Looking for hints of a reconstructible seesaw model 
at the Large Hadron Collider

Gulab Bambhaniya, Srubabati Goswami, Subrata Khan, Partha Konar, and Tanmoy Mondal

1Physical Research Laboratory (PRL), Ahmedabad-380009, Gujarat, India
2Department of Physics, Indian Institute of Technology, Gandhinagar, Ahmedabad, India.

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Abstract

We study the production of heavy neutrinos at the Large Hadron Collider (LHC) through the dominant s-channel production mode as well as the vector boson fusion (VBF) process. We consider the TeV scale minimal linear seesaw model containing two heavy singlets with opposite lepton number. This model is fully reconstructible from oscillation data apart from an overall normalization constant which can be constrained from meta-stability of the electroweak vacuum and bounds coming from lepton flavor violation (LFV) searches. Dirac nature of heavy neutrinos in this model implies suppression of the conventional same-sign-dilepton signal at the LHC. We analyze the collider signatures with tri-lepton final state and missing transverse energy as well as VBF type signals which are characterized by two additional forward tagged jets. Our investigation reveals that due to stringent constraints on light-heavy mixing coming from LFV and meta-stability bounds, the model can be explored only for light to moderate mass range of heavy neutrinos. We also note that in case of a positive signal, flavor counting of the final tri-lepton channel can give information about the mass hierarchy of the light neutrinos.

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1. INTRODUCTION

The discovery of the Higgs boson at the Large Hadron Collider both by ATLAS [1] and CMS [2] collaborations have put the Standard Model (SM) on a firm footing. However, no signal of physics beyond the Standard Model (BSM) has been found so far at the LHC. On the other hand, convincing indications of BSM physics have already emerged from the phenomenon of neutrino oscillation observed in terrestrial experiments. These results have conclusively established that neutrinos have non-zero mass and flavor mixing. Oscillation data together with the cosmological bound on sum of neutrino masses ($\Sigma m_i < 0.23$ eV including the PLANCK data [3]) indicate that neutrino masses are much smaller as compared to the other fermions in the SM. Such small masses can be generated naturally by the seesaw mechanism. The origin of seesaw is the dimension 5 effective operator $\frac{c_5}{M} L L H H$, where $L (H)$ being the SM lepton (Higgs) doublet and $c_5$ is a dimensionless coupling, $M$ is the mass scale at which the effective operator gets generated [4]. Such operators arise by integrating out heavy fields added to the SM Lagrangian and they violate lepton number by two units. The smallness of neutrino mass in these models is related to the scale of lepton number violation which is required to be very high $\sim \mathcal{O}(10^{15}$ GeV) to generate neutrino masses in the right ballpark. The most economical in terms of particle contents is the type-I seesaw in which heavy singlet right-handed neutrinos are added to the SM Lagrangian [5–9]. However, the natural seesaw scale is far beyond the reach of the LHC. To have signatures of seesaw models at the LHC, the heavy neutrino ($N$) mass needs to be $\sim \mathcal{O} (\text{TeV})$. However, if one lowers the scale of seesaw to TeV then it also requires much smaller neutrino Yukawa couplings ($\sim 10^{-6}$) to obtain correct light neutrino masses. Such small Yukawa couplings lead to suppression of the production of the heavy neutrinos in natural TeV scale Type-I seesaw models. This leads to the question whether it is possible to achieve both the requirements simultaneously, i.e. having TeV scale heavy neutrinos along with large Yukawa coupling leading to large light-heavy mixing. Such possibilities can be realized in some specific mass textures [10–18]. Other options include models with higher-dimensional operators arising due to exchange of new particles belonging to larger representations [19–27], radiative mass generations [28–34] etc. One of the most popular options to generate TeV scale seesaw is through the inverse seesaw models in which one includes additional singlet states. These models were first proposed in the context of E(6) Grand Unified Theories [35]. In these models the seesaw scale is decoupled from the scale of lepton number violation and the smallness of neutrino mass originates from the small lepton number violating terms in the Lagrangian.

In type-I Seesaw model the heavy and light neutrinos are both Majorana particles. It is well
known that Majorana nature of neutrinos can be established by observing a positive signal in neutrino-less double beta decay experiments. It was noticed in [36], in the context of the Left-Right symmetric model that resonant production of $N$ and its subsequent decay giving same-sign di-lepton (SSDL) signal in colliders can also constitute evidence for Majorana nature of neutrinos. Given the importance of this signal, there have been several studies of this channel at the hadron colliders [37–42] including searches at the LHC [43]. Enhanced contribution from infrared $t$-channel, especially for heavier masses was proposed [44] together with $s$-channel production.

The heavy neutrinos in inverse seesaw model are of pseudo-Dirac nature and in this case the SSDL signal is suppressed by the small lepton number violating coupling. For such models the heavy neutrinos are produced by the $s$-channel process along with a charged lepton. This neutrino further decays to a second lepton (of sign opposite to the first lepton to conserve lepton number) together with a $W$-boson. The $W$-boson can further decay leptonically to produce a lepton and a neutrino. Thus the final signal consists of tri-lepton and missing energy which is expected to have tiny contamination from standard model backgrounds. Detailed studies including the SM background in the context of pseudo-Dirac neutrinos has been done in [41, 45]. Similar studies in the context of Left-Right symmetric model and non-minimal supersymmetric inverse seesaw models have been performed in [46] and [47] respectively. Experimental searches for multi-lepton signals have been carried out by the CMS collaboration using an integrated luminosity of 19.5 $fb^{-1}$ a center of mass energy $\sqrt{s} = 8$ TeV at the LHC [48]. They considered at least three leptons in the final state using a search strategy not specific to any particular model.

In this work, we consider the minimal linear seesaw model (MLSM) studied in [49, 50] as an example of the TeV scale seesaw model. This is a variant of the inverse seesaw model but in this case the minimal scheme consists of adding just two heavy singlets with opposite lepton number as opposed to four heavy neutrinos in canonical minimal inverse seesaw models [51]. It was shown in [49] that the Yukawa couplings matrices for this model can be fully reconstructed in terms of the oscillation parameters apart from an overall normalization factor. It was further shown in [50] that this normalization constant can be constrained from consideration of the meta-stability of the electroweak vacuum and lepton flavor violation bounds. The heavy neutrinos in this model are of Dirac type and the SSDL signal is suppressed. In the context of this model we consider two possible production channels for the heavy neutrinos resulting in two different class of signals. The first one of this is the $s$-channel process to produce heavy Dirac neutrinos associated with a lepton and finally giving the tri-lepton and missing energy signal. The second one is the production of heavy neutrinos through vector boson fusion (VBF) in which two electroweak vector bosons coming from
two partons ‘fuse’ to produce the signal under consideration (tri-leptons) along with two highly forward jets. It becomes important in the context of hadron colliders since the tagging of forward jets allows us to reduce the background considerably. Also the lack of color exchange between these jets makes the central region free from the color activities and this is exploited by vetoing central jets; see [52] and references therein in the context of Higgs search. This helps in minimizing the backgrounds further. For these reasons VBF remains an important channel to look for new physics [53–55] at hadron colliders.

We consider both normal hierarchy (NH) as well as inverted hierarchy (IH) for the light neutrino mass spectra. We also estimate the corresponding standard model backgrounds for the 14 TeV LHC. In each case, we perform a realistic simulation with extensive event selections using MadGraph and PYTHIA.

The paper is organized as follows: Sec. 2 contains a brief description of the model. The production and decay of the right handed neutrino at LHC, are discussed in Sec. 3. Simulation details and results are presented in Sec. 4 while in Sec. 5 we discuss discovery potential of the signals at the LHC. Finally, we conclude in Sec. 6.

2. THE LINEAR SEESEA W MODEL

The most general Lagrangian containing heavy singlet fields $N_R$ and $S$ with opposite lepton numbers, is given by

$$-L = N_R Y_{\nu} \tilde{\phi}^\dagger l_L + S Y_{S} \tilde{\phi}^\dagger l_L + \sum N_R N_R^c + \frac{1}{2} \mu S_c + \frac{1}{2} \mu_N N_R^c + h.c.,$$

(1)

where $l_L = (\nu, x, e, \mu, \tau)^T$, $x = e, \mu, \tau$.

Once the symmetry is broken spontaneously, the Higgs field $\phi$ obtains a vacuum expectation value (VEV) equal to $v/\sqrt{2}$. This generates the Dirac mass term $m_D = Y_{\nu} v/\sqrt{2}$ and the lepton number breaking mass term $m_S = Y_S v/\sqrt{2}$. In the linear seesaw models [56–58] one assumes $m_S$ to be small and non-zero while the $\mu$ and the $\mu_N$ terms are set to zero. This can be done since they contribute towards light neutrino mass in the sub-leading orders [59]. Since lepton number violating mass terms are set to zero, the heavy neutrinos are purely Dirac type. Then the mass matrix takes the form

$$M_\nu = \begin{pmatrix}
0 & m_D^T & m_S^T \\
M_D & 0 & M_N \\
m_S & M_N^T & 0
\end{pmatrix},$$

(2)
in the \((\nu_L, N_R^c, S^c)\) basis.

The minimal model which can successfully generate two light neutrinos with non-zero mass is when only two extra heavy singlets are added to the SM Lagrangian. This is called the Minimal Linear Seesaw Model (MLSM) \([49, 50]\). The full mass matrix has dimension \(5 \times 5\) and can be written as,

\[
M_\nu = \begin{pmatrix} \ 0 & m'_D & \\ m'_D^T & M \end{pmatrix},
\]

(3)

where \(m'_D = (m^T_D, m^T_S)\) and

\[
M = \begin{pmatrix} \ 0 & M_N \\ M_N & 0 \end{pmatrix}.
\]

(4)

For the minimal case \(M_N\) is just a number, not a matrix. \(M_\nu\) can be diagonalized by a \(5 \times 5\) unitary matrix \(U_0\) as

\[
U_0^T M_\nu U_0 = M^{\text{diag}}_\nu,
\]

(5)

where \(M^{\text{diag}}_\nu = \text{diag}(m_1, m_2, m_3, M_1, M_2)\). Following a two-step diagonalization procedure \([60]\), \(U_0\) can be expressed as,

\[
U_0 = \begin{pmatrix} \ (1 - \frac{1}{2} \epsilon) U_\nu & m^1_D(M^{-1})^* U_R \\ -M^{-1} m_D U_\nu & (1 - \frac{1}{2} \epsilon') U_R \end{pmatrix} \equiv \begin{pmatrix} \ U_L & V \\ S & U_H \end{pmatrix},
\]

(6)

where, \(U_L\) is the \(U_{PMNS}\) mixing matrix, and \(V, S\) are the light-heavy mixing matrices. Interaction of heavy neutrinos with the SM fields are determined by the mixing matrix \(V\), whose elements will be denoted as \(V_{iN}\) hereafter. We would notice afterwards that the strong constraints on some elements of this matrix \(i.e.\ V_{eN}\) and \(V_{\mu N}\) would restrict the production signal. The diagonalizing matrix is now non-unitary which is characterized by the factor \((1 - \epsilon/2)\). The non-unitary corrections \(\epsilon\) and \(\epsilon'\) are given in \([60]\). \(U_\nu\) is the unitary component of \(U_{PMNS}\) which is same as \(U_{PMNS}\) for \(\epsilon \ll 1\). We use the standard parametrization for this:

\[
U_\nu = \begin{pmatrix} \ c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i \delta} \\ -c_{23} s_{12} - s_{23} s_{13} c_{12} e^{i \delta} & c_{23} c_{12} - s_{23} s_{13} s_{12} e^{i \delta} & s_{23} c_{13} \\ s_{23} s_{12} - c_{23} s_{13} c_{12} e^{i \delta} & -s_{23} c_{12} - c_{23} s_{13} s_{12} e^{i \delta} & c_{23} c_{13} \end{pmatrix} P,
\]

(7)

where \(c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}\) and \(\delta\) denotes the Dirac CP phase. The Majorana phase matrix \(P\) is expressed as \(P = \text{diag}(e^{-ia}, e^{ia}, 1)\), there is only one Majorana phase because one of the mass eigenvalues is zero.
Using the seesaw approximation one obtains the light neutrino mass matrix,

\[ m_{\text{light}} = m_D'^T M^{-1} m_D'. \]  

This being a rank 4 matrix the light neutrinos belonging to this model are hierarchical. Thus there are two possible mass spectra:

- Normal Hierarchy (NH): \((m_1 < m_2 < m_3)\)
- Inverted Hierarchy (IH): \((m_3 << m_2 \approx m_1)\).

Since \(Y_\nu\) and \(Y_S\) in this case are 3 \times 1 matrices they can be considered as two independent vectors

\[ Y_\nu \equiv y_\nu \hat{a}; \quad Y_S \equiv y_s \hat{b}, \]

where \(\hat{a}\) and \(\hat{b}\) denotes complex vectors with unit norm while \(y_\nu\) and \(y_s\) represent the norms of the Yukawa matrices \(Y_\nu\) and \(Y_S\), respectively. Using Eq. 8 and 9 one can reconstruct the Yukawa matrices \(Y_\nu\) and \(Y_S\) in terms of the oscillation parameters barring an overall normalization factor. The parametrization of the Yukawa matrices depend on the mass hierarchy and can be expressed as \([49, 50]\),

\[
Y_\nu = \frac{y_\nu}{\sqrt{2}} \left( \sqrt{1 + \rho} \, U_j^\dagger + e^{i \frac{\pi}{2}} \sqrt{1 - \rho} \, U_k^\dagger \right), \\
Y_S = \frac{y_s}{\sqrt{2}} \left( \sqrt{1 + \rho} \, U_j^\dagger - e^{i \frac{\pi}{2}} \sqrt{1 - \rho} \, U_k^\dagger \right),
\]

where, \(j = 2, k = 3\) for NH and \(j = 2, k = 1\) for IH. \(U_j\)'s denote the columns of the unitary matrix \(U_\nu\) that diagonalizes the light neutrino mass matrix \(m_{\text{light}}\) in Eq. 8. The parameter \(\rho\) is given as,

\[
\rho = \frac{\sqrt{1 + r} - \sqrt{r}}{\sqrt{1 + r} + \sqrt{r}} \quad (NH), \quad \rho = \frac{\sqrt{1 + r} - 1}{\sqrt{1 + r} + 1} \quad (IH).
\]

Here \(r\) denotes the ratio of the solar and atmospheric mass squared differences, \(r = \Delta m^2_{\odot}/\Delta m^2_{\text{atm}}\), with \(\Delta m^2_{\odot} \equiv m_2^2 - m_1^2\) and \(\Delta m^2_{\text{atm}} \simeq m_3^2 - m_1^2 \quad (m_2^2 - m_3^2)\) for NH (IH).

The overall coupling \(y_\nu\) can be constrained from the metastability of the electro-weak vacuum and LFV. For normal hierarchy the most stringent constraint comes from LFV, whereas for IH case vacuum meta-stability is more restrictive. This is because of cancellations occurring for IH for LFV processes \([50]\). In our analysis we have used \(y_\nu\) to be 0.4(0.1) \(^1\) for IH(NH) scenario. These will be

\(^1\) These are the approximate upper bounds on \(y_\nu\), obtained in \([50]\).
translated into the bounds on the mixing matrix elements, $V_{lN}$, depending on the heavy neutrino mass $M_N$. Since $y_s$ is extremely small ($O(10^{-10})$), $Y_S$ does not play any role in determining $V_{lN}$.

The elements of the matrix $V$ (or $V_{lN}$) can be expressed in terms of $U_{PMNS}$ matrix, $\rho$ and $y_\nu$ as follows:

\[
V_{eN_1} = \frac{-i}{\sqrt{2}M_N} \frac{y_\nu v}{2} \left[ \sqrt{1+\rho} (U_{PMNS})_{12}^* + i \sqrt{1-\rho} (U_{PMNS})_{11}^* \right]
\]
\[
\simeq \frac{y_\nu v}{4M_N} \left[ e^{i(\alpha+\delta)} (-2 + \sqrt{r}) r^{\frac{1}{2}} s_{12} - 2 i s_{13} \right] + O \left( (\sqrt{r}, s_{13})^2 \right)
\]
\[
V_{\mu N_1} = \frac{-i}{\sqrt{2}M_N} \frac{y_\nu v}{2} \left( \sqrt{1+\rho} (U_{PMNS})_{22}^* + i \sqrt{1-\rho} (U_{PMNS})_{21}^* \right)
\]
\[
\simeq \frac{y_\nu v}{4M_N} \left[ (-2 + \sqrt{r}) (e^{i\alpha} r^{\frac{1}{2}} c_{12} c_{23} + i s_{23}) + 2 e^{i(\alpha+\delta)} r^{\frac{1}{2}} s_{12} s_{23} s_{13} \right] + O \left( (\sqrt{r}, s_{13})^2 \right)
\]

The above expressions are for NH scenario and similar expressions can be computed for IH also. The element $V_{eN_2}$ ($V_{\mu N_2}$) differs from $V_{eN_1}$ ($V_{\mu N_1}$) by a phase factor.

To get some perspective on the degree of suppression in cross section coming from these constraints we note down the corresponding $V_{lN}$ values for $M_N = 100$ GeV as: $V_{eN} = 0.087(0.044)$ whereas, $V_{\mu N} = 0.311(0.108)$ for IH(NH) scenario respectively.

3. PHENOMENOLOGY AT THE LHC

The dominant production channel of the heavy neutrinos at LHC is the s-channel process through virtual W-boson exchange. At the leading order the parton level process ($q\bar{q}' \rightarrow W^\pm \rightarrow \ell^\pm N$) is depicted in Fig. 1(left plot). The heavy neutrinos can also be produced through the VBF process where production of $N$ is associated with two forward jets. Fig. 2 contains the
FIG. 2: Representative parton level diagrams contributing to $N\ell jj$ production through vector boson fusion at hadron colliders. Mirror diagrams are not shown here and also the last diagram is one of the four diagrams with $W^{\pm}$ emitting from each of the quark legs.

Representative parton level Feynman diagrams for VBF processes $^2$. Estimated total production cross sections of these heavy Dirac neutrinos at the 14 TeV LHC for both s-channel(solid-line) as well as VBF (dashed-line) are shown in Fig. 3. Basic cuts such as $p_T \ell > 20$ GeV and $|\eta_\ell| < 2.5$ are applied and $y_\nu$ is consistent with neutrino mass bound, vacuum metastability and LFV. Two lines represent two different cases of light neutrino mass hierarchy. In both production mechanisms upper and lower curves are for IH and NH scenarios respectively. In these analyses CTEQ6L1 [63] parton distribution functions have been used with the factorization scale set at the heavy neutrino mass $M_N$.

Heavy neutrinos $N$ can decay into charged lepton or neutrino associated with gauge (or Higgs) boson.

$$N \rightarrow W^{\pm} l^{\mp}/Z l \eta/H l \eta, \quad \text{where} \quad l \equiv e, \mu, \tau.$$  \hspace{1cm} (13)

Representative diagram for some of these decay channels used in our analysis is shown in Fig. 1(right plot):

\hspace{1cm} $^2$ Note that there are some diagrams which are not truly VBF type, i.e. two gauge boson are not fused via t-channel (e.g. bottom right diagram in Fig. 2), but they can lead to the same final states. These diagrams are necessary for the requirements of gauge invariance and included both for BG [61, 62] and signal calculations.
FIG. 3: The total cross section is shown (solid line) for production of heavy neutrino associated with light lepton at the 14 TeV LHC through the leading order s-channel process. Upper and lower curves are for IH and NH scenarios. Dotted lines represent VBF production cross section.

FIG. 4: The decay branching ratios of the heavy neutrino ($N$) in different channels as a function of its mass in the case of normal hierarchy (left) and inverted hierarchy (right). Total decay widths in each case are also demonstrated with the solid line in the same figure.

In Fig. 4 we present the branching ratios for these decay channels as a function of heavy neutrino mass $M_N$ both in the case of normal hierarchy (left) and inverted hierarchy (right). Total decay widths in each case are also demonstrated with the solid line in each figure. Identifying that the charged lepton decay modes for heavy neutrino i.e. $N \rightarrow W^\pm l^\mp$ being the main channel for search at the hadron collider, we discuss the corresponding decay modes in detail for both scenarios. The figure clearly shows that for NH, heavy neutrinos mostly decay into muon ($\mu$) and $W$ boson. On the other hand for IH, decay into the third generation lepton ($\tau$) possesses the maximum branching ratio. For NH the decay to both $\tau$ and $e$ are suppressed, while for IH the decay to $e$ has a very low
ratio. The $W^\pm$ can have hadronic decay modes ($W^\pm \to jj$) or leptonic decay modes ($W^\pm \to l^\pm \nu$). The tri-lepton signal $pp \to l^\pm l^\mp l^\pm \nu$ comes from the later decay mode.

Other than charged lepton decay mode, $N$ can also decay to $Z$-boson or Higgs boson associated with neutrinos as listed in Eq. 13. The corresponding branching ratios are also shown in Fig. 4. In the IH case, for higher masses the decay branching ratios to $W^\pm \mu^\mp$ and $W^\pm \tau^\mp$ become comparable to that of other bosons ($Z$ and Higgs) rate whereas $W^\pm e^\mp$ rate is tiny. Note that the branching ratio for $Z\nu$ is suppressed for lower values of the masses of the heavy neutrinos essentially because of $W$ mass threshold. For the $H\nu$ decay mode, the Higgs mass threshold suppresses the decay rate for lower values of $M_N \sim 100$ GeV. However, as $M_N$ increases these branching ratios increase to retain a $\sim 25\%$ level. Both these channels can contribute to the tri-lepton signal via leptonic decays and we have considered their contributions in our simulation. However since we will apply $Z$-veto (to minimize the SM background), the contribution coming from $Z\nu$ decay mode will be suppressed after final event selection. As lepton Yukawa is small, the $H\nu$ mode is also not going to contribute to our signal even for higher values of $M_N$.

4. SIMULATION AND RESULTS

We have implemented the model in FeynRules and generated the Feynman rules compatible with MadGraph5. After generating Les Houches Event (LHE) file from MadGraph, we have passed that to PYTHIA6 for showering and hadronization.

4.1. Selection criteria

To get enhancement in signal over background, we use the following selection criteria:

\begin{itemize}
  \item The choice of Parton Distribution Function (PDF): We use the CTEQ6L1 for this purpose and the factorization scale is set at the heavy neutrino mass $M_N$.
  \item Identification criteria of a lepton: pseudorapidity $|\eta| < 2.5$ and $p_T \ell > 20$ GeV have been used.
  \item Detector efficiency for leptons:
    \begin{itemize}
      \item For electron (either $e^-$ or $e^+$) detector efficiency is 0.7 (70%);
      \item For muon (either $\mu^-$ or $\mu^+$) detector efficiency is 0.9 (90%).
    \end{itemize}
\end{itemize}
Smearing of electron energy and muon $p_T$ are incorporated.

Lepton-lepton separation: for this $\Delta R_{ll} \geq 0.2$ is used.

Lepton-photon separation: this is taken as $\Delta R_{l\gamma} \geq 0.2$ with all the photons having $p_T\gamma > 10$ GeV.

Lepton-jet separation: The separation of a lepton with all the jets is set at $\Delta R_{lj} \geq 0.4$; otherwise that lepton is not counted as lepton. Jets are constructed from hadrons using PYCELL within the PYTHIA.

Hadronic activity cut: This cut is applied to take only pure kind of leptons that have very less hadronic activity around them. The hadronic activity within the cone of radius 0.2 around the lepton should be small, $\sum_{\text{hadrons}} \frac{p_T}{p_T} \leq 0.2$.

Hard $p_T$ cuts used are: $p_T l_1 > 30$ GeV, $p_T l_2 > 30$ GeV and $p_T l_3 > 20$ GeV.

Missing $p_T$ cut: Due to the presence of neutrino, a missing $p_T$ cut ($> 30$ GeV) is applied.

$Z$-veto$^4$ is applied to suppress the SM background.

VBF cuts:

- Central jet veto is also applied$^6$, in which we consider any jet with $E_{T3} > 20$ GeV and compute the rapidity with respect to the average of the two forward jets: $\eta_0 = \eta_3 - (\eta_1 + \eta_2)/2$. We veto the event if $|\eta_0| < 2$.
- Charged leptons need to fall in between the rapidities of two forward tagging jets i.e. $\eta_{j\text{,min}} < \eta_\ell < \eta_{j\text{,max}}$.
- $p_T$ of jets: $p_T j_1, j_2 > 20$ GeV.
- Invariant mass of jets: $M_{j_1 j_2} > 600$ GeV.
- Pseudorapidity of jets: $\eta_{j_1}, \eta_{j_2} < 0$ and $|\eta_{j_1} - \eta_{j_2}| > 4$.

$^3$ Choice of corresponding $\eta$ dependent parameters is similar to one of our earlier work$^8$.

$^4$ Same flavored but opposite sign lepton pair invariant mass $m_{\ell_1 \ell_2}$ must be sufficiently away from $Z$ mass, such that, typically, $|m_{\ell_1 \ell_2} - M_Z| \geq 6\Gamma_Z \sim 15$ GeV.
4.2. Background

4.2.1. For s-channel signal

To calculate the SM background we consider all channels that can produce or mimic the tri-lepton production with missing \( P_T \). We closely follow the reference \[68, 70\] where similar background analysis was done with the event selection criteria listed as above except the cuts related to the VBF. Events are generated using ALPGEN \[71\] for the processes coming from \( \bar{t}t, \bar{t}t(Z/\gamma^*) \), \( \bar{t}tW^\pm, W^\pm(Z/\gamma^*) \), \( (Z/\gamma^*)(Z/\gamma^*) \) at the parton level and passed into PYTHIA. As expected \( \bar{t}t \) and \( W^\pm(Z/\gamma^*) \) contribute dominantly. These and other SM backgrounds are listed in Table I. For each process we classify the tri-lepton signals into four different flavor combinations and compute the cross section in each case along with the total contribution.

| Process | Cross section (fb) |
|---------|--------------------|
| \( \ell\ell\ell \) | 18.972 1.1383 7.0831 8.2214 2.5297 |
| \( W^\pm(Z/\gamma^*) \) | 10.832 0.0677 0.1311 5.9891 4.6440 |
| \( (Z/\gamma^*)(Z/\gamma^*) \) | 1.175 0.0734 0.0525 0.6400 0.4090 |
| \( \bar{t}t(Z/\gamma^*) \) | 1.103 0.0429 0.1329 0.4997 0.4275 |
| \( \bar{t}tW^\pm \) | 0.639 0.0328 0.2655 0.2424 0.0983 |
| TOTAL | 32.721 1.3551 7.6651 15.5926 8.1085 |

TABLE I: Dominant Standard Model background cross sections contributing to tri-lepton and missing transverse energy. These are calculated satisfying all the cuts (except VBF cuts) for the 14 TeV LHC. For each process we also classify the tri-lepton background into four different flavor combinations and present the cross section in each case along with the total contribution.

4.2.2. For VBF signal

Tri-lepton signal with missing \( P_T \) and two forward jets in VBF can be faked by different SM backgrounds. Processes like \( \bar{t}t \) would produce b-jets and mostly effective in central region. Vetoing on jet activities in central region can eliminate most of the non-VBF type SM processes. However most important irreducible background comes from \( W^\pm Z \) and \( ZZ \) together with two extra forward jets once the gauge bosons decay leptonically. These processes can construct dominant SM background for the VBF production of \( 3\ell + \not{E}_T \) since they includes the typical VBF topology and hence
can easily pass the central jet veto criteria. These backgrounds are calculated\textsuperscript{5} using \texttt{MadGraph5} and \texttt{PYTHIA6}. In the Table [II] the dominant background cross sections after satisfying all the cuts including VBF cuts at 14 TeV LHC is tabulated. Like the case of s-channel backgrounds, for each process we also classify the tri-lepton signals into four different flavor combinations and compute the cross section in each case as well as the total contribution.

| Process   | Cross section (fb) |
|-----------|--------------------|
|           | $\ell\ell\ell$   | $ee\ell$ | $e\ell\mu$ | $e\mu\mu$ | $\mu\mu\mu$ |
| $W^+Zjj$  | 0.04068            | 0.00073  | 0.00105  | 0.02157  | 0.01734    |
| $W^-Zjj$  | 0.01923            | 0.00038  | 0.00055  | 0.00994  | 0.00836    |
| ZZjj      | 0.00094            | 0.00002  | 0.00002  | 0.00066  | 0.00024    |
| TOTAL     | 0.06085            | 0.00113  | 0.00162  | 0.03216  | 0.02594    |

TABLE II: Dominant Standard Model background cross section contributing to tri-lepton and missing transverse energy associated with two forward jets. These are calculated satisfying all the cuts including VBF cuts for the 14 TeV LHC. Cross sections of four different flavor combinations as well as the total cross section are listed.

4.3. Signal

Earlier in section 3 we have presented the total heavy neutrino production cross sections for different light neutrino hierarchy with basic selection criteria. In this section we consider all leptonic decay modes of heavy neutrinos for a benchmark mass of $M_N$ at 100 GeV with the cuts discussed in section 4.1.

4.3.1. Signal for s-channel

The signal coming from decay of heavy neutrinos

$$pp \rightarrow \ell^\pm N \rightarrow \ell^\pm (\ell^\mp W^\pm) \rightarrow \ell^\pm \ell^\mp \ell^\pm + \not{E_T}, \quad \text{where } \ell \equiv e, \mu.$$  

Table III lists the final tri-lepton signal cross section through s-channel heavy neutrino production at 14 TeV LHC for the benchmark point $M_N = 100$ GeV incorporating all event selection

\textsuperscript{5} Next to leading order QCD corrections are available in [61, 62].
criteria except VBF cuts as described earlier. The total contribution from the light leptons as well as the contributions from the four different flavor combinations are presented.

| Hierarchy | Cross section (fb) |
|-----------|--------------------|
|           | ϵℓℓ | eee | eμμ | μμμ |
| IH        | 9.27 | 0.02 | 0.55 | 4.38 | 4.32 |
| NH        | 2.53 | 0.01 | 0.27 | 1.23 | 1.02 |

TABLE III: Final tri-lepton signal cross section through s-channel heavy neutrino production at the 14 TeV LHC for the benchmark point $M_N = 100$ GeV including all event selection cuts except VBF cuts. For each hierarchy we classify the tri-lepton signals into four different flavor combinations and present the cross section in each case along with the total light lepton contribution.

As we can see from the Table III cross section in terms of flavors has the ordering: $eμμ > μμμ > eεμ > eee$. We can understand this in the following way. There are total 8 possibilities which can produce $ℓℓℓ$ events. There is only one way to produce $μμμ$ and $eee$ final states. However, there are three possible ways to get the $eμμ$ channel depending on which one of $l_i$'s in figure II is associated with $e$ and $μ$. Similarly for the $eεμ$ final state also we get 3 possibilities. Since $V_{μN} > V_{eN}$, $μμμ$ cross section is much larger than $eee$ cross section. For the case of $eμμ$ final state, out of three channels one channel gives the same contribution as $μμμ$ channel but the remaining two channels will enhance the cross section compared to that of $μμμ$. The same thing happens for $eεμ$ and $eee$ final states which gives larger $eμμ$ cross section than the $eee$ case. Now let us consider the case of $μμμ$ and $eμμ$. At amplitude level, $μμμ$ events is proportional to $|V_{μN}|^2$, whereas, $eμμ$ is proportional to $|V_{εN}|^2 + 2V_{εN}V_{μN}$. Depending on the values of $V_{εN}$ and $V_{μN}$ one of the channels can dominate over the other. In our case for both IH and NH, we got the before mentioned hierarchy. However, one should keep in mind that the detector efficiency is different for $e$ and $μ$.

It is interesting to note that the ratio of tri-lepton cross sections of different flavor types are independent of $y_ν$ values and are governed by $U_{PMNS}$ matrix elements and the parameter $ρ$ defined in Eq. III. It is clear from Eq. III that $Y_ν$ matrix contains different columns of $U_{PMNS}$ matrix for different hierarchies as well as $ρ$ is also different. As a result, ratio of two particular flavor combinations will be different for different hierarchy. For e.g. the cross section ratio of $eee$ to $μμμ$ is 216(102) for IH(NH) scenario irrespective of $y_ν$. Hence, the cross section ratio between different flavor combinations can be a probe of neutrino mass hierarchy.
4.3.2. **Signal for VBF**

In this section we present the results for the case where $N$ is produced by VBF:

$$pp \rightarrow \ell^\pm N jj \rightarrow \ell^\pm (\ell^\mp W^\pm)jj \rightarrow \ell^\pm \ell^\mp \ell^\mp + \not{E}_T + jj \text{(forward jets)}, \quad \text{where } \ell \equiv e, \mu.$$  

In Table [IV](#) we present the final tri-lepton signal cross sections through VBF production of heavy neutrinos at the 14 TeV LHC for the benchmark point $M_N = 100$ GeV, after including all cuts. Here we have only shown the case of inverted hierarchy which is quite small, omitting the normal hierarchy cross sections since they are even smaller. Although VBF backgrounds are small, these tiny production cross sections are insufficient for the proposed LHC luminosity. We would not discuss this channel further for discovery potential which is presented for low luminosity option of 14 TeV LHC. Some indications from VBF can appear only at the HL-LHC (3000 $fb^{-1}$). But at that luminosity VBF channel is expected to face major challenge from pile-up.

| Hierarchy | Cross section (fb) |
|-----------|--------------------|
|           | $\ell\ell\ell$ | $eee$ | $ee\mu$ | $e\mu\mu$ | $\mu\mu\mu$ |
| IH        | 0.00476           | $8 \times 10^{-6}$ | $2.6 \times 10^{-4}$ | 0.00214 | 0.00236 |

TABLE IV: Final tri-lepton Signal through VBF production of heavy neutrino for the benchmark point $M_N = 100$ GeV at 14 TeV LHC for IH after all event selection cuts.

5. **DISCOVERY POTENTIAL**

After numerical computation all necessary signals and backgrounds, results are better represented in terms of significance, defined as $S/\sqrt{S+B}$, where $S(B) = \mathcal{L}\sigma_{S(B)}$. Here $\mathcal{L}$ being integrated luminosity available for the collider at certain machine energy and $\sigma_{S(B)}$ is the final cross section after all event selection, for given parameters like heavy neutrino mass and corresponding allowed couplings. Fig. [5](#) demonstrates the expected significance coming from s-channel production of heavy Dirac neutrino of mass 100 GeV as a function of integrated luminosity at 14 TeV LHC. Both IH(red-solid) and NH(blue-dot dashed) scenarios are presented. In the figure black-dotted (green-dashed) line shows $5\sigma$ ($3\sigma$) significance. For VBF case the cross section and hence signal significance is very small. Therefore this was not included in Fig. [5](#). If light neutrinos have inverted hierarchy, the discovery potential is better compared to that of normal hierarchy since for the latter the constraints on $y_\nu$ are more stringent. From the figure it is clear that for the case of IH, $3\sigma(5\sigma)$
significance can be achieved within the integrated luminosity $\sim 5(12) \, fb^{-1}$. For NH scenario the corresponding luminosities are $50(140) \, fb^{-1}$.

FIG. 5: Demonstration for the variation of significance $S/\sqrt{S+B}$ for the s-channel production signal for benchmark point $M_N = 100$ GeV with the integrated luminosity available for the low luminosity option at 14 TeV LHC. Both the cases for normal (dot-dashed line) and inverted (solid line) hierarchy are shown. Black-dotted (green-dashed) line represents $5\sigma$ ($3\sigma$) significance.

6. SUMMARY AND CONCLUSION

In this work we have considered TeV scale minimal linear seesaw model which generates correct order of light neutrino masses and has sizable light-heavy mixing to produce heavy neutrinos at colliders like LHC. One of the important features of this model is that it can be fully reconstructible from oscillation data excepting an overall factor $y_{\nu}$ characterizing the Dirac Yukawa matrix. However this parameter gets constrained by LFV and vacuum meta-stability bounds. The neutral fermion mass spectrum of this model consists of one massless, two light and two heavy neutrinos.

We have studied the collider phenomenology of TeV scale linear seesaw at 14 TeV LHC. The heavy neutrinos in the model can be dominantly produced through the s-channel. In a leading order calculation, subsequent decay of these leads to characteristic tri-lepton signal with missing $p_T$. We also consider the production of heavy neutrinos through the VBF process. The signal for this is tri-leptons with additional two forward jets which can be tagged. Both these signals as well as SM backgrounds have been estimated with realistic simulations using MadGraph and PYTHIA.

We found that s-channel tri-lepton production process have potential to be discovered at the LHC for both NH and IH. For a benchmark point with heavy neutrino mass $M_N$ as 100 GeV,
5σ significance can be achieved with integrated luminosity of $\sim 12(140)fb^{-1}$ for IH(NH) scenario. Thus the IH scenario has a greater significance since the light-heavy mixing ($V_{lN}$) in this case can be larger. On the other hand, for the VBF channel the significance is found to be very low with the proposed LHC luminosity due to very small cross section. Our choice of the elements $V_{lN}$ of the light-heavy mixing matrix are consistent with the constraints coming from vacuum metastability and LFV and thus are small. Any freedom for choosing arbitrary large value (e.g. $\sim O(1)$) of these parameters can extend the discovery limit by a very significant amount. We also pointed out that in the scenario with positive signal, one can look at the ratio in which different flavor combinations of tri-leptons are produced. This can uncover the hierarchy structure of the light neutrino mass spectrum.

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