

Heavy Majorana Neutrinos in the Effective Lagrangian Description: Application to Hadron Colliders

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Abstract

We consider the effects of heavy Majorana neutrinos N with sub-TeV masses. We argue that the mere presence of these particles would be a signal of physics beyond the minimal seesaw mechanism and their interactions are, therefore, best described using an effective Lagrangian. We then consider the complete set of leading effective operators (up to dimension 6) involving the N and Standard Model fields and show that these interactions can be relatively easy to track at high-energy colliders. For example, we find that an exchange of a TeV-scale heavy vector field can yield thousands of characteristic same-sign lepton number violating $\ell^+\ell^+jj$ events ($j = \text{light jet}$) at the LHC if $m_N \lesssim 600$ GeV, which can also have a distinctive forward-backward asymmetry signal; even the Tevatron has good prospects for this signature if $m_N \lesssim 300$ GeV.

The spectacular discovery in the past decade of neutrino oscillation and its interpretation in terms of a non-vanishing neutrino mass matrix is one of the most important recent discoveries in particle physics. The $m_\nu \gtrsim O(10^{-2})$ eV neutrino masses that appear in this scenario are difficult to generate naturally in the Standard Model (SM) using the Yukawa interactions; the sub-eV mass

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scale then suggests the presence of new physics (NP) beyond the SM. One attractive framework for generating light neutrino masses naturally is the so-called seesaw mechanism, which requires the presence of one or more heavy right-handed neutrino species N_a with interactions of the form

$$\mathcal{L}_{\nu SM} \equiv \mathcal{L}_{SM} + \left(\frac{1}{2} \bar{N}_a M_{ab} N_b^c - \bar{L}_i \tilde{\phi} Y_{ia} N_a + \text{H.c.} \right), \quad (1)$$

where L denotes the left-handed SU(2) lepton doublet, ϕ the SM scalar isodoublet, Y the Yukawa coupling matrix, and M the Majorana mass matrix. If the structure of M does not allow for a conserved fermion number then the heavy neutrinos are of Majorana type and they exhibit characteristic lepton number violation (LNV) effects that have very distinctive observable signatures.

In this case, the light neutrino mass matrix is

$$m_\nu = -m_D M^{-1} m_D^T, \quad m_D = Y \langle \phi \rangle = Y \frac{v}{\sqrt{2}}. \quad (2)$$

so that $m_\nu \sim 0.01$ eV if, for example, $M \sim 100$ GeV and $m_D \sim m_{\text{electron}}/10$ or if $M \sim 10^{15}$ GeV and $m_D \sim m_W$. The second choice, which seems to be favored by naturalness (since then $Y \sim O(1)$), clearly leads to the decoupling of the N . In fact, even if $M \sim 100$ GeV, such that Y is fine-tuned to the level $\sim 10^{-7}$, we expect N to decouple since (2) necessarily leads to a vanishingly small $N - \nu_L$ mixing, $U_{\ell N} \sim \sqrt{m_\nu/M} \sim 10^{-7}$, and this parameter governs all interactions of N with the SM particles, e.g., the V-A $\ell N W$ vertex [1]:

$$\mathcal{L}_{V-A}^W = -\frac{g}{\sqrt{8}} U_{\ell N} \bar{N}^c \gamma^\mu (1 - \gamma_5) \ell W_\mu^+ + \text{H.c.} \quad (3)$$

Thus, any LNV signal of an EW-scale N would unambiguously indicate the existence of NP beyond the minimal seesaw framework encoded in $\mathcal{L}_{\nu SM}$; the study of heavy Majorana neutrino physics is then of central importance for our understanding of the short distance dynamics underlying EW physics.

In this letter we will thus consider N interactions and phenomenology in the Majorana scenario when M is relatively light, $M \lesssim O(1)$ TeV, and its mixing with ν_L negligible. Our primary purpose here is to present a natural, model-independent formalism that allows a broader and a more reliable view of the expected physics of heavy TeV-scale Majorana neutrinos, and lays the ground for further investigations of N -mediated LNV phenomenology at high-energy colliders. We will give a complete set of leading effective operators (up to dimension 6) involving the N and SM fields and then, as an illustration, use it to demonstrate some aspects of N -phenomenology at present or near future high-energy colliders, such as the Tevatron and the LHC. Our approach departs from the traditional viewpoint (see, e.g. [1, 2, 3, 4, 5]), where the couplings in (3) (and the associated $\nu N Z$ and $\nu N H^0$ interactions) was assumed to determine the rate of N -mediated LNV signals and to satisfy $U_{\ell N} \lesssim O(0.1)$, i.e., many orders of magnitude larger than the value $\sim O(10^{-7})$ derived from the seesaw mechanism (2). Although there are models that can accommodate this scenario [6], they usually rely on fine tuning or on an extended spectrum, as it is difficult to meet these conditions otherwise.

The effects of the NP underlying $\mathcal{L}_{\nu SM}$ can be parameterized by a series of effective operators \mathcal{O}_i constructed using the νSM fields and whose coefficients are suppressed by inverse powers of the NP scale Λ ,

$$\mathcal{L} = \mathcal{L}_{\nu SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i \alpha_i \mathcal{O}_i^{(n)}, \quad (4)$$

where n is the mass dimension of $\mathcal{O}_i^{(n)}$ (we assume decoupling and weakly coupled heavy physics, so n equals the canonical dimension). Dominating NP effects are generated by contributing operators with the lowest n value that can be generated at tree level. The complete list of baryon and lepton number conserving effective operators of dimension below 6 involving only SM fields are listed in [7]; some LNV operators constructed with SM fields are listed in [8]. Those involving also N are listed below.

There are two tree-level-generated (TLG) dimension 5 operators involving the neutrinos, $(\bar{L}\tilde{\phi})(\phi^\dagger L^c)$ first presented in [9], and a new one: $(\bar{N}N^c)(\phi^\dagger\phi)$. Both these terms violate lepton number; the effects of the second one on the reactions studied below can be absorbed in a renormalization of the Majorana mass M . The dimension 6 TLG operators can be sub-divided into those involving scalars and vectors (we will use e, u, d and L, Q to denote the right-handed SU(2) singlets and left-handed SU(2) doublets, respectively):

$$\mathcal{O}_{LN\phi} = (\phi^\dagger\phi)(\bar{L}N\tilde{\phi}), \quad \mathcal{O}_{NN\phi} = i(\phi^\dagger D_\mu\phi)(\bar{N}\gamma^\mu N), \quad \mathcal{O}_{Ne\phi} = i(\phi^T \varepsilon D_\mu\phi)(\bar{N}\gamma^\mu e), \quad (5)$$

and 4-fermion contact terms that either conserve baryon-number (here $f = u, d, Q, N, e$ or L):

$$\begin{aligned} \mathcal{O}_{duNe} &= (\bar{d}\gamma^\mu u)(\bar{N}\gamma^\mu e), & \mathcal{O}_{fNN} &= (\bar{f}\gamma_\mu f)(\bar{N}\gamma^\mu N), \\ \mathcal{O}_{LNLe} &= (\bar{L}N)\varepsilon(\bar{L}e), & \mathcal{O}_{LNQd} &= (\bar{L}N)\varepsilon(\bar{Q}d), \\ \mathcal{O}_{QuNL} &= (\bar{Q}u)(\bar{N}L), & \mathcal{O}_{QNLd} &= (\bar{Q}N)\varepsilon(\bar{L}d), \\ \mathcal{O}_{LN} &= |\bar{L}N|^2, & \mathcal{O}_{QN} &= |\bar{Q}N|^2, \\ \mathcal{O}_{NN} &= (\bar{N}N^c)^2, & \mathcal{O}'_{NN} &= |\bar{N}N^c|^2, \end{aligned} \quad (6)$$

or violate baryon-number by one unit:

$$\begin{aligned} \mathcal{O}_{QdN} &= (\bar{Q}Q^c)(\bar{d}N^c), & \mathcal{O}_{QNdQ} &= (\bar{Q}N^c)(\bar{d}Q^c), \\ \mathcal{O}_{uNd} &= (\bar{u}N^c)(\bar{d}d^c), & \mathcal{O}_{uddN} &= (\bar{u}d^c)(\bar{d}N^c). \end{aligned} \quad (7)$$

In addition, there are loop-generated operators whose coefficients are naturally suppressed, $\alpha \sim \mathcal{O}(1/16\pi^2)$:

$$\begin{aligned} \mathcal{O}_{NNB}^{(5)} &= \bar{N}\sigma^{\mu\nu}N^c B_{\mu\nu}, \\ \mathcal{O}_{NB} &= (\bar{L}\sigma^{\mu\nu}N)\tilde{\phi}B_{\mu\nu}, & \mathcal{O}_{NW} &= (\bar{L}\sigma^{\mu\nu}\tau^I N)\tilde{\phi}W_{\mu\nu}^I, \\ \mathcal{O}_{DN} &= (\bar{L}D_\mu N)D^\mu\tilde{\phi}, & \mathcal{O}_{\bar{D}N} &= (D_\mu\bar{L}N)D^\mu\tilde{\phi}. \end{aligned} \quad (8)$$

The above operators can give rise to a rich N -collider phenomenology. In this paper we will focus only on N -signals at hadron colliders. Specifically, we will consider the widely studied Drell-Yan like production of the N in association with a charged lepton: $p\bar{p}, pp \rightarrow N\ell$, followed by the

decays $N \rightarrow \ell jj$ (j stands for a light-quark jet), which gives a distinct LNV signal: same-sign charged leptons in association with a pair of light jets¹

$$p\bar{p}, pp \rightarrow \ell^+ \ell^+ jj, \quad (9)$$

which is traditionally taken to be the leading N -signature at the LHC [1, 2, 3, 4], since it is expected to be the easiest to detect. However, all previous studies on this signal assumed that the underlying hard process is $u\bar{d} \rightarrow W^{+\ast} \rightarrow N\ell_L^+$ followed by $N \rightarrow W^-\ell_L^+ \rightarrow jj\ell_L^+$, with an unnaturally large coupling $U_{\ell N} \sim \mathcal{O}(0.1)$ in (3). In contrast, we will see that the effective Lagrangian description outlined above suggests that the $\ell^+ \ell^+ jj$ signature is expected to be dominated by other operators.

The TLG operators \mathcal{O}_i that contribute to the process (9) correspond to $i = Ne\phi, duNe, QuNL, LNQd$ and $QNLd$, so that (after spontaneous symmetry breaking) the relevant terms in the effective theory are

$$\begin{aligned} \mathcal{L}_{eff}^N = & \frac{1}{\Lambda^2} \left[-\sqrt{2}vm_w \left(\alpha_{wl} \bar{N}^c P_R + \alpha_{wr} \bar{N} P_L \right) \gamma^\mu e W_\mu^+ + \alpha_v \left(\bar{d} \gamma^\mu P_R u \right) \left(\bar{N} \gamma_\mu P_R e \right) \right. \\ & \left. + \alpha_{s1} (\bar{u} P_L d) (\bar{e} P_R N) - \alpha_{s2} (\bar{u} P_R d) (\bar{e} P_R N) + \alpha_{s3} (\bar{u} P_R N) (\bar{e} P_R d) + \text{H.c.} \right], \quad (10) \end{aligned}$$

where $\alpha_{wr} \equiv \alpha_{Ne\phi}/2$, $\alpha_v \equiv \alpha_{duNe}$, $\alpha_{s1} \equiv \alpha_{QuNL}$, $\alpha_{s2} \equiv \alpha_{LNQd}$ and $\alpha_{s3} \equiv \alpha_{QNLd}$. Although not explicitly indicated, (10) will in general contain non-diagonal flavor interactions that may involve heavy quarks; we will return to these issues in a future publication.

For comparison with the literature we also included a general SM-like V–A term [see (3)], $U_{\ell N} \equiv \alpha_{wl} \times v^2/\Lambda^2$, even though such a coupling is expected to be $\sim 10^{-7}$, in which case the corresponding vertex will have no observable effects. Thus, the observation of LNV effects associated with an N with $M = \mathcal{O}(100)$ GeV will be most likely associated with $\alpha_i \neq 0$ for some $i \neq wl$, indicative of physics beyond the classic seesaw mechanism.

Underlying the use of the effective interactions (10) is the presumption that this NP is not directly observable. Nonetheless one can use observables contributing to (9) to extract (or constrain) the values of the various coefficients in (10) and use this information to restrict the possible types of NP responsible for these effects. While a detailed study in this direction lies beyond the scope of this paper, we will comment on how this can be done and on the precision to which these coefficients can be measured in the LNV reaction (9).

Using (10), we find that the differential cross-section for the hard process $u\bar{d} \rightarrow N\ell^+$ and the spin-averaged differential decay width for $N \rightarrow \ell^+ jj$ are respectively

$$\frac{d\hat{\sigma}}{dc_\theta} = \frac{(\hat{s} - M^2)^2}{128\pi \hat{s}\Lambda^4} \left\{ \alpha_{s1}^2 + \alpha_{s2}^2 - \alpha_{s2}\alpha_{s3}(1 + c_\theta) + \alpha_{s3}^2 \Upsilon_+ + 4\alpha_v^2 \Upsilon_- + 16 \left(\alpha_{wl}^2 \Upsilon_- + \alpha_{wr}^2 \Upsilon_+ \right) \Pi_w(\hat{s}) \right\} \quad (11)$$

$$\frac{d\Gamma}{dx} = \frac{M}{128\pi^3} \left(\frac{M}{\Lambda} \right)^4 \left\{ \left(\alpha_{s1}^2 + \alpha_{s2}^2 - \alpha_{s2}\alpha_{s3} \right) f_s + \left[\alpha_{s3}^2 + 4\alpha_v^2 + 16 \left(\alpha_{wl}^2 + \alpha_{wr}^2 \right) \Pi_w(2zM^2) \right] f_v \right\}, \quad (12)$$

where we assume real coefficients and

$$\Upsilon_\pm = \frac{1}{4} \left[(1 \pm c_\theta)^2 + M^2 \frac{s_\theta^2}{\hat{s}} \right], \quad \Pi_w(\hat{s}) \equiv \frac{m_w^4}{(\hat{s} - m_w^2)^2 + (m_w \Gamma_w)^2}, \quad (13)$$

¹We focus on the positively-charged di-lepton signal; at the Tevatron $\sigma(p\bar{p} \rightarrow \ell^+ \ell^+ jj) = \sigma(p\bar{p} \rightarrow \ell^- \ell^- jj)$ while at the LHC $\sigma(pp \rightarrow \ell^+ \ell^+ jj) \sim 2 \sigma(pp \rightarrow \ell^- \ell^- jj)$.

Γ_w denotes the total W width, c_θ is the cosine of the center of mass (CM) scattering angle between ℓ and u , \hat{s} the CM energy squared of the hard process, $f_s(x) = 12x^2z$, $f_v(x) = 2x^2(x + 3z)$, with $z = 1/2 - x$, and Mx is the energy of the N decay lepton in the N rest frame.

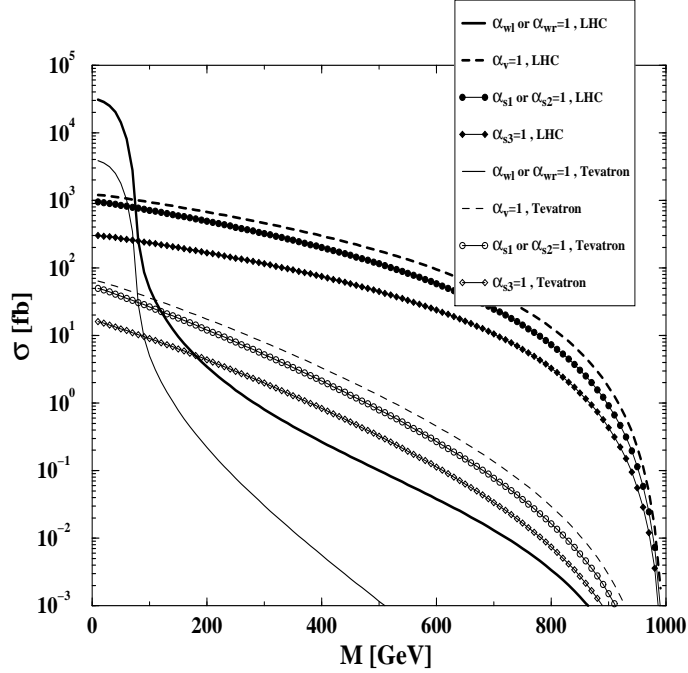


Figure 1: The total cross-section $\sigma(pp, pp \rightarrow \ell^+ N)$ derived from (10) for the Tevatron and the LHC, as a function of M , for $|c_\theta| < 0.9$, $\Lambda = 1 \text{ TeV}$ and $\hat{s} < \Lambda^2$ (for this Λ , $\alpha_{wl} = 1$ corresponds to $U_{\ell N} \sim 0.06$). See text.

In Fig. 1 we plot the total cross-sections σ , convoluted with the initial parton densities inside the (anti)protons, as a function of M and for $\Lambda = 1 \text{ TeV}$ and various values of the coefficients α_i . The cross-section is integrated for $|c_\theta| \leq 0.9$ up to $\sqrt{\hat{s}} < \Lambda$ (the decrease in σ with M results from this cut), imposed in order to insure the validity of the effective Lagrangian approach. The signal to background analysis described in [1, 2, 3, 4] for $pp \rightarrow \mu N \rightarrow \mu\mu jj$ also applies to the cross-sections in Fig. 1, based on which we expect a 5σ same-sign leptons signal at the LHC if $M \lesssim 200 \text{ GeV}$, $\Lambda \sim \mathcal{O}(1) \text{ TeV}$, and $\alpha_{wr} \sim \mathcal{O}(1)$ with $\alpha_i = 0$ otherwise [2]. The Tevatron is, however, not sensitive to this process and coupling for $M > m_w$ [2].

Also note that the 4-fermion terms can significantly contribute to σ , especially for $M > m_w$ when the s-channel W -exchange process is non-resonant. Hence, if $\alpha_v \sim 1$ and $\Lambda \sim 1 \text{ TeV}$, then $\sigma \gtrsim 10$ (100) fb at the Tevatron (LHC) for $M \lesssim 300$ (600) GeV. Based on the results of [2], such a large $\mu^+ N$ production rate is within the sensitivity of both colliders with integrated luminosities of $\mathcal{O}(10) \text{ fb}^{-1}$. The 4-fermion interactions are generated, e.g., by a new right-handed gauge interaction mediated by a W'_R too heavy to be directly observable.²

²If the W'_R were to be directly observable, the sensitivity to N would be markedly improved [1], though the effective theory approach would no longer be applicable.

As mentioned previously, one can use observables such as (11) and (12) to measure or bound the magnitudes of the α_i in (10) and the $\alpha_{s2} - \alpha_{s3}$ relative phase (terms containing other relative phases are multiplied by a light lepton or quark mass). Perhaps the simplest example is the forward-backward (FB) asymmetry (A_{FB}) in the underlying process $p\bar{p}, pp \rightarrow \ell^+ N$, which requires the proper lepton assignment, usually that of largest transverse momentum, and can be used to extract the terms linear in c_θ in (11). Note that for the LHC the conventional A_{FB} vanishes (due to the identical colliding beams) but we can use A_{FB}^y , the double asymmetry in θ and the rapidity y , as described, e.g., in [10]. In Table 1 we give the expected FB asymmetries at the Tevatron and the LHC when a single α_i is not zero and for $M = 200$ GeV (the asymmetries depend very weakly on M).

	<u>non-zero coefficient</u>				
	α_{wl}	α_{wr}	α_v	$\alpha_{s1,s2}$	α_{s3}
A_{FB} (Tevatron)	0.55	-0.55	0.62	0	-0.62
A_{FB}^y (Tevatron)	0.11	-0.11	0.12	0	-0.12
A_{FB}^y (LHC)	0.35	-0.35	0.40	0	-0.40

Table 1: *The expected FB asymmetries A_{FB} at the Tevatron and A_{FB}^y at the Tevatron and at the LHC (see text), corresponding to each of the effective operators in (10) when $M = 200$ GeV.*

Other differential distributions for the reaction (9) can also be utilized. For instance, we find that the invariant mass distribution of the two leptons or of the two jets, can differentiate between the W and 4-fermion mediated processes. On the other hand, by taking the moments of (12) with appropriate functions of x , the coefficient combinations multiplying f_s and f_v can be measured. Additional information can be extracted from other differential distributions involving the N spin dependence. A realistic determination of the constraints on the α_i requires careful consideration of the various backgrounds and event selection efficiencies; this lies beyond the scope of the present work but will be detailed in a future publication. Here we only remark that the very distinctive characteristics of LNV signatures of this type should allow for a drastic reduction of the backgrounds after an optimal event (distribution) selection, see e.g., [11].

To summarize, we have argued that the natural size of the heavy-to-light $N - \nu_L$ mixing is expected to be $\mathcal{O}(\sqrt{m_\nu/M}) \ll 1$ within the classic seesaw mechanism, leading to the decoupling of the heavy Majorana neutrinos even if their masses are ~ 100 GeV – 1 TeV, unless additional interactions are present. Thus, any signal of EW-scale heavy Majorana neutrinos provides a strong indication of physics beyond the minimal seesaw mechanism, at a near-by scale.

Adopting this viewpoint, we re-examined heavy Majorana neutrino physics using an effective Lagrangian approach. We gave a complete set of the leading effective operators (of dimension ≤ 6) involving the N and the SM fields. As an illustration, we studied the effects of the higher dimensional operators that yield a new (V+A) $\ell N W$ interaction and new 4-fermion $ud\ell N$ contact

terms, on the LNV process $p\bar{p}, pp \rightarrow \ell^+ N$ followed by $N \rightarrow \ell^+ jj$ at the Tevatron and the LHC.

We found that these new effective operators can significantly enhance the production of N at hadron colliders, potentially leading to hundreds or even thousands of LNV $\ell^+ \ell^+ jj$ events at the Tevatron and at the LHC, if the typical scale of the new physics is $\Lambda \sim 1$ TeV. We have also found that it is possible, to a certain extent, to discriminate between the various types of new physics responsible for the effective interactions, by measuring differential distributions of the outgoing charged leptons and jets. For example, if the new physics is manifest only through a new (V+A) $\ell N W$ interaction, then we expect $\sigma(\ell_R^+ \ell_R^+ jj) \gg \sigma(\ell_L^+ \ell_L^+ jj)$, which would manifest in the FB asymmetry and will thus stand as an unambiguous signal of beyond the $N - \nu_L$ mixing scheme implied by the classic seesaw mechanism.

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