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Flavor and lepton number violation in effective interactions of heavy Majorana neutrinos: collider phenomenology

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Individual lepton flavors and the total lepton number are strictly conserved quantities in the standard model (SM). However, neutrino oscillations evidence lepton flavor violation in the neutral lepton sector, suggesting the need to consider SM extensions capable of accounting for massive light neutrinos and lepton mixing. The extensions considering sterile right-handed neutrinos, with Majorana mass terms, lead to Majorana massive states (being their own anti-particles) which predict the occurrence of total lepton number violation (LNV). In turn, the observation of LNV would be a clear signal of new physics, and of the existence of Majorana fermions. The effective field theory extending the standard model with right-handed neutrinos (νSMEFT) parameterizes new high-scale weakly coupled physics in a model independent manner. We consider massive Majorana neutrinos coupled to ordinary matter by dimension-6 effective operators, focusing on a simplified scenario with only one right-handed neutrino added, which provides us with a manageable parameter space to probe. Here we present the prospects of the future LHeC electron-proton collider to discover or constrain the νSMEFT interactions, with a realistic analysis of the well known lepton-trijet signals, both for the lepton flavor violating $p\, e^- \to \mu^- + 3\mathrm{j}$ (LFV) and the lepton number violating $p\, e^- \to \mu^+ + 3\mathrm{j}$ (LNV) channels, for HNLs masses in the electroweak scale range: $100~\mathrm{GeV} \leq \mathrm{m_N} \leq 500~\mathrm{GeV}$.

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Type	**Operator**		**Interactions**	**Coupling**
N mass $d=5$	$\mathcal{O}_{N\phi}^{d=5}$ ($\mathcal{O}_{\text{Higgs}}^{d=5}$)	$(\bar{N}N^c)(\phi^\dagger\phi)$	hNN and Majorana mass term	$\alpha_{N\phi}^{d=5}$
Dipole $d=5$	$\mathcal{O}_{NB}^{(5)}$	$(\bar{N}_a\sigma_{\mu\nu}N_b^c)B^{\mu\nu}$, $a\neq b$	Dipoles d_γ, d_Z	$\alpha_{NB}^{d=5}$
h-dressed mixing	$\mathcal{O}_{LN\phi}^{(i)}$ ($\mathcal{O}_{\text{LNH}}^{\beta}$)	$(\phi^\dagger\phi)(\bar{L}_iN\tilde{\phi})$	Yukawa+doublet ($U_{\ell N}$. and m_ν)	$\alpha_{LN\phi}^{(i)}$
Bosonic	$\mathcal{O}_{NN\phi}$ ($\mathcal{O}_{\text{HN}}$)	$i(\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\bar{N}\gamma^\mu N)$	Neutral current (NNZ)	$\alpha_{NN\phi}=\alpha_Z$
Currents	$\mathcal{O}_{Nl\phi}^{(i)}$ ($\mathcal{O}_{\text{HN}\ell}^{\beta}$)	$i(\phi^T\epsilon D_\mu\phi)(\bar{N}\gamma^\mu l_i)$	Charged current (NlW)	$\alpha_{Nl\phi}^{(i)}=\alpha_W^{(i)}$
Dipoles	$\mathcal{O}_{NB}^{(i)}$ ($\mathcal{O}_{\text{NB}}$)	$(\bar{L}_i\sigma^{\mu\nu}N)\tilde{\phi}B_{\mu\nu}$	One-loop level generated	$\alpha_{NB}^{(i)}$
	$\mathcal{O}_{NW}^{(i)}$ ($\mathcal{O}_{\text{NW}}^{\beta}$)	$(\bar{L}_i\sigma^{\mu\nu}\tau^I N)\tilde{\phi}W_{\mu\nu}^I$	d_γ, d_Z, d_W	$\alpha_{NW}^{(i)}$
4-fermion NC	$\mathcal{O}_{QNN}^{(i)}$ ($\mathcal{O}_{\text{QN}}$)	$(\bar{Q}_i\gamma^\mu Q_i)(\bar{N}\gamma_\mu N)$	4-femion	$\alpha_{QNN}^{(i)}$
	$\mathcal{O}_{LNN}^{(i,j)}$ ($\mathcal{O}_{\text{LN}}^{\beta}$)	$(\bar{L}_i\gamma^\mu L_j)(\bar{N}\gamma_\mu N)$	vector- mediated	$\alpha_{LNN}^{(i,j)}$
	$\mathcal{O}_{fNN}^{(i)}$ ($\mathcal{O}_{\text{ff}}$)	$(\bar{f}_i\gamma^\mu f_i)(\bar{N}\gamma_\mu N)$	$f=u,d,l$	$\alpha_{fNN}^{(i)}$
4-fermion CC	$\mathcal{O}_{duNl}^{(i,j)}$ ($\mathcal{O}_{\text{duN}\ell}^{\beta}$)	$(\bar{d}_j\gamma^\mu u_j)(\bar{N}\gamma_\mu l_i)$	4-fermion vector- mediated	$\alpha_{duNl}^{(i,j)}=\alpha_{V_0}^{(i,j)}$
4-fermion CC/NC	$\mathcal{O}_{QuNL}^{(i,j)}$ ($\mathcal{O}_{\text{QuNL}}^{\alpha}$)	$(\bar{Q}_iu_i)(\bar{N}L_j)$	4-fermion	$\alpha_{QuNL}^{(i,j)}=\alpha_{S_1}^{(i,j)}$
	$\mathcal{O}_{LNQd}^{(i,j)}$ ($\mathcal{O}_{\text{LNQd}}^{\alpha}$)	$(\bar{L}_iN)\epsilon(\bar{Q}_jd_j)$	scalar-mediated	$\alpha_{LNQd}^{(i,j)}=\alpha_{S_2}^{(i,j)}$
	$\mathcal{O}_{QNLd}^{(i,j)}$	$(\bar{Q}_iN)\epsilon(\bar{L}_jd_j)$		$\alpha_{QNLd}^{(i,j)}=\alpha_{S_3}^{(i,j)}$
	$\mathcal{O}_{LNLl}^{(i,j)}$ ($\mathcal{O}_{\text{LNL}\ell}^{\delta\beta}$)	$(\bar{L}_iN)\epsilon(\bar{L}_jl_j)$		$\alpha_{LNLl}^{(i,j)}=\alpha_{S_0}^{(i,j)}$

Table 1: Basis of $d=5$ and $d=6$ operators with a right-handed neutrino N [2, 5]. Here l_i, u_i, d_i and L_i, Q_i denote the right handed singlets and the left-handed $SU(2)$ doublets, respectively. The field ϕ is the scalar doublet, $B_{\mu\nu}$ and $W_{\mu\nu}^I$ are the $U(1)_Y$ and $SU(2)_L$ field strengths. Also $\sigma^{\mu\nu}=\frac{i}{2}[\gamma^\mu,\gamma^\nu]$ and $\epsilon=i\sigma^2$ is the anti symmetric symbol in two dimensions.

1. Neutrino SMEFT

The effective field theory extending the standard model with sterile right-handed neutrinos νSMEFT is the adequate tool for parameterizing new high-scale weakly coupled physics in a model independent manner, and allows for a systematic study of the HNLs phenomenology in current and future experiments [1–5]. We consider heavy Majorana neutrinos coupled to ordinary matter by dimension 6 effective operators in table 1, focusing on a simplified scenario with only one right-handed neutrino added. The total Lagrangian we consider is organized as follows:

$$\mathcal{L}=\mathcal{L}_{SM}+\sum_{d=5}^{\infty}\frac{1}{\Lambda^{d-4}}\sum_{\mathcal{J}}\alpha_{\mathcal{J}}\mathcal{O}_{\mathcal{J}}^{d} \tag{1}$$

where d is the mass dimension of the operator $\mathcal{O}_{\mathcal{J}}^{d}$, $\alpha_{\mathcal{J}}$ are the effective (Wilson) couplings, the new physics scale is Λ and the sum in $\mathcal{J}$ goes over all independent interactions at a given dimension d. In our simplified setup, we will not include the renormalizable $d=4$ Type I seesaw Lagrangian and thus neglect the heavy-active mixings $U_{\ell N}$ [2, 5]. The full expressions of the Lagrangian terms can be found in [6] and its implementation in `FeynRules 2.3` is discussed in [7].

For the studied processes the N production and decay into the muon-trijet final state can be driven by the bosonic charged current operator $\mathcal{O}_{Nl\phi}^{(i)}$, the four-fermion vector charged current $\mathcal{O}_{duNl}^{(i,j)}$, and the scalar operators $\mathcal{O}_{QuNL}^{(i,j)}$, $\mathcal{O}_{LNQd}^{(i,j)}$ and $\mathcal{O}_{QNLd}^{(i,j)}$. The charged current couples the W boson with right-handed chiral leptons: a $(V+A)$ structure as opposed to the $(V-A)$ SM charged weak interaction. We classify the four-fermion interactions in terms of the possible UV mediators connecting the fermion lines in the Lagrangian terms given by each operator. There are three types

Label	Process	$\sigma_{(LHeC)}\,[Pb]$
$B1$	$p\,e^- \to \mathrm{j}e^-(VV) \to \mathrm{j}e^-(\mathrm{jj}\mu^+\mu^-)$	$1,049\times10^{-4}$
$B2$	$p\,e^- \to \mathrm{j}e^-(VV) \to \mathrm{j}e^-(\mathrm{jj}\mu^-\overline{\nu_\mu})$	$1,795\times10^{-3}$
$B3$	$p\,e^- \to \mathrm{j}\nu_e(VV) \to \mathrm{j}\nu_e(\mathrm{jj}\mu^+\mu^-)$	$7,072\times10^{-5}$
$B4$	$p\,e^- \to \mathrm{j}\nu_e(VV) \to \mathrm{j}\nu_e(\mathrm{jj}\mu^-\overline{\nu_\mu})$	$5,359\times10^{-4}$
$B5$	$p\,e^- \to \mathrm{j}e^-(VV) \to \mathrm{j}e^-(\mathrm{jj}\mu^+\nu_\mu)$	$1,868\times10^{-3}$
$B6$	$p\,e^- \to \mathrm{j}\nu_e(VV) \to \mathrm{j}\nu_e(\mathrm{jj}\mu^+\nu_\mu)$	$2,441\times10^{-4}$

Table 2: Background processes considered for $p\,e^- \to \mu^\pm + 3\mathrm{j}$.

of vector-mediated neutral currents involving two N fields, one vector-mediated charged current, and the last four-fermion operators in table 1 induce Lagrangian terms that can be obtained from an UV completion where the fermion lines are mediated by neutral or charged scalars.

As the N is a Majorana particle, these interactions allow it to decay into muons or anti-muons and quarks, besides being produced from the electron in the collider beam, if we also allow for the flavor indices of the charged leptons to be different in the production and decay vertices. Here we assume that the quark flavors for each four-fermion operator belong to the same family, as indicated in table 1.

2. LFV and LNV at the LHeC

We study the prospects of the future LHeC electron-proton collider, with 1.3 TeV center-of mass energy and an integrated luminosity of 100 fb^{-1} [8] to discover or constrain the νSMEFT interactions, performing a dedicated and realistic analysis of the well known lepton-trijet signals, both for the lepton flavor violating $p\ e^- \to \mu^- + 3\mathrm{j}$ (LFV) and the lepton number violating $p\ e^- \to \mu^+ + 3\mathrm{j}$ (LNV) channels [6].

In our numerical simulations we give the value of the total N decay-width [9, 10] calculated considering all the effective operators couplings equal to the same value α for each mass $\Gamma_N(m_N, \alpha)$ as input for the MC events generation in `MadGraph` for every signal benchmark point. The details of the simulation and analysis are given in [6].

Despite of both LNV and LFV processes being irreducible SM background-free, we take into account the possible backgrounds in table 2 due to charge misidentification and final states with extra unobserved light neutrinos, performing a dedicated simulation and analysis at the reconstructed level, testing the performance of a multivariate analysis with a boosted decision tree (BDT) algorithm using the `TMVA` package . We use many high level observables obtained from the information of the final reconstructed objects as input for the `TMVA` analysis to classify signal and background events. The discriminating power of the BDT relies on the fact that the signal and the background are characterized by different features that can be entangled.

The obtained 95% CLs exclusion limits in the $m_N - \alpha$ plane are presented in figure 1. For each signal point we calculate the upper number of signal events s^{up} consistent at 95% CLs with the observation of the expected number of background events. The shaded areas (lower mass, higher couplings) correspond to the parameter regions where the interpolated expected number of signal events exceeds the upper allowed value s^{up}. As the number of events classified as background after the BDT cut changes from one signal benchmark point to another, we show the curves corresponding

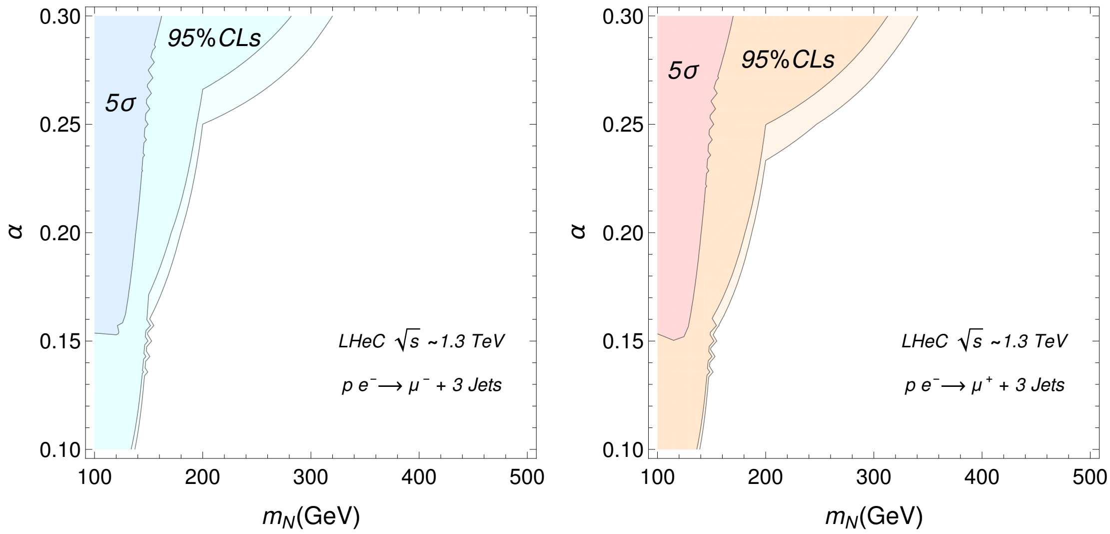

Figure 1: 5σ-Discovery and 95% CLs limits, for the muon-trijet (left) and anti-muon-trijet (right) channels at the LHeC (Taking $\Lambda = 1$ TeV).

to the greatest (and lowest) upper number of signal events s^{up} for each channel. The region between this two curves is displayed in a lighter color in the plots in figure 1. The lower mass and higher coupling ($m_N < 175$ GeV, $\alpha > 0.15$) regions in the parameter space could be separated with 5σ significance from the expected backgrounds for both the LFV and LNV channels, meaning the LHeC would be able to discover this lepton-trijet signals after collecting 100 fb^{-1} of data.

The heavy Majorana neutrinos could also be produced in leptonic and semileptonic decays of B mesons, a theoretically clean system to probe new physics effects in lepton colliders and B factories. In past works we have exploited known bounds on B meson decays to derive constraints on the effective parameter space of order-GeV HNLs masses, proposing the use of angular observables to disentangle the contributions of different effective operators [11, 12].

3. Concluding remarks

The results presented show that the LHeC could constrain the effective couplings (mostly those of the muon family) to a region of the parameter space as tight as the bounds that are currently considered for the sub-electroweak scale masses (see Refs. [13–15]). Our results demonstrate that the LHeC is also an excellent facility for discovering heavy Majorana neutrinos around the electroweak scale, even in the limit of the νSMEFT where one discards their mixing with the active neutrino states. The LNV and LFV lepton-trijet signatures could be "golden channels" for HNLs searches.

A discovery of heavy neutrinos would have far-reaching consequences, but also constraining the possible new physics involved in neutrino mass generation can be a path to resolve the origin of the observed neutrino masses, which is one of the most challenging open questions in particle physics.

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