Snowmass2021 - Letter of Interest

BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons

Primary Topical Group:
■ (EF07) Heavy Ions

Other relevant topical Groups:
■ (NF02) Sterile neutrinos
■ (NF03) BSM
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Introduction. The future Electron Ion Collider (EIC)[1] at Brookhaven National Laboratory, along with its primary capacity to elucidate nuclear structure, will offer new opportunities to probe physics beyond the Standard Model coupled to the electroweak sector. Among the best motivated examples of such new physics are new heavy neutral leptons (HNLs), which are likely play a key role in neutrino mass generation. In this Letter of Interest we highlight the capability of the EIC to search for HNLs.

The primary goals of the EIC physics program include the precise 3D tomographic imaging of partonic substructure, the determination of quark and gluon contributions to the proton spin, and the exploration of novel phases of nuclear matter at high densities. To achieve these ends, the EIC will collide polarized electrons with polarized protons and ions over a wide range of energies and with high luminosities (100-1000 times the accumulated luminosity of HERA). Furthermore, access to a broad range of the partonic momentum and its momentum transfer (x, Q^2) in the scattering processes will require a multipurpose hermetic detector with excellent tracking resolution and particle identification capabilities over a broad momentum range.

BSM studies at the EIC. The EIC will not only lead us to a new QCD frontier but will also have excellent prospects to study precision electroweak (EW) physics and to search for new physics phenomena associated with the EW sector. This exciting potential is a consequence of the high design luminosity, the relatively clean experimental environment inherent in eA collisions, and the multi-purpose hermetic detector design[2]. Indeed, there are a range of novel beyond the Standard Model (SM) physics processes for EIC to explore[3]. For example, the precision study of the the EW neutral current will lead to sensitive probes of SMEFT operators[4–6], which could arise from, e.g., new neutral gauge bosons. Furthermore, the intense incoming electron beam provides a good laboratory for searching for charged lepton-flavor transitions[7]. Given the substantial investment in the experiment, it is clearly of great interest to broadly explore the capabilities of the EIC to probe physics beyond the SM, and new ideas toward this end are warranted.

Heavy Neutral Leptons at the EIC. Here we discuss another class of new physics signatures at the EIC arising in models with new heavy neutral leptons (HNLs). HNLs are motivated by the need for new dynamics associated with neutrino masses, as in the Type-I Seesaw mechanism[8–13], and light HNLs near the weak scale may also play a role in the generation of the matter-antimatter asymmetry[14;15]. In the standard Type-I scenario, there exists a Majorana mass term and neutrinos are thus all Majorana. A smoking-gun signature would be lepton-number violation by two-units. The neutrinoless double-beta decay experiments have been the dedicated driver in the search lepton number violation for decades[16;17]. However, in some other scenarios, the heavy neutrino may be (quasi) Dirac without the observable effect of lepton-number violation[18–21]. Direct searches for HNLs can be carried out in both scenarios through studies of rare meson decays, fixed-target experiments, and collider searches[17;22;23]. The EIC can also contribute to the search for HNLs, and we set out to identify the experimental signatures, quantify the signal and backgrounds, and estimate the achievable sensitivities at EIC.

HNLs, denoted as N, couple to SM through the neutrino portal operator $L\,HN$, where H is the Higgs doublet and L is the SM lepton doublet. Following electroweak symmetry breaking, the HNLs will mix with the SM neutrinos. The physics of HNLs then largely follows from their induced couplings to electroweak bosons with interaction strengths governed by the mixing matrix U. Assuming for simplicity a single N state in the mass range of interest that dominantly mixes with electron-flavor neutrino, the EIC phenomenology is determined by two parameters, the HNL mass m_N and the single mixing angle $|U_e|$. We note that there are scenarios in which the mixing angles can be much larger than suggested by the naive Type-I seesaw relation[18–21], leading to significant HNL production at the EIC.

We consider a benchmark EIC run scenario with electron - proton collisions, $e(20\,\mathrm{GeV})+p(250\,\mathrm{GeV})$, corresponding to a center-of-mass energy $\sqrt{s}=140$ GeV, and an integrated luminosity of $\mathcal{L}=200$ fb^{-1} [1]. HNLs will be produced through the reaction $e+p\to N+X$. The production cross section scales as $|U_e|^2$ and is as large as ~ 30 pb (20 pb) for $|U_e|^2=1$ and $m_N\simeq 1$ GeV (10 GeV). This suggests the EIC will have sensitivity to squared mixing angles of order $|U_e|^2\sim 10^{-6}-10^{-4}$ if backgrounds can be brought under control (see below). Once produced in the primary ep collisions, the HNL will decay through the weak interactions to a variety of SM final states, many of which contain a charged lepton $\ell=e,\mu$. Furthermore, the HNL can naturally be long lived on account of small mixing angle and the heavy weak boson mass governing the decays, leading to the possibility of displaced signals at the EIC.

We consider two broad classes of search strategies that depend on the HNL lifetime: 1) prompt HNL decays, relevant for larger HNL masses and mixing angles, and 2) displaced HNL decays, relevant for smaller HNL masses and mixings. For the prompt HNL decays, we take into account the isolated charged leptons and jets as the primary search signatures. For the long lived HNL regime, a common strategy involves the search for a displaced vertex. Another option is to undertake a displaced lepton search – hard lepton having large transverse impact parameter. Both approaches are expected to have low or negligible SM backgrounds, particularly in the clean EIC environment. Preliminary investigations indicate these strategies will be able to probe mixing angles down to the level of $|U_e|^2\sim$ few $\times\,10^{-6}-10^{-3}$ for HNL masses in the 5 GeV - ~ 100 GeV range, extending beyond current experimental constraints from LEP by up to one order of magnitude for certain mass values.

Outlook. Our investigations indicate that the EIC will be able to make important contributions to the search for HNLs, with the capability to probe HNL masses in the few-100 GeV range for mixing angles that are currently unconstrained. The proposed searches we outlined should provide important input to the EIC detector design considerations, particularly in regards to the displaced searches. We note that our search strategies are generally applicable to other new physics searches involving final states of charged leptons and jets, along with displaced/long-lived particle decays, which are likely to provide general guidance for future considerations.

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