charge may produce HNLs with a mass in the range of 10 MeV to 2 GeV. The higher masses arise from decays of charmed $D_s^{\pm}$ mesons. The HNLs couple very weakly with the SM particles, and as a consequence, can have long lifetimes, allowing them to travel from the production target for several hundred meters, and decay inside the active fiducial volume of one of the detectors located at that distance. The boost in the beam direction is more important than it is for SM neutrinos, and can lead to an enhancement in the flux that reaches the detector[15;16].

The correct description of the helicity components in the beam is important for predicting the angular distributions of HNL decays, as they might depend on the initial helicity state. In fact, there is a different phenomenology for a Majorana or a Dirac fermion decaying HNL[17;18].

HNL Signatures and backgrounds: Typical decay channels are two-body decays into a charged lepton and a pseudo-scalar meson or a vector meson, if the mass allows it, two-body decays into mesons, and three-body leptonic decays are accessible as well.

The most characteristic experimental signature of an HNL is a decay-in-flight event with no interaction vertex (which is typical of neutrino–nucleon scattering), and a rather forward direction with respect to the beam. The dominant decay channels into visible final states, for HNLs in the low-mass region, typically are: HNL $\rightarrow e\pi, \nu e\mu, \nu ee, \nu\mu\mu, \nu\pi^0$, and $\mu\pi$. The most significant contributions to the sensitivity come from the $e\pi$ and the $\mu\pi$ channels. The mass range for HNLs up to 2 GeV can be explored in all flavor-mixing channels. Decay channels for masses above 500 MeV include channels containing heavier mesons and tau leptons (see, e.g., Table 1 in[18]).

The main background to this search comes from SM neutrino–nucleon scattering events in which the hadronic activity at the vertex is below threshold, see e.g.[18]. Charged-current quasi-elastic events with pion emission from resonances are background to the semi-leptonic decay channels. Moreover, mis-identification of long pion tracks as muons can constitute a background to three-body leptonic decays. Neutral pions are often emitted in neutrino scattering events and can be a challenging background for HNL decays that include a neutral meson or channels with electrons in the final state.

A liquid Argon detector system (like the ND-LAr or the SBN detectors) are most susceptible to background neutrino interactions, while the precision gas detector[15;19] of the DUNE-ND system is less vulnerable. SBN detectors are however closer to the production target and are operational sooner. Neutrino-nucleus background could be additionally suppressed using the fast timing of the detectors. To quantify these background levels, we intend to perform detailed simulation studies and estimate the impact on the detector requirements.

Tools for the HNL studies: We have developed a number of tools for the initial HNL sensitivity studies with the DUNE-ND detector as reported in[15;16;19]. These tools use the LBNF neutrino flux files, including kinematic corrections for the HNL masses, and use consistent expressions for all relevant effective operators involving mesons with masses up to 2 GeV.

Project for the Snowmass 2021: We propose to contribute to the Snowmass 2021 discussion with sensitivity studies for searches of decays-in-flight of HNL particles up a mass of 2 GeV. For example, for DUNE this study will be based on total of 6×10^{21} POT and 2×10^{22} POT, i.e., for a running scenario of 6 years with a 120 GeV proton beam of 1.2 MW, followed by 6 years of 2.4 MW and using both the neutrino and anti-neutrino mode configurations. For other experiments with discovery potential tools developed for the initial DUNE-ND studies can be used to explore sensitivity, based on specific detector capabilities. The studies will be performed coordinating with the ongoing HNL searches in SBN.

The project is based on the experience with a recent study, illustrating the potential sensitivity for HNL searches with the DUNE-ND[15;16;18;19], updated for the most recent LBNF neutrino flux predictions and including results for the anti-neutrino beam configuration. This shows that DUNE will have a superior sensitivity at small values of the mixing parameters compared to the presently available and planned experimental limits on mixing parameters of HNLs with the three lepton flavors. The ultimate sensitivity will be achieved only in about twenty years from now. Therefore, it remains useful to explore any SBN experimental capabilities which can be achieved within the next five years, like the combination of the NUMI-beam with the ICARUS detector.

For the DUNE-ND we will present sensitivities for the mixing parameters, with the electron and muon neutrino flavors, which can be as low as 10^{-9} to 10^{-10} in the mass range of 300 MeV to 500 MeV. It would be the first such search to reach down to mixing angles favored by the seesaw mechanism. In the region above 500 MeV the sensitivity will be reduced to 10^{-8} for eN mixing and 10^{-7} for μN mixing. The τN mixing sensitivity will be weaker but will still cover an unexplored regime.

Further, we intend to explore new directions as in the effect of off-axis detectors on signal and background for HNLs, or the sensitivity for using the T2K upgraded near detector, or scenarios that can include additional new exotic particles. If an HNL observation is made additional information can also be extracted from the measurements beyond the mass and couplings, e.g. the Majorana/Dirac nature.

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