Probing vector-like top partner from same-sign dilepton events at the LHC

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Abstract
The standard model is a successful theory but is lacking a mechanism for neutrino mass generation as well as a solution to the naturalness problem. In the models that are proposed to simultaneously solve the two problems, heavy Majorana neutrinos and top partners are usually predicted to lead to a new decay mode of the top partner mediated by the heavy Majorana neutrinos: \( T \rightarrow b W^+ \rightarrow b \ell^+ \ell^- q q' \). In this paper, we will study the observability of such a new signature via the pair production process of a top partner \( pp \rightarrow TT \rightarrow 2b + \ell^+ \ell^- + 4j \) in a model independent way. By performing Monte Carlo simulations, we present the 2\( \sigma \) exclusion limits of the top partner mass and mixing parameters at the HL-LHC.

Keywords: top quark partner, LHC, same sign leptons

(Some figures may appear in colour only in the online journal)

1. Introduction

The standard model (SM) has been a successful low-energy effective theory in describing microscopic phenomena and was completed by the discovery of the Higgs boson in 2012 at the LHC. However, a theory beyond the SM (BSM) is necessary from both theoretical and experimental points of view, one of which is the so-called naturalness problem. With the mass of the observed scalar (\( \sim 125 \text{ GeV} \)) being comparable to the electroweak scale (\( \sim 10^2 \text{ GeV} \)), the naturalness arguments require some mechanism or symmetries to suppress or cancel out the large quadratic divergence when considering loop corrections from heavy particles, such as the SM top quark, which can lead the Higgs mass up to the Planck scale (\( \sim 10^{19} \text{ GeV} \)) instead of the electroweak one. Many BSM models, such as the little Higgs models [1, 2] and composite Higgs models [3–6], have been proposed to solve this problem by introducing a spontaneously broken global symmetry, leading the Higgs boson to a pseudo Goldstone boson. In these BSM models, vector-like top partners (VLTs), usually referred to as \( T \), are predicted. VLTs are color-triplet fermions but with the left- and right-handed components transforming in the same way under the gauge group \( SU(2) \otimes U(1) \). These new particles have been searched for at hadron colliders, where they can be produced both singly and in pairs, with subsequent decays into an SM quark and a gauge boson or Higgs boson [7–16]. Searches at the LHC for VLTs have been performed and presented by the ATLAS and CMS collaborations with the lower mass bounds on \( T \) reaching up to about \( 740 \sim 1370 \text{ GeV} \), depending on the SU(2) multiplets they belong to and different branching fractions assumed [17, 18].

Another motivation for BSM is the observation of neutrino oscillation in solar, atmospheric, reactor and accelerator experiments, which implies that neutrinos of three flavors are mixed and have tiny masses (\( \sim \text{sub-eV} \)) [19]. Various schemes have been proposed to include neutrino masses in the SM, among which the most popular one is the so-called seesaw mechanism [20–30], since it not only generates neutrino mass in an elegant way, but also connects the observed baryon asymmetry in the Universe (BAU) and the origin of neutrino mass through leptogenesis [31–41]. Some variations of the seesaw mechanism can also accommodate dark matter candidates [42–45]. Among several seesaw mechanisms, the type-I seesaw [20–23] in a straightforward way introduces three singlet right-handed (RH) neutrinos (\( N_R \)), leading to Dirac mass terms as well as the RH Majorana mass terms. Consideration of both mass terms can generate sub-eV Majorana neutrino masses if the RH Majorana mass is set at \( \sim 10^{14} \text{ GeV} \). Neutrino mass generation via the seesaw...
mechanism comes with violation of lepton number (LNV) by \( \Delta L = 2 \), which may be used on experiments as a sign for the Majorana nature of neutrinos. Many experiments and tests on the nature and properties of neutrinos are already in progress, such as the search for neutrinoless double beta decay (0νββ) [46, 47], as well as other LNV processes including rare \( \tau \) decays, meson decays and hyperon decays [48–53]. However, the \( \Delta L = 2 \) processes are suppressed either by a factor of \( m_\nu^2/m_{\Delta}^2 \) due to the smallness of the light neutrino mass \( m_\nu \), or by a factor of \( |V_{\text{mix}}|^2 \) due to the small mixings, depending on whether the exchanged neutrino is light or heavy compared to the scale of the LNV processes [54]. Fortunately, the LNV processes may be enhanced substantially as a result of resonant production of heavy neutrinos, if the heavy neutrino mass can be kinematically accessible (below TeV) as in some low-scale type-I seesaw scenarios [55–64], which may be produced directly at collider experiments and searched for [54, 65–75]. An upper bound has been given by the LEP experiments on the mixings \( |V_{\text{mix}}|^2 \) \(< \mathcal{O}(10^{-5}) \) for a heavy neutrino mass of \((80, 205)\) GeV [76]. CMS broadened the mass range to \((20, 1600)\) GeV and put a similar limit as \( |V_{\text{mix}}|^2 \) \(< \mathcal{O}(10^{-5}) \) [77, 78].

To solve the above two problems of naturalness and neutrino oscillation, models have been proposed to incorporate neutrino masses into some scenarios with the VLTs, such as ones that include lepton-number violation between the scalar triplet and lepton doublet within the Little Higgs scenario [79], as well as other Little Higgs [80–90], Composite Higgs [91–95], Top Seesaw [96–98], Higgs Inflation models [99], etc [100, 101]. A common feature of these new models is that VLTs and heavy Majorana neutrinos are predicted, which leads to a new decay mode of VLT through the mediation of heavy Majorana neutrinos. Taking into account that VLTs and heavy Majorana neutrinos in low-energy type-I seesaw models are both within the search abilities at the LHC, in a model-independent way, we propose in this paper a search strategy for the above new decay channel of the VLT. There are some traditional ways to search for the vector-like top partner at the LHC, such as \( T \to b l j \). These searches have been performed [17, 18] and exclude the top partner mass up to \( 740 \) GeV. In this work, we will investigate the process \( T \to b l^+ l^+ j j \), which can be used to probe the top partner and to test the seesaw mechanism simultaneously at the LHC. In a scenario that incorporates three right-handed Majorana neutrinos and a top partner \( T (+2/3 \) electrically charged and SU(2) singlet), we demonstrate that with the heavy Majorana neutrinos at the TeV scale, the new decay mode of \( T \) can be probed at the LHC by searching for a signal of same-sign dileptons [102], which has also been utilized in a phenomenological study on a topcolor-assisted technicolor model [103] and rare \( B \) decay [104].

2. Effective Lagrangian and the new decay mode of top partner

Without losing generality, we will adopt the effective interaction method to perform a phenomenological study in the following sections. The relevant interaction between a singlet top partner and \( W \) boson is given by,

\[
\mathcal{L}_T = \frac{g}{\sqrt{2}} b_{l,l} \gamma^\mu V_{l1} d_{l1} W_\mu^+ + \text{H.c.},
\]

where \( V \) is the CKM matrix but generalized to \( 4 \times 4 \) dimensionally to include the additional VLT. Note that \( \alpha = 1 \sim 4 \) runs over all generations of quarks including the VLT (here for brevity we label the singlet top partner \( T \) as the 4th generation), while \( i = 1 \sim 3 \) is the index for three generations of the SM fermions. \( g \) is the weak coupling. As for the type-I seesaw, for simplicity and without losing the features of a low-scale type-I seesaw, the model is parameterized as a mass scale of the RH Majorana neutrino \( M_\nu \) and a mixing parameter between the light and heavy neutrinos \( V_{\nu l} \), then the effective Lagrangian for interactions between the heavy Majorana neutrinos and charged leptons can be written as

\[
\mathcal{L}_N = -\frac{g}{2\sqrt{2}} V_{Nl} W_\mu^+ \bar{\ell} l\gamma^\mu (1 - \gamma_3) N^c + \text{H.c.},
\]

where \( \ell \) (\( \ell = e, \mu, \tau \) are charged leptons) and \( N (N = N_{1,2,3} \) label heavy Majorana neutrinos) are mass eigenstates.

Introduction of interaction terms equations (1) and (2) leads to \( T \) decay channel through the heavy Majorana neutrinos into a same-sign dilepton plus jets,

\[
T \to b W^+ \to b l^+ l^+ q\bar{q},
\]

the Feynman diagram of which is presented in figure 1. The final same-sign dilepton may serve as a distinct signature at the LHC as a probe for this rare decay, as we will show in the next section. The relevant interaction terms for the process can be parameterized and written as an effective Lagrangian

\[
\mathcal{L} = -\frac{g}{2\sqrt{2}} W_\mu^+ [V_{Nl} \bar{\ell} l\gamma^\mu (1 - \gamma_3) N^c + V_{lB} T \gamma^\mu (1 - \gamma_3) b] + \text{H.c.},
\]

in which the indices are the same as equation (2). Assuming \( \text{Br}(T \to b W^+) = 50\% \), the branching ratio of the rare decay of \( T \) is shown in figure 2, with respect to mass of the heavy.
Majorana neutrino. In the calculation we set $m_T = 2$ TeV, $V_{TB} = 0.1$ and $V_{MN} = 0.004$ which are not excluded by current experiments (note that $V_{MN} = 0.004$ survives [76] in the mass range of figure 2 while $V_{MN}$ does not [105]). As can be seen, the branching ratio of the rare decay decreases as $m_N$ grows in the kinematically accessible range ($15 \sim 75$ GeV). For a larger $m_N$ from $10^5$ GeV to TeV scale, the rare decay can be enhanced a bit due to on-shell W boson from $N$ decay, but the branching ratio of $T$ rare decay is still lower ($\sim 10^{-8}$) than that in a light mass region. Therefore in section 3 we will focus on the relatively small mass range of the heavy Majorana neutrino with $m_N \lesssim m_T$ and explore the possibilities for a probe of the top partner’s new decay channel.

3. Search at the LHC

In the scenario we introduced in the last section, the $SU(2)$ singlet top partner can be produced in pairs via QCD processes at the LHC, and then goes through a rare decay mediated by the heavy Majorana neutrino. If one of the paired VLTs goes through the rare decay $T \to b \ell^+ \ell^- + q\bar{q}$ and the other decays into hadrons $T \to b W^- + jj$, then we have the distinct signal at the hadronic environment of the LHC as a same-sign dilepton with multi-jets including two b-tagged ones:

$$pp \to TT \to \ell^+\ell^- + b\bar{b} + j_1j_2j_3j_4.$$  

(5)

However, the GERDA experiments [105] already put a very stringent limit on the $e$-flavor mixing $|V_{eN}|^2$ to about $10^{-8}$ in the GeV~100 GeV mass range of the heavy Majorana neutrino. Besides, probing for $\tau$-flavor mixing $V_{\tau N}$ requires accurate tagging of final $\tau$’s, which is not realized with high efficiency in the current collider simulation. Given these facts, we expect an improvement of sensitivity for the $\mu$-flavor mixing $V_{\mu N}$ in the kinematically accessible mass range of heavy neutrino ($m_N \lesssim m_T$ in our case), which can lead to its resonant production as we discussed in section 1. The contribution of CP-conjugate process of (5),

$$pp \to TT \to \ell^-\ell^+ + b\bar{b} + j_1j_2j_3j_4,$$  

(6)

is also included in the following simulations. Note that the top partner can also be produced singly via electroweak processes. The cross section of the singly production is smaller than that of the pair production in a small mass range of VLT. As the VLT mass increases ($\gtrsim 1.1$ TeV), the singly production cross section will surpass that of pair production and lead to a better sensitivity for the new decay mode.

For the signal processes (5) and (6) whose final states contain a same-sign dilepton and jets, major SM backgrounds at the LHC come from prompt multi-leptons (mainly from events with $t\bar{t} W^\pm$ and $W^\pm W^\pm + j$) and fake leptons (mainly from events with jets of heavy flavor, such as $t\bar{t}$). To be exact, opposite-sign dileptons with one of which mismeasured should also constitute our backgrounds, but as the rate of mismeasurements for muons is generally low enough that we ignore its effects, then the SM backgrounds we consider are

$$pp \to t\bar{t} W^\pm,$$

$$pp \to W^\pm W^\pm + j + jets,$$

$$pp \to t\bar{t}.$$  

(7)

Monte Carlo simulations are performed for both the signal (5), (6) and backgrounds (7) at the LHC with the center-of-mass energy of 14 TeV. For the signal we specify the $N_1$-mediated decay processes for the probing of $V_{\mu N}$. As we adopt a diagonalized mixing matrix $V_{MN}$, thus $N_2$ couples only to the $\mu$-flavor. In the simulation, we use the benchmark point as follows,

$$m_N = 50 \text{ GeV}, \quad m_T = 2 \text{ TeV}, \quad V_{TB} = 0.1, \quad V_{MN} = 1.0,$$  

(8)

whereby $m_N$ means the mass of $N_2$ for simplicity, while for $N_1$ ($N_3$) that couples to $e$ ($\tau$), we assume a kinematically inaccessible mass $300 \text{ GeV}$ (1 TeV). Hence the processes mediated by $N_{1,3}$ are not included in the simulation of the search for the VLT new decay, due to their inaccessible large masses. Parton-level events of signal and backgrounds are generated through MadGraph5_aMC@NLO [106] with the NN23LO1 PDF [107], then go through parton showering and hadronization by Pythia-8.2 [108]. The renormalization and factorization scales are set at the value of VLT mass, that is, 2000 GeV. Detector simulations are carried out by tuned Delphes3 [109] within the framework of CheckMATE2 [110]. Jet-clustering is done using FastJet [111] with an anti-$k_t$ algorithm [112]. We assume $b$-tagging efficiency to be $70\%$ in our simulation. In addition, contributions from higher order QCD corrections are taken into account by normalizing the leading-order cross sections of $t\bar{t}$ and $t\bar{t} W^\pm$ to NNLO and NLO, respectively [113, 114].

We present the distributions of kinematic variables for signal and the SM background processes at the 14 TeV LHC in figure 3, including the product of charges of the final dimuon (figure 3(a)), missing transverse energy $E_T$ (figure 3(b)), the relative distance between the final dimuon $\Delta R_{\mu\mu}$ (figure 3(c)) and the transverse momentum of the leading b-jet (figure 3(d)). Figure 3(e) is the distribution of $m_{(b\mu)}$, the invariant mass reconstructed from the final two muons, a leading b-jet and two jets. It can be seen from figure 3(a) that the charges of final dimuon for the
and $W$ tend to be opposite, compared with the signal. The distribution of missing transverse energy for the signal is more flat than that for the backgrounds and more signal events are found in the range of large $E_T$ ($100 \text{ GeV} \sim 900 \text{ GeV}$). Intuitively there are no neutrinos present in the final states of signal and hence signal events tend to have smaller $E_T$ compared with the backgrounds, in which neutrinos from $W$ decay constitute much of the missing transverse energy. However, note that it is the jets after parton-showering that arrive at the detectors, rather than the partonic final states. $b\bar{b}$ quarks from the signal (5) and (6) are highly energetic as they are decay products of $T$ with mass of $2 \text{ TeV}$ and by parton-showering, these $b\bar{b}$ quarks decay to neutrinos that are highly energetic as well, leading to the $E_T$ distribution shown in figure 3(b). The dimuon in the signal comes from decay of the same top partner (equations (5) and (6)) while in the SM backgrounds, the final leptons come from decays of different parent particles, that is, $W^+W^-$ in the $t\bar{t}$, $W^\pm$ and $W^\pm W^\pm$+jets events. The final two muons thus tend to be closer in the signal than in the backgrounds, which is reflected in the distributions of the relative distance between them (figure 3(c)). Moreover, we set $m_T$ in the benchmark point to be $2 \text{ TeV}$, which is much more massive than the SM top quark and whose decay product b quark tends to be much harder than that from top decay in the backgrounds event (figure 3(d)). Furthermore, to distinguish the signal and backgrounds more efficiently, we reconstruct the parent $T$ by the invariant mass $m_{bbj_2}$ clustering the decay products from the VLT rare decay, in which we use the leading b-jet and two soft jets, since the jets come from the secondary decay of the mediating Majorana neutrino and hence tend to be softer than ones in the SM backgrounds. As can be seen from figure 3(e), more events of the signal distribute around the range $800 \text{ GeV} \lesssim m_{bbj_2} \lesssim 2000 \text{ GeV}$, while for the three backgrounds the peaks of the distributions are all below $800 \text{ GeV}$.

Based on the above analysis, we apply the following kinematic cuts to the events to distinguish a signal from the SM backgrounds.

- Cut 1: a same-sign muons is required with each of them satisfying $p_T(\mu) > 10 \text{ GeV}$ and $|\eta(\mu)| < 2.8$. 

Figure 3. Kinematic distributions of the signal $pp \rightarrow \mu^+\mu^- + 2b + 4j$ and the SM backgrounds $t\bar{t}$, $tW^\pm$, $W^\pm W^\pm$+jets at the 14 TeV LHC. The benchmark point is chosen as $m_T = 2 \text{ TeV}$, $m_N = 50 \text{ GeV}$, $V_{tb} = 0.1$, $V_{\nu N} = 1.0$. 

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For example, we can reach an effective probe towards the parameter space in the present scenario. We present in Figure 4 the exclusion bounds at 2σ on the signal $pp \rightarrow t\bar{t} \rightarrow \mu^+\mu^- + b\bar{b} + 4j$, where the statistical significance is calculated using the formula

$$\alpha = \frac{S}{\sqrt{B + (\beta B)^2}},$$

where $S(B)$ is the event number after the above cuts for signal(background). $\beta$ denotes the systematic uncertainty, which in our case mainly comes from the background with misidentified leptons and is assumed to be 5% in the following discussion. The integrated luminosity at the 14 TeV LHC is set to be 3 ab$^{-1}$. Figure 4(a) shows the 2σ limits on the parameter plane of $|V_{\nu}\bar{\nu}|^2$ versus $m_T$, in which three colored lines correspond to $V_{TB} = 0.1, 0.5, 1.0$, respectively. It can be seen that for a relatively low mass range of $m_T \lesssim 1.4$ TeV and $V_{TB} \gtrsim 0.5$, the heavy-light Majorana neutrino mixing $|V_{\nu}\bar{\nu}|^2$ can be probed to orders of $10^{-5}$ and below, which surpasses the current bounds on $|V_{\nu}\bar{\nu}|^2 \sim 10^{-4}$ for $m_{\nu} \sim 50$ GeV given by the DELPHI Collaboration [76], as well as the LHC search for same-sign dileptons [77] and trileptons events [78]. For example, we can read from Figure 4(a) that, at the point of $m_T = 1.3$ TeV and $V_{TB} = 1.0$, the exclusion limit on $|V_{\nu}\bar{\nu}|^2$ reaches $7.6 \times 10^{-6}$. Figure 4(b) is plotted on the plane of $V_{TB}$ versus $m_T$, in which three
colored lines correspond to $V_N = 0.002, 0.004, 0.01,$ respectively. Within the mass range of $m_T$ below $1.8 \text{ TeV}$, the upper bound on the coupling of the top partner with the SM $b$ quark can be given at $V_Tb \lesssim 0.1$ with $V_N \sim 10^{-3}$. For instance, at $V_N = 0.004$ and $m_T = 1.3 \text{ TeV}, V_Tb > 0.35$ can be excluded at $2\sigma$. Finally in figure 5 we present the $2\sigma$ exclusion limit on the cross sections of the signal process $pp \rightarrow TT \rightarrow \mu^+\mu^- + b\bar{b} + 4j$ with respect to the top partner mass at the 14 TeV LHC, with $V_Tb = 0.1, V_N = 0.004$ and $m_T = 50 \text{ GeV}$. Furthermore, it can be inferred from figure 2 that with a less massive heavy Majorana neutrino, the branching ratio of the top partner’s rare decay will increase and may lead to a better sensitivity.

It should be noted that we have not considered pileup effects in our discussion, which is important for a fully realistic simulation and needs proper removal techniques [115–117]. However, the pileup effects can be limited on our results since the event-selection is based on a pair of hard same-sign leptons.

4. Conclusion

In this paper, we investigate the observability for the rare decay of a singlet top partner in a model-independent scenario that combines the low-energy type-I seesaw and a vector-like singlet top partner. We present a search strategy at the 14 TeV LHC for a distinguishable signal with a same-sign dilepton plus multiple jets. In a kinematically accessible mass range of the heavy Majorana neutrino (we choose $m_N = 50 \text{ GeV}$ as a benchmark point), the detector-level simulation at the 14 TeV LHC with integrated luminosity of $3 \text{ ab}^{-1}$ shows that, the $\mu$-flavor mixing with the heavy Majorana neutrino $|V_N|^2 > 7.6 \times 10^{-6}$ can be excluded at $2\sigma$ for $V_Tb \lesssim 1.0$ and $m_T \sim 1.3 \text{ TeV}$. The coupling between the singlet top partner and the SM $b$ quark $V_Tb > 0.35$ can be excluded at $2\sigma$ for $V_N = 0.004$ and $m_T \sim 1.3 \text{ TeV}$. It is then concluded that in a kinematically accessible mass range of the heavy Majorana neutrino, searching at the LHC for the rare decay of a singlet top partner mediated by the heavy Majorana neutrino can be promising through the same-sign dilepton signal.

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