PROCEEDINGS OF SCIENCE

Light Sterile Neutrino and the μ-Jet Techniques in ν-THDM at a Hadron Collider

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We show that the prospects for the searches of a sterile neutrino with the mass smaller than 100 GeV, emerging from the decay of a heavy exotic charged Higgs boson, can be greatly enhanced at the LHC by utilizing the muon-jet tagging technique to suppress the background.

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1. Introduction

Searches for the TeV-scale sterile neutrinos at a collider usually involve its interactions with the W or Z bosons [1, 2, 3]. Such channels are highly suppressed due to the extremely small see-saw Yukawa coupling constants and, equivalently, the mixing parameters $\theta_l^2 \ll 10^{-4}$ at the TeV-scale. Therefore, in the ν-Two-Higgs-Doublet-Model (ν-THDM) [4, 5, 6, 7, 8, 9], the collider searches have been discussed in literature only for a neutrino mass $(m_N) \gtrsim 100$ GeV [9], when the sterile neutrinos decays dominantly into two separately identifiable objects. In Ref. [8], the use of secondary vertices has been analysed in this context.

In this work, we discuss the supplementary parameter space with $m_N < 100$ GeV. We note that in the scenario when $m_{H^\pm} \gg m_N$, the highly boosted sterile neutrino can decay dominantly via the $\mu^\pm$+jet+jet channel, which can be probed at the LHC. The complete process is illustrated in Fig. 1.

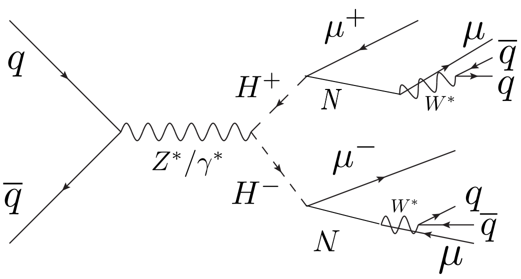

Figure 1: Production of the N at the LHC, and its subsequent decay into collimated objects that look like a jet.

2. Model Setup

The ν-THDM is based on the type-I Two-Higgs doublet model [10]. It contains two Higgs doublets, $\Phi_{1,2}$, with the hypercharge $Y = \frac{1}{2}$. All the Standard Model (SM) particles Q_L, u_R, d_R, L_L, e_R couple (conventionally) only with the Φ_2 field, so that the Yukawa Lagrangian can be written as

$$\mathscr{L}_{\text{Yukawa}}^{\text{SM}} = -Y_{uij}\overline{Q}_{Li}\tilde{\Phi}_2 u_{Rj} - Y_{dij}\overline{Q}_{Li}\Phi_2 d_{Rj} - Y_{lij}\overline{L}_{Li}\Phi_2 l_{Rj} + \text{h.c.}. \tag{2.1}$$

The left-handed lepton doublets also couple with Φ_1, together with the sterile neutrino, as

$$\mathscr{L}_{\text{Yukawa}}^{\nu} = -m_N\overline{N}N - (Y_i\overline{L}_{Li}\tilde{\Phi}_1 N + \text{h.c.}), \tag{2.2}$$

where the subscript $i = 1,2,3$ corresponds to the e, μ, τ lepton doublets, respectively. For large $\tan\beta \equiv \frac{v_2}{v_1}$, where $v_{1,2}$ are the vacuum expectation values of the $\Phi_{1,2}$, Y_i can become sizable, while the coupling of N with the SM-like Higgs boson remains sufficiently small.

3. Background Analysis and the Cut Flow

For the $m_N \ll m_{H^\pm}$ and the $m_N \lesssim 100$ GeV region, the high-energy-fraction muons emerging from the N that behaves like a jet can help identify it. Muons occasionally appear in a SM jet. For example, a b-jet can contain a muon through the semi-leptonic decay of the B-meson. Therefore, the main irreducible background for our process is $pp \to b\bar{b}l^+l^-$, $b \to B + X \to \mu + \nu + X$. Additionally, processes like $pp \to jb + l^+l^-$ and $pp \to jj + l^+l^-$ are also important, since a muon can also appear inside a non-b-jet.

As for the reducible backgrounds, the most crucial one results from the $pp \to j/b + j/b + l^+l^- +$ missing transverse energy (MET). We will limit ourselves to the $pp \to t\bar{t} \to b\bar{b}l^+l^- +$ MET background here. In view of the MET reconstruction efficiency as well as the possibly large pile-up effect in the future, we will show our result both with and without this background, thus covering the two extreme cases.

The signal events are selected by imposing some kinematic cuts. These include the anti-mass window around the Z-boson mass, and the mass window around the $H^\pm$ mass. Furthermore, we identify a μ-jet as the one carrying more than 30% of the total jet energy. The events containing at least one tagged N-jet are suffixed by "-1N-jet" and the ones with two tagged N-jet by "-2N-jet".

4. Numerical Results

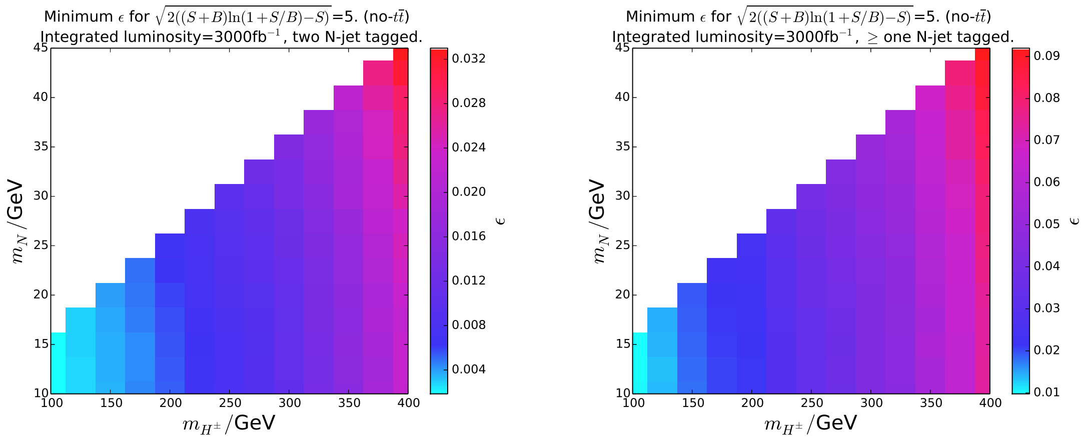

Figure 2: Minimum ε for $\sqrt{2((S+B)\ln(1+S/B)-S)} = 5$. The integrated luminosity is set to 3 ab^{-1} for a 13 TeV LHC. $pp \to t\bar{t} \to \mu^+\mu^-b\bar{b}\nu\bar{\nu}$ contributions to the background are not taken into account.

We show the minimum efficiency, ε, required to obtain a 5σ signal significance with an assumed luminosity of 3 ab^{-1} at the LHC in Fig. 2 for the "no-$t\bar{t}$" case, and in Fig. 3 for the "$t\bar{t}$" background taken into account. The ε is defined by multiplying all the branching ratios corresponding to each decay vertex in the process shown in Fig. 1. The left panels in the figures shows the "-2N-jet" and the right panels shows the "-1N-jet" results.

5. Summary

Within the framework of the ν-THDM, we have simulated the signal and backgrounds at a 13 TeV LHC for a particular parameter space $m_N \ll m_{H^\pm}$ and $m_N < 100$ GeV. The muons appearing in the collimated decay products of the sterile neutrinos can help us discriminate the N-jets from the QCD jet backgrounds. In some regions of the parameter space, an integrated luminosity of

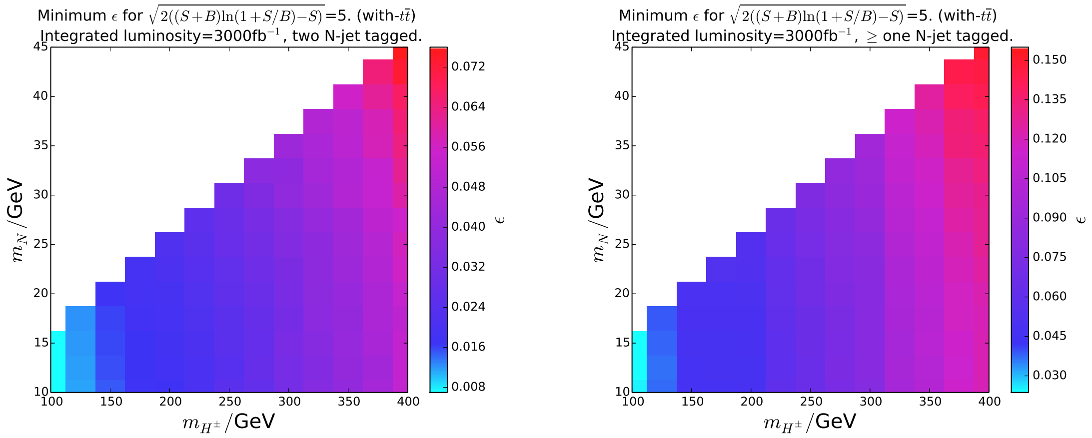

Figure 3: Minimum ε for $\sqrt{2((S+B)\ln(1+S/B)-S)} = 5$. The integrated luminosity is set to 3 ab^{-1} for a 13 TeV LHC. $pp \to t\bar{t} \to \mu^+\mu^- b\bar{b}\nu\bar{\nu}$ contributions are included.

3000 ab^{-1} expected at the HL-LHC can be sensitive to the $\varepsilon \lesssim 0.01$ cases. The reducible $pp \to t\bar{t}$ background may prove crucial in this regard, if the pile-up effect is not improved significantly in the future [11].

References

[1] Georges Aad et al. Search for heavy Majorana neutrinos with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV. *JHEP*, 07:162, 2015.

[2] P. Abreu et al. Search for neutral heavy leptons produced in Z decays. *Z. Phys.*, C74:57–71, 1997. [Erratum: *Z. Phys.C75,580(1997)]*.

[3] Vardan Khachatryan et al. Search for heavy Majorana neutrinos in $\mu^\pm\mu^\pm+$ jets events in proton-proton collisions at $\sqrt{s}$ = 8 TeV. *Phys. Lett.*, B748:144–166, 2015.

[4] Ernest Ma. Naturally small seesaw neutrino mass with no new physics beyond the TeV scale. *Phys. Rev. Lett.*, 86:2502–2504, 2001.

[5] S. Gabriel and S. Nandi. A New two Higgs doublet model. *Phys. Lett.*, B655:141–147, 2007.

[6] Shainen M. Davidson and Heather E. Logan. Dirac neutrinos from a second Higgs doublet. *Phys. Rev.*, D80:095008, 2009.

[7] Enrico Bertuzzo, Yuber F. Perez G., Olcyr Sumensari, and Renata Zukanovich Funchal. Limits on Neutrinophilic Two-Higgs-Doublet Models from Flavor Physics. *JHEP*, 01:018, 2016.

[8] Naoyuki Haba and Koji Tsumura. ν-Two Higgs Doublet Model and its Collider Phenomenology. *JHEP*, 06:068, 2011.

[9] Chao Guo, Shu-Yuan Guo, Zhi-Long Han, Bin Li, and Yi Liao. Hunting for Heavy Majorana Neutrinos with Lepton Number Violating Signatures at LHC. *JHEP*, 04:065, 2017.

[10] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, Marc Sher, and Joao P. Silva. Theory and phenomenology of two-Higgs-doublet models. *Phys. Rept.*, 516:1–102, 2012.

[11] Yi-Lei Tang. Probing the Light Sterile Neutrino Through the Heavy Charged Higgs Decay at the LHC. arXiv:1712.10108.