Looking for Minimal Inverse Seesaw scenarios at the LHC with Jet Substructure Techniques

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Simple extensions of the Standard Model (SM) with additional Right Handed Neutrinos (RHNs) can elegantly explain the existence of small neutrino masses and their flavor mixings. Collider searches for sterile neutrinos are being actively pursued currently. Heavy RHNs may dominantly decay into $W^± e^±$ after being produced at the LHC. In this paper, we consider collider signatures of heavy pseudo-Dirac neutrinos in the context of inverse seesaw scenario, with a sizable mixing with the SM neutrinos under two different flavor structures, viz., Flavor Diagonal and Flavor Non-Diagonal textures. For the latter scenario we use a general parametrization for the model parameters by introducing an arbitrary orthogonal matrix and nonzero Dirac and Majorana phases. We then perform a parameter scan to identify allowed parameter regions which satisfy all experimental constraints. As an alternative channel to the traditional trilepton signature, we propose the opposite-sign di-lepton signature in the final state, in association with a fat jet from the hadronic decay of the boosted $W^±$. We specifically consider a fat jet topology and explore the required enhancements from exploiting the characteristics of the jet substructure techniques. We perform a comprehensive collider analysis to demonstrate the effectiveness of this channel in both of the scenarios, significantly enhancing the bounds on the RHN mass and mixing angles at the 13 TeV LHC.

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I. INTRODUCTION

Neutrino oscillation experiments have unambiguously established the existence of light neutrino masses and lepton flavour mixings [1–5]. These are not a priori incorporated in the structure of the SM. Understanding the origin of the fermion mass hierarchy and mixing angles, along with exploring new states and sources of CP violation in the lepton sector are of much current interest.

To satisfy the neutrino oscillation data, a simple extension of the SM in the form of the seesaw mechanism suffices to a large extent [6–12]. In these frameworks, SM-singlet heavy Majorana RHNs are introduced, which through a dimension five operator [13] subsequently lead to very small Majorana neutrino masses. If the singlet RHNs reside at the electroweak scale, then the RHNs can be produced at the LHC. Being singlets, these RHNs interact with the SM gauge bosons only through mixing with light SM neutrinos. There is another version of the seesaw mechanism [14–18] wherein the small neutrino mass can be obtained from a naturally small [19] lepton number violating parameter, rather than being suppressed by a heavy RHN mass. In this case, the RHN is of a pseudo-Dirac type and their Dirac Yukawa coupling can be large enough to produce RHNs at the LHC.

The Run-II of the LHC has already accumulated significant amounts of data at $\sqrt{s} = 13$ TeV. The discovery of a fundamental scalar particle, the Higgs boson in the Standard Model (SM) has laid the foundations for a successful understanding of electroweak symmetry breaking. Nevertheless, the non-appearance of any significant excess, supporting any scenario beyond the SM (BSM), strongly motivates us to develop and apply new strategies. The aim of the latter should be to enhance discovery potentials from existing searches as well as to help efficiently explore difficult corners of signal and phase space.

The powerful techniques of jet substructure is one such strategy and in many contexts takes one along untrodden paths. LHC searches have benefitted immensely from developments in jet substructure techniques over the past many years and have enabled investigations of many hitherto challenging signals. Starting from the earlier ideas in jet substructure [20–23] we now have a large toolkit of methods suited to a diverse array of theoretical and experimental challenges. As mentioned, the lack of any unambiguous indications of new physics at collider and non-collider experiments is perplexing though. This has recently reinvigorated searches for novel methodologies and paradigms, for instance, to categorize anomalous objects [24], or efficiently groom jets either stochastically [25] or using the unparalleled power of machine learning [26]. Please see [27, 28] and references therein for detailed discussions.

In collider searches for sterile neutrinos and related
models, there have indeed been studies that have effectively utilized collimated, merged or large-radius objects in the signal topology \[29,37\]. The use of jet substructure methods, that have proven so powerful in other searches, have nevertheless remained underutilized in sterile neutrino searches; especially in the relevant di-lepton + jet(s) topologies. For example, the importance of jet substructure over and above a merely boosted or collimated topology, in improving significance and mitigating backgrounds, is given by the seminal BDRS paper \[23\]. In an earlier work, while considering a generic model with Majorana type heavy neutrinos, we presented a novel strategy, leveraging final states with same-sign di-leptons in the signal topology \[29–37\]. The use of jet substructure while exploring heavy neutrinos to exclusion limits. In the present work, we aim to broaden the scope of sterile neutrino searches to encompass a larger region of the model space. Due to these reasons pursuit of the much more demanding OSDL+fat jet channel may be considered pertinent.

The paper is organized in the following way – in Sec. II we discuss the prototypical model of interest for the searches at the LHC. In Sec. III we then proceed to our analysis, present details of our simulation, benchmark points and the final results. Finally, in Sec. IV we summarize our results and conclude.

\section{Inverse Seesaw Scenario}

In the inverse seesaw \[14,16\] framework, the SM particle content is extended by two SM singlet Majorana RHNs, \(N^\beta\) and \(S^\beta_L\) with same lepton number. \(\beta\) is the flavor index. The relevant part of the Lagrangian can again be written as

\[ \mathcal{L} \supset -Y_D^{\alpha \beta} \bar{\ell} H N^\beta_R - M^{\alpha \beta} S^\beta_L N^\beta_R - \frac{1}{2} \mu_{\alpha \beta} S^{\beta}_{L} S^{\beta}_{L} C + \text{H.c.} \quad (1) \]

Here, \(\ell^\alpha\) and \(H\) are the SM lepton doublet and Higgs doublet, respectively. \(M_D\) is a Dirac mass matrix and \(\mu\) is a small lepton number violating Majorana mass matrix. After EWSB we obtain the neutrino mass matrix

\[ M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M^T \end{pmatrix}. \quad (2) \]

Diagonalizing the mass matrix in Eq. (2), we obtain the inverse seesaw formula for the light neutrino masses as

\[ M_\nu \simeq M_D M^{-1} \mu M^{-1}^T M_D^T. \quad (3) \]

The Dirac mass \(M_D = \frac{Y_D \mu}{\sqrt{2}}\) is generated after EWSB. In order to make our discussions simple we assume degenerate RHMs, with \(M = N_N \times 1\). \(1\) is the unit matrix as before and \(N_N\) is the RHN mass eigenvalue. With these assumptions, the neutrino mass matrix may be simplified as

\[ M_\nu = \frac{1}{M_N^2} M_D \mu M_D^T. \quad (4) \]

Consider a typical flavor structure of the model where \(M_D\) and \(M_N\) are proportional to the unit matrix such as \(M_D \rightarrow M_D \times 1\) and \(M_N \rightarrow M_N \times 1\) respectively. Thus, the flavor structure is now fully encoded in the \(3 \times 3\) matrix \(\mu\). We refer to this scenario as Flavor Diagonal (FD). It has been shown that the FD case in the inverse seesaw mechanism is also accommodated by neutrino oscillation data \[39\]. Another flavor structure possible in the inverse seesaw scenario is where \(M_D\) carries flavor structure while \(\mu \rightarrow \mu \times 1\) and \(M \rightarrow M_N \times 1\). This is called the Flavor Non-Diagonal (FND) scenario. This has been studied for different signals in \[39,40\], under general parametrization \[41\].

Assuming \(M_D M_N^{-1} \ll 1\), we can express the flavor eigenstates \((\nu)\) of the light Majorana neutrinos in terms of the mass eigenstates of the light \((\nu_m)\) and heavy \((N_m)\) Majorana neutrinos such as

\[ \nu \simeq N\nu_m + R N_m, \quad (5) \]

where

\[ R = M_D M_N^{-1}, \quad N = \left(1 - \frac{1}{\epsilon}\right) U_{\text{PMNS}}, \quad \epsilon = R^* R^T, \quad (6) \]
and $U_{PMNS}$ is the usual neutrino mixing matrix by which the mass matrix $m_\nu$ is diagonalized as

$$U_{PMNS}^T m_\nu U_{PMNS} = \text{diag}(m_1, m_2, m_3).$$

In the presence of $\epsilon$, the mixing matrix $\mathcal{N}$ is not unitary. The charged current (CC) and neutral current (NC) interactions may be expressed in terms of the mass eigenstates of the RHNs as

$$\mathcal{L}_{CC} \supset -\frac{g}{\sqrt{2}} P_L \bar{\nu}_m \gamma^\mu P_L R N_m + \text{H.c.},$$

where $\epsilon$ denotes the three generations of charged leptons, and $P_L = \frac{1}{2} (1 - \gamma_5)$ is the projection operator. Similarly, in terms of the mass eigenstates the neutral current interaction may be written as

$$\mathcal{L}_{NC} \supset -\frac{g}{2 c_w} Z_m \left[ \overline{N}_m \gamma^\mu P_L (R \gamma^\gamma R) N_m \right. + \left. \epsilon L \gamma^\mu P_L (N \gamma^\gamma N) N_m + \text{H.c.} \right],$$

where $c_w = \cos \theta_w$ with $\theta_w$ being the weak mixing angle. We notice from Eqs. (8) and (9) that the production cross section of the RHN in association with a SM charged lepton (or SM light neutrino) is proportional to $|V_{eN}|^2$.

In our analysis, we will consider two degenerate pseudo-Dirac type RHNs separately being coupled to the SM charged leptons $e$ and $\mu$ respectively. Hence in our analysis we consider $M_N \rightarrow M_N \times \mathbb{I}_{2 \times 2}$. In this model framework we will also separately study the case when a RH is coupled with $\mu$, which we name as the single flavor case. The two flavor case, without considering flavor detection efficiencies, will roughly double the number of signal events relative to the single flavor case.

At this point, for completeness, we must also comment that the seesaw and inverse seesaw mechanisms in the context of Left-Right (LR) models will also produce OSDL + fat jet final states. In the seesaw framework we have already tested the same-sign di-lepton (SSDL) signature in association with a fat jet [35]. OSDL + fat jet provides another important channel towards completeness of RHN searches. Also, the neutral charge multiplet in type-III seesaw [43] is a Majorana candidate and may also be studied in the final state of interest. Finally, there is another version of the seesaw mechanism, commonly known as linear seesaw [44, 45] where pseudo-Dirac RHNs are introduced, which too contributes to this channel.

The elements of the $\mathcal{N}$ and $\mathcal{R}$ matrices in the Eqs. (5) and (7) can be constrained by the experimental results. To do this we adopt the current neutrino oscillation data: $\sin^2 2\theta_{13} = 0.092$ [4], along with the other oscillation data \[46\]: $\sin^2 2\theta_{12} = 0.87$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{21} = m^2_2 - m^2_1 = 7.6 \times 10^{-5}$ eV$^2$, $\Delta m^2_{32} = |m^2_3 - m^2_2| = 2.4 \times 10^{-3}$ eV$^2$. The neutrino mixing matrix is given by

$$U_{PMNS} = \begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{i\delta} \\ S_{12}C_{12} - C_{12}S_{13}e^{i\delta} & C_{12}C_{12} - S_{12}S_{13}e^{i\delta} & S_{13}e^{i\delta} \\ S_{12}C_{23} - C_{12}S_{13}e^{i\delta} & -C_{12}C_{23} - S_{12}S_{13}e^{i\delta} & C_{23}C_{13} \end{pmatrix} \mathcal{P}$$

where $C_{ij} = \cos \theta_{ij}$, $S_{ij} = \sin \theta_{ij}$ and the Majorana phase $\delta$ and the Dirac CP-phase $\rho$ as free parameters.

The elements of the mixing matrix $\mathcal{N}$ are severely constrained by the neutrino oscillation data, the precision measurements of weak gauge boson decays and the lepton-flavor-violating decays of charged leptons due to the effect of non-unitarity. Using the most recent data for the lepton flavor violating (LFV) experiments we write

$$|\mathcal{N}^\dagger \mathcal{N}| = \begin{pmatrix} 0.994 \pm 0.00625 & < 1.288 \times 10^{-5} & < 8.76356 \times 10^{-3} \\ < 1.288 \times 10^{-5} & 0.995 \pm 0.00625 & < 1.046 \times 10^{-2} \\ < 8.76356 \times 10^{-3} & < 1.046 \times 10^{-2} & 0.995 \pm 0.00625 \end{pmatrix}.$$
estimate $\epsilon$ using $N \mathcal{N}^\dagger \simeq 1 - \epsilon$. The stringent bound is coming from the (12) element which is obtained by the $\mu \rightarrow e\gamma$ process.

In the minimal scenario, one eigenstate can be predicted as massless. For the light neutrino mass spectrum, we consider both the normal hierarchy (NH) and the inverted hierarchy (IH). In the NH case, the diagonal mass matrix is given by

$$D_{\text{NH}} = \text{diag} \left( 0, \sqrt{\Delta m^2_{\text{12}}}, \sqrt{\Delta m^2_{\text{12}} + \Delta m^2_{\text{23}}} \right),$$

while in the IH case

$$D_{\text{IH}} = \text{diag} \left( \sqrt{\Delta m^2_{\text{23}} - \Delta m^2_{\text{12}}}, \sqrt{\Delta m^2_{\text{23}}}, 0 \right).$$

For the FND case, we describe $\epsilon$ as

$$\epsilon = \frac{1}{M^2} m_D^T m_D = \frac{1}{\mu} U_{\text{PMNS}}^T D_{\text{NH/IH}} U_{\text{PMNS}}^T,$$

and determine the minimum $\mu$ value ($\mu_{\text{min}}$) so as to give $\epsilon_{12} = 1.288 \times 10^{-5}$ we use the oscillation data. We have found $\mu_{\text{min}} = 6.114$ keV and $3.832$ keV for the NH and IH cases, respectively. Here we have used the fact that all parameters are real according to our assumption. In this way, we can completely determine the mixing matrices $R$ and $N$ considering $\mu = \mu_{\text{min}}$, which optimizes the production cross sections of the heavy neutrinos at the LHC. We also consider a general parameterization for the neutrino Dirac mass matrix for the FND case. From the inverse seesaw formula,

$$m_\nu = \mu R R^T = \frac{\mu}{M^2} m_D^T m_D^T = U_{\text{PMNS}}^* D_{\text{NH/IH}} U_{\text{PMNS}}^T,$$

we can generally parameterize $R$ as

$$R(\delta, \rho, X, Y) = \frac{1}{\sqrt{\rho}} U_{\text{PMNS}}^* \sqrt{D_{\text{NH/IH}}} O,$$

where $O$ is a general orthogonal matrix expressed as

$$O = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \cos Y & i \sinh Y \\ -i \sinh Y & \cosh X \end{pmatrix} \begin{pmatrix} \cos X & \sin X \\ -\sin X & \cosh X \end{pmatrix} \begin{pmatrix} \cos Y & i \sinh Y \\ -i \sinh Y & \cosh X \end{pmatrix},$$

with a complex number $\alpha = X + iY$. Thus in this general parameterization we express

$$\epsilon(\delta, \rho, Y) = R^* R^T = \frac{1}{\mu} U_{\text{PMNS}}^* \sqrt{D_{\text{NH/IH}}} O^* O^T \sqrt{D_{\text{NH/IH}}} U_{\text{PMNS}}^T.$$  

Note that

$$O^* O^T = \begin{pmatrix} \cosh^2 Y + \sinh^2 Y & -2i \cosh Y \sinh Y \\ 2i \cosh Y \sinh Y & \cosh^2 Y + \sinh^2 Y \end{pmatrix}$$

is independent of $X$, and hence the $\epsilon$-matrix is a function of $\delta$, $\rho$ and $Y$.

### III. COLLIDER ANALYSIS AND RESULTS

We are interested in a very specific decay topology arising from the production and decay of heavy sterile neutrinos. The schematic of the prototypical parton level process, at the leading order, is shown in Fig. 1:

$$q \bar{q}^* \rightarrow W^{\pm*} \rightarrow \mu^{\pm} N, N \rightarrow \mu^+ W^-, W^\pm \rightarrow J$$

We focus on opposite-sign (OS) muon pair final states, in association with a reconstructed fat jet, at $\sqrt{s} = 13$ TeV LHC. For simplicity, we demonstrate explicitly our analysis assuming a simple, single flavor scenario where the light-heavy mixing is non-zero only for the muon flavor. This is also motivated by the fact that muons provide a clear detection at the LHC with high efficiency and hence is of primary interest. We will however also include the electron channel while discerning the final exclusion results.

As motivated earlier, the OSDL signature, unlike our previously studied SSDL signature, is prone to much larger SM backgrounds – coming from $t\bar{t}$, mono-boson, di-boson and tri-boson productions. This makes the analysis challenging and interesting. Here we will argue and demonstrate that the additional W-like fat jet can be identified effectively by looking at different jet substructure parameters and that this consequently will lead to clear OSDL signatures, emerging over and above the humongous backgrounds.

We generate events using Madgraph5 (v2.5.4) [60] [67] followed by Pythia (v8) [58] for showering and hadronization. MLM matching [59] [60] of the shower jets and the matrix element jets have been done using the default $k_t$-MLM algorithm with $x_{\text{cut}} = 30$ and the corresponding jet matching parameter (QCUT) is 1.5 times the $x_{\text{cut}}$ [61]. $p_T^j$ and $\Delta R_{ij}$ are set to zero for $k_t$-MLM matching. MLM matching reduces double counting of jets coming from the showers and the matrix element partons. Subsequent to this, the detector simulation is implemented using Delphes-v3.4.1 [62]. We use Fastjet-v3.3.2 [63] to identify fat jets using the Cambridge-Aachen algorithm [64]. Jet parameters corresponding to $R = 0.8$ and $p_T^{\text{min}} = 10$ GeV are adopted.

Opposite-sign di-leptons can arise from different production channels with gauge boson decays. Leptonic decays from $t\bar{t}$ can also give a substantial contribution. Our signal characteristic of a W-like fat jet can be faked by all such channels in association with additional QCD jets. Hence, to be consistent and thorough, all background production channels were produced with additional partons; with proper matching to showers. Moreover, associated $W^\pm$ bosons decaying hadronically may also generate irreducible backgrounds. We considered all the relevant dominant SM backgrounds which can mimic the OS di-muon and fat jet signal.

Significantly large contribution can come from $Z + \text{jets}$ when the $Z$ boson decays leptonically. This is a large background and can be effectively controlled by applying
much stronger cuts on the invariant mass of opposite-sign di-leptons ($M_{ll}$). QCD jets in these process can be controlled in addition through jet substructure. A significant background is also expected from $t\bar{t} plus jets$, where top decays leptonically. Vetoing $b$-jets and proper implementation of fat jet variables can again control this background. The efficiency of $b$-tagging is approximately 70% while misidentification of a light parton jet as a $b$-tagged jet is 1.5% \cite{75}. Additional modes that may contribute include $VV + plus jets$ and $V V V + plus jets$, where either of the vector bosons ($V=W^{\pm},Z$) decay leptonically to generate di-lepton pairs. Note that a number of these backgrounds subsequently produce missing neutrino(s) and/or missing charged leptons that can substantially add to the missing transverse momentum. In the signal process of interest whereas this is not the case, since we are considering hadronic decays of the $W^{\pm}$. The only dominant source of missing energy in the signal arises from possible jet energy mis-measurements. We use next-to-next-leading order estimate in QCD perturbation theory for the production cross section for $Z$ boson as 2089 pb \cite{76} and $W^{\pm}Z = 51.11$ pb \cite{77}. Furthermore, $W^+ W^- and W^+ W^- Z$ the production cross section is computed at NLO to be 112.64 pb \cite{78} and 103.4 fb \cite{79} respectively. For $t\bar{t}$ we use production cross section as 835.61 pb computed at $N^3LO$ \cite{80}. The next-to-leading order QCD correction for heavy neutrino production and scale uncertainties are studied in \cite{81}. For signals, we use suitable NLO cross section. Before moving for our analysis we list our basic selection criteria as following.

**Primary selection criteria** - To identify the leptons as well as the fat jet, we implement the following **baseline selection** of the events.

- Two opposite sign muons are selected with $p_T > 10$ GeV within the detector rapidity range $|\eta_{\mu}| < 2.4$, assuming a muon detection efficiency of 95%. We veto the event if any additional reconstructed lepton with $p_T > 10$ GeV is present.
- We demand at least one fat jet, reconstructed adopting the CA algorithm with radius parameter $R = 0.8$ and $|y| < 2.4$. We select events with the hardest reconstructed fat jet ($J_0$) having minimum transverse momentum $p_T^{J_0} > 100$ GeV.

Let us now discuss the main kinematic characteristics that may be important in differentiating signal events from the various large backgrounds. Several such features were already identified during the description of the background processes and they were suggestive in their effectiveness in controlling specific background channels. Before moving further, we identify our signal benchmark points - labelled in terms of the sterile neutrino mass $M_N$ and mixing angle $|V_{\mu N}|^2$, they are $M_N = 400$ GeV, 800 GeV and $|V_{\mu N}|^2 = 0.01$. Kinematic distributions are independent of the mixing angle and they are presented as normalized distributions, with differences between signal benchmark points and background processes highlighted.

Two extreme mass points are chosen to establish the significantly different kinematic characteristics, which could be leveraged to identify the optimized selection cuts for various masses.

As the two leptons in the signal process are produced at two different stages of decay, they carry distinctly different transverse momentum profiles. The second lepton originating from the heavy neutrino decay is expected to be significantly boosted, since the relevant $M_N$ are large. The hardest lepton in the signal event is hence generally expected from this stage and is expected to peak around $(M_N^2 - M_W^2)/(2M_N)$. This may be noted in Fig. 2 (left). All the SM backgrounds display milder hard-lepton transverse momentum profiles in comparison.

**Distributions**

- **FIG. 2:** Normalized distributions of transverse momentum $p_T$ of leading muon (left) and sub-leading muon (right). These distributions are after the **baseline selection cuts**. The distribution of heavy neutrino benchmark points with $M_N = 400$ and 800 GeV is shown along with three dominating background processes.
Here, $N_{\text{subjettiness}}$ is defined as $\Delta R_{\alpha i} = \sqrt{(\Delta \eta)_{\alpha i}^2 + (\Delta \phi)_{\alpha i}^2}$. N-subjettiness tries to quantify how much the original jet seems to be composed of N daughter subjets. A small value of $\tau_N$ suggests that the original jet may consist of N or fewer subjets. It has been demonstrated that a good discriminant to tag an N-subjet object is to consider ratios of adjacent N-subjettiness values $\tau_{N+1}/\tau_N$. For W-tagging, since the $W^{\pm}$ yields two subjets that are collimated, the variable of interest would therefore be $\tau_{N+1}/\tau_N$. The mass of the fat jet ($M_J$), is another discriminant that may be leveraged to identify the jet as originating from a hadronically decaying $W^{\pm}$. The fat jet four momenta is the vector sum of all the constituent four momenta, in the E-scheme. From this reconstructed fat jet four momenta ($p_T^J$) the invariant fat jet mass ($M_J^2$) may be computed.

**Delphes 3.3.2** hadron calorimeter outputs are clustered using **FastJet 3.1.3** to reconstruct the candidate fat jet. The N-subjettiness extension, available through **FastJet-contrib**, is used to compute $\tau_{N+1}/\tau_N$. For tagging the hadronically decaying $W^{\pm}$ we adopt parameter choices from a CMS analysis [75], as a starting point. We choose Cambridge-Aachen [64, 76] for the recombination algorithm, with a jet-cone radius $R = 0.8$. Further refinements for W-tagging are then made by requiring specific cuts on $\tau_{N+1}/\tau_N$ and $M_J$.

The $p_T$ of the boosted $W^{\pm}$ scales as $p_T^W \sim (M_N^2 - M_{W^{\pm}}^2)/(2M_N)$. Fig. 3 (right) presents the distributions for fat jet transverse momenta $p_T^J$. With the minimum transverse momentum of 100 GeV already implemented during primary selection, one notices the spread and second peak (towards higher values) for the signal distributions suggestive of its origin from the decay of the heavy $N$. This second peak in comparison to one at the lower value becomes more and more prominent as expected for various backgrounds. MET is calculated from the transverse momentum imbalance of all the isolated objects such as leptons, photons and jets, as well as any unclustered deposits. MET for our signal process is expected to be relatively small, affected only by mismeasurements in clustering and jet reconstructions; no missing particles are involved per se. On the contrary, a large fraction of the background processes come with leptons from $W$ decays which are always associated with corresponding neutrinos. These thereby produce substantial MET contribution over and above contributions from jet mismeasurements. This trend is discernible in the plots.

The next three distributions we discuss primarily define the characteristics of the highest transverse momentum fat jet ($J_0$), which we rely upon heavily to mitigate backgrounds further. We will primarily utilize fat jet transverse momentum ($p_T^J$), jet mass ($M^J_0$) and N-subjettiness ($\tau_{N+1}^J$) for signal background discrimination and tagging.

Boosted fat jet topologies and their associated jet substructures have proven crucial in various supersymmetric and non-supersymmetric LHC searches [27]. In the $t\bar{t}f\bar{f}J$ topology of present interest, the fat jet evolves from the boosted, hadronically decaying $W^{\pm}$; the right handed sterile neutrinos $N_R$ are heavier than $W^{\pm}$ giving the latter large boosts. In the analysis, the importance of jet substructure therefore primarily manifests as a means to efficiently tag boosted, hadronically decaying $W^{\pm}$. As mentioned, we will utilize two well-known jet substructure variables towards this requirement – N-subjettiness [72, 73] and jet-mass.

The fat jet appearing from $W^{\pm} \rightarrow q\bar{q}'$ potentially retains some information of its two-prong structure. We would like to leverage this aspect to help tag it. N-subjettiness [72, 73] is defined as

$$\tau_N^J = \frac{1}{N_0} \sum_i p_{i,T} \min \left\{ \Delta R_{i1}^\beta, \Delta R_{i2}^\beta, \ldots, \Delta R_{iN}^\beta \right\}. \quad (21)$$

Here, $N_0 = \sum_i p_{i,T} R_0$ for a jet radius $R_0$, with $i$ running over the constituent particles, and $p_{i,T}$ is the respective transverse momentum. We compute N-subjettiness with the thrust measure $\beta = 2$. The $\eta \rightarrow \phi$ distance between a candidate $\alpha$-subjet and constituent particle $i$ is defined as $\Delta R_{\alpha i} = \sqrt{(\Delta \eta)_{\alpha i}^2 + (\Delta \phi)_{\alpha i}^2}$. N-subjettiness tries to quantify how much the original jet seems to be composed of N daughter subjets. A small value of $\tau_N$ suggests that the original jet may consist of N or fewer subjets. It has been demonstrated that a good discriminant to tag an N-subjet object is to consider ratios of adjacent N-subjettiness values $\tau_{N+1}/\tau_N$. For W-tagging, since the $W^{\pm}$ yields two subjets that are collimated, the variable of interest would therefore be $\tau_{N+1}/\tau_N$. The mass of the fat jet ($M_J$), is another discriminant that may be leveraged to identify the jet as originating from a hadronically decaying $W^{\pm}$. The fat jet four momenta is the vector sum of all the constituent four momenta, in the E-scheme. From this reconstructed fat jet four momenta ($p_T^J$) the invariant fat jet mass ($M_J^2$) may be computed.

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larger $M_N$. The $P_T$ of candidate fat jets from all background processes monotonously fall. Evidently, larger values for the transverse momentum cut helps us in selecting relatively more signal-like fat jets, in comparison to background events. This may probably be at the cost of some signal events but would nevertheless also help mitigate backgrounds, and potentially result in a net significance gain.

The two plots in Fig. 4 highlight the internal characteristics of the identified fat jets, in the form of the invariant jet mass $M^{J_0}$ (left) and the N-subjettiness ratio $\tau^{J_0}_{21}$ (right). These jet substructure variables help correctly tag the candidate fat jet as W-like or not. Construction of these variables are as defined earlier in this section and they provide a powerful tool to discriminate the QCD jet contaminations.

Signal distributions for $M^{J_0}$ clearly peak at $M_W$ reflecting their origin as W-like jets. For low $M_N$, the $W^\pm$ boosts are smaller and with the $P_T > 100$ GeV cut and $R = 0.8$ jet radius some of the $W^\pm$ hadronic decay products are not captured inside the cone. This is evident as a secondary, spurious peak at a lower mass value in the plots. However, for heavier $M_N$ or with a choice of a larger transverse momentum cut, only the peak around 80 GeV survives. We retain the $P_T$ cut at 100 GeV, as this gives an overall higher signal significance across the $M_N$ mass ranges under consideration. The most SM backgrounds peak at low $M^{J_0}$, except those where fat jets are indeed W-like e.g. backgrounds from $Z^0W^+W^-$ or $Z^0W^+W^-$ (superscript $l/h$ for leptonic/hadronic decay modes). These particular backgrounds are not shown in the plots for readability and for the reason that their final contributions in the present channel will be minuscule after applying all selection criteria.

The N-subjettiness ratio $\tau_{21} = \tau_2/\tau_1$ is the other jet substructure quantity of interest. It quantifies the two-pronged nature of the fat jet arising from boosted-$W^\pm$ hadronic decays and discriminates it from the structureless jets coming from QCD. The distribution of $\tau_{21}$ for signal and backgrounds is shown in Fig. 4 (right). By construction $\tau^{J_0}_{21}$ for W-like fat jets is expected to peak at low values. The separation between the hadronic decay products of $W^\pm$ scale as $M_W/P_T$. It is observed that the W-like fat jets from the signal benchmark points peak around 0.15, whereas most backgrounds with QCD jets peak at much higher values, around 0.6.

With a detailed understanding of the above kinematic and jet substructure variable distributions we are now in a position to make appropriate choices for the final selection criteria. Choice for the final event selection criteria are optimized towards the lower mass regions with the benchmark point at $M_N = 400$ GeV. This is chosen for simplicity of demonstration and the fact that one gets a large cross-section here with a reasonable efficiency from jet characteristics. It nevertheless also provide good signal significance across the full mass range of interest. Various kinematic variables along with fat jet observables are constrained in the following way:

- The highest $p_T$ muon is selected with $p_T > 100$ GeV and the next $p_T$ ordered muon is selected with $p_T > 60$ GeV. These relatively harder selection criteria are effective in mitigating most of the backgrounds, as motivated from Fig. 2. The large $t\bar{t}$ background is reduced without affecting the signal substantially.
- To control the huge backgrounds coming from leptonic decays of $Z$ bosons, we veto events if the opposite-sign di-muon invariant mass ($M_{\mu^+\mu^-}$) is less than 200 GeV. The harder cut on $M_{\mu^+\mu^-}$ also reduces parts of the $t\bar{t}$ background further.
- We apply a b-veto to reduce the $t\bar{t}$ background without affecting signal acceptance.
- As mentioned earlier, it is evident that our signal does not have any missing particle per se, hence should have relatively low MET. The final $P_T$ would of course get contributions from measurements and uncertainties. Taking into account the
FIG. 5: The figure shows the exclusion limits, in terms of heavy neutrino mass $M_N$ and $|V_{eN}|^2$, at 3000 fb$^{-1}$ of integrated luminosity at the 13 TeV LHC.

unclustered towers, we consider only events with a maximum MET of 60 GeV.

- Events with the leading fat jet ($J_0$) having transverse momentum $p_T^{J_0} > 150$ GeV are selected. This is done in order to increase the purity of the boosted jets further.

- For signal events, the fat jet is reconstructed from the boosted $W$ boson. Hence, we demand for the corresponding mass, $M^{J_0} > 50$ GeV.

- We choose events with N-subjettiness $\tau_{21} < 0.4$.

We present the analysis and describe the results explicitly for a few example benchmark signal points – $M_N = 300$ GeV and 400 GeV – for single flavour Dirac neutrino, together with the main backgrounds. In Table I we summarize the effect of each selection cut in the order presented before. Expected number of events after baseline selection and the number of surviving events after each subsequent cuts (also in terms of percentages) are presented in the first and successive rows, assuming an integrated luminosity of 3000 fb$^{-1}$. Here, one can follow sequentially the cut efficiency for the signal and background events as per our previous discussions. It is seen that harder cuts for leptons indeed reduce all the backgrounds, without affecting the signal significantly. One can have an even harder choice for the highest-PT lepton, when probing larger $M_N$. Veto on b-jets shrinks events from $t\bar{t}$ and missing transverse energy (MET) is effective for all backgrounds possessing additional MET contributions from neutrinos. The other three selections in the form of $p_T^{J_0}$, $M^{J_0}$ and $\tau_{21}$ rely on the fat jet substructure and reduce all dominant backgrounds where fat jets are mimicked by QCD jets. Overall efficiency for the 400 GeV signal can be observed to be around 22\%, whereas different backgrounds are reduced to between $4 \times 10^{-5}$\% and 0.9\%. Note that the signal cross-section for heavier mass falls significantly, due to production s-channel suppression. However, better substructure efficiencies partially mitigate that reduction. This is evident from the $M_N = 300$ GeV and 400 GeV results. Statistical significances for the observed signal events ($S$) over the total irreducible standard model backgrounds ($B$) are calculated adopting the familiar expression $S = \sqrt{2 \times ((S + B) \ln(1 + S/B) - S)}$.

A. Flavor democratic case

In this section we study the FD scenario where the two degenerate RHNs are equally mixed with the $e$ and $\mu$ leptons. After the signal and SM background analyses we have displayed the exclusion limits on the $|V_{eN}|^2$ as a function of the $M_N$ in Fig. 5. We have assumed 3000 fb$^{-1}$ integrated luminosity at 13 TeV LHC. There is no direct search result for the RHNs at this mass range for the inverse seesaw scenario at the colliders. In this same figure limits are also indicated if the OSDL along with a fat-jet is searched for the Majorana neutrino. Heavy Majorana neutrino, if exits in nature, should also show up in equal strength producing lepton number violating same sign di-leptons, where backgrounds are immensely suppressed. Evidently SSDL bounds are extremely strong and studied extensively [35] in see-saw framework along with fat-jet. Corresponding efficiency for selecting muon signals is at 70\% while it is reduced to 50\% for electron events. For different seesaw models, the exclusion limits for lower $M_N$ values can be as low as $5 \times 10^{-3}$. The heavy neutrino production, especially at heavier mass, can get (10\% − 60\%) additional contribution for the mass limit under consideration from $\gamma - W^\pm$ fusion [77, 78], and thus can potentially improve the exclusion limits further.

We reiterate that the given limits are based on simple criteria, optimized at $M_N = 400$ GeV. There is ample scope for improvements at higher masses. One can readily recognize the quantities which may crucially factor in for higher masses. For instance, RHN possessing mass of several hundreds of GeV would often produce both
| Cut | Signal | Background |
|-----|--------|------------|
| $M_N = 300\,\text{GeV}$ | 1071.17 | 500.95 |
| $M_N = 400\,\text{GeV}$ | 5.1 $\times 10^7$ | 5.6 $\times 10^6$ |
| | 2.2 $\times 10^5$ | 5.7 $\times 10^5$ |
| | 1.4 $\times 10^3$ | 120.8 |
| b-veto | 525.76 | 308.05 |
| | 530.6 | 6.2 $\times 10^4$ |
| | 2.0 $\times 10^4$ | 8.54 |
| | 647.74 | 8.5 | 10.42 |
| $p_T(f_1) > 100\,\text{GeV}$ | 800.38 | 144.55 |
| | 928.6 | 126.89 |
| $p_T(f_2) > 60\,\text{GeV}$ | 2.2 $\times 10^4$ | 530.6 |
| | 1.4 $\times 10^3$ | 120.8 |
| | 273.73 | 33.64 |
| $M_{\mu^+\mu^-} > 200\,\text{GeV}$ | 428.82 | 359.81 |
| | 583.7 | 4.2 $\times 10^4$ |
| | 2.2 $\times 10^4$ | 9.4 |
| | 724.76 | 10.42 |
| $p_T^{\ell b} > 150\,\text{GeV}$ | 482.77 | 371.4 |
| | 735.9 | 2.1 $\times 10^4$ |
| | 779.6 | 6.0 |
| | 353.04 | 3.8 |
| $M^{\ell b} > 50\,\text{GeV}$ | 48.95 | 178.06 |
| | 265.32 | 7635.9 |
| | 3898 | 8.27 |
| | 195.96 | 2.5 |
| $M^{\ell b}_\ell > 500\,\text{GeV}$ | 145.55 | 126.89 |
| | 42.4 | 1754.2 |
| | 843.08 | 0.68 |
| | 48.21 | 1.3 |
| $\tau_{21} < 0.4$ | 123.23 | 112.73 |
| | 21.18 | 928.6 |
| | 396.7 | 0.34 |
| | 32.66 | 1.0 |
| $\tau_{12} > 100\,\text{GeV}$ | 409.05 | 614.61 |
| | 437.45 | 582.7 |
| | 144.55 | 126.89 |
| | 42.4 | 1754.2 |
| | 843.08 | 0.68 |
| | 48.21 | 1.3 |
| $\tau_{32} > 100\,\text{GeV}$ | 145.55 | 126.89 |
| | 42.4 | 1754.2 |
| | 843.08 | 0.68 |
| | 48.21 | 1.3 |

**TABLE I:** Expected number of events in $\mu^+\mu^- + J$ channel after implementation of the corresponding event selection criteria for an integrated luminosity of 3000 fb$^{-1}$ at the 13 TeV LHC. We choose the value of mixing angle $|V_{\mu N}|^2$ to be 0.01. The signal events are shown for Dirac neutrino mass $M_N = 300$ and 400 GeV in the case of single flavor.

**B. General parametrization: Flavor non democratic case**

In this section we study the flavor non democratic (FND) scenario where the flavor structure is carried out by the Dirac Yukawa coupling. According to our formalism the mixing between the light and heavy neutrinos ($R = V_{N}$) is a function of the Dirac phase ($\delta$) and the Majorana phase ($\rho$). $R^* R^T$ is a function of the general parameter $Y$ coming from the general orthogonal matrix $O$. We perform a parameter scan by varying these parameters between $-\pi \leq \delta, \rho \leq \pi$ with an interval of $\frac{\pi}{20}$ and $0 \leq Y \leq 1$ with an interval of 0.02. The elements of the Dirac mass matrix grow exponentially with $|Y|$. For a value $Y > 1$, the neutrino oscillation data are realized under the fine-tuning between the large elements. Although the neutrino oscillation data are correctly reproduced for any values of $Y$ in the general parametrization, we only consider $Y \leq 1$ to avoid the fine-tuning. The ranges of the independent parameters like $\delta, \rho$ and $Y$ satisfy the constraints on $\epsilon$. Hence we calculate the cross section for the $i-th$ generation RHN at the LHC through the W boson exchange process $u_d \rightarrow \ell_{\alpha}^{+} N_i$ and $d_u \rightarrow \ell_{\alpha}^{+} N_i$. Hence the production cross section at the LHC can be written as

$$\sigma(qq^* \rightarrow \ell_{\alpha}^{+} N_i) = \sigma_{\text{LHC}}|R_{\alpha i}(\delta, \rho, Y)|^2$$ (22)
TABLE III: Calculated upper limits on the mixing angles for the NH and IH cases and comparison with the EWPD

| Mixing Angles | Calculated upper limits | EWPD |
|---------------|-------------------------|------|
| $|V_{eN}|^2$ (NH) | $6.908 \times 10^{-4}$ | $1.68 \times 10^{-3}$ |
| $|V_{eN}|^2$ (IH) | $1.884 \times 10^{-4}$ | |
| $|V_{\mu N}|^2$ (NH) | $8.963 \times 10^{-4}$ | $9.0 \times 10^{-4}$ |
| $|V_{\mu N}|^2$ (IH) | $1.923 \times 10^{-4}$ | |

where $\sigma_{\text{LHC}}$ is the production cross section the RHNs at the LHC. The partial decay widths of the RHN ($N_i \rightarrow \ell_i W^+/\nu_\ell Z/\nu_\ell h$) can be found by multiplying the corresponding decay widths by $|R_{\alpha}\delta,\rho,Y|^2$. As a result the corresponding branching ratios can be expressed in terms of $\delta, \rho$ and $Y$ through the elements of the mixing matrix. Running the parameters within the allowed ranges and satisfying the constraints obtained from $\Delta N^2 \simeq 1 - \epsilon$ we obtain the upper limits on the mixing angles for the NH and IH cases with two electron ($|V_{eN}|^2$) and two muon ($|V_{\mu N}|^2$) final states, respectively in Tab. III. We compare our results with the bounds obtained from the EWPD [79–81] on $|V_{eN}|^2$ $(1.68 \times 10^{-3})$ and $|V_{\mu N}|^2$ $(9.0 \times 10^{-4})$ respectively. We notice that the allowed upper limit on $|V_{\mu N}|^2$ and $|V_{eN}|^2$ in the NH and IH cases are below the corresponding EWPD limits.

IV. SUMMARY AND CONCLUSION

The Seesaw framework gives an elegant but simple mechanism for tiny neutrino masses and flavor mixings. If the sterile neutrinos in these models appear close to the electroweak scale, they may be probed at the 13 TeV LHC. Conventionally such searches for heavy neutrinos, Majorana or pseudo-Dirac, are made in the di-lepton+jets or trilepton channels. Jet substructure methods have been relatively underutilized in these contexts. In this work we extended the same-sign di-lepton + fat jet channel investigated earlier, to the more challenging opposite-sign di-lepton + fat jet final state. The opposite-sign di-lepton state is expected to encounter a huge standard model background. This channel is nevertheless very important as it may be the only final state, with jets, for a class of models with Dirac or pseudo-Dirac type neutrinos. Hence, strategies to effectively investigate the opposite-sign di-lepton along with a fat jet would greatly broaden the scope of collider sterile neutrino searches – both in terms of probing model aspects as well as uncovering the nature of the heavy sterile neutrinos.

In the present analysis we propose a new strategy to search for intermediate to heavy mass sterile neutrinos,
We also investigate the lepton flavor conserving modes in the flavor non-diagonal cases, for electron and muon flavors both in normal as well as inverted hierarchy. Such models are studied after utilizing extensive constraints coming from neutrino oscillation data, lepton flavor violation constraints and LEP considerations with general parametrization being constrained by non-unitarity. For $M_N = 175$ GeV, a signal $\mu^+\mu^-+\text{fat jet}$ with a significance of $5\sigma$ in the NH case can potentially be constrained in the near future at the 13 TeV LHC, with a luminosity of 3000 fb$^{-1}$.

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