Probing the Light Sterile Neutrino Through the Heavy Charged Higgs Decay at the LHC

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I will show in this paper that a sterile neutrino emerged from the decay of a heavy charged Higgs boson can be probed by utilizing the muon-jet tagging technique at the LHC.

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1. Introduction

Probing the TeV-scale sterile neutrino through the $W$ or $Z$ bosons [1, 2, 3] suffers from the extremely small see-saw Yukawa coupling constants. In some models, other new physics sector might help enhance the signal. For example, in the $\nu$-Two-Higgs-Doublet-Model ($\nu$-THDM) [4, 5, 6, 7, 8, 9], Ref. [9] had discussed the $(m_N) \gtrsim 100$ GeV situation when separated objects can be detected. Secondary vertices are also discussed in Ref. [8].

In this work, we only concern the $m_N < 100$ GeV. When $m_{H^\pm} \gg m_N$, the highly boosted sterile neutrino decays via the $\mu^\pm$+jet+jet channel. Fig. 1 shows the complete diagram

![Diagram showing the production and subsequent decay channel of the $N$ at the LHC.](image)

Figure 1: Production and subsequent decay channel of the $N$ at the LHC.

2. Model Setup

We briefly show the Lagrangian of the $\nu$-THDM, which is a variant of the type-I Two-Higgs doublet model [10]. There are two Higgs doublet fields, $\Phi_{1,2}$, with the hypercharge $Y = \frac{1}{2}$. $\Phi_2$ couples with the Standard Model (SM) particles $Q_L, u_R, d_R, L_L, e_R$ through

$$L^{SM}_{\text{Yukawa}} = - Y_{ii} d_{ij} \overline{Q}_{Li} \Phi_2^* u_{Rj} - Y_{ij} d_{ij} \overline{Q}_{Li} \Phi_2^* d_{Rj} - Y_{ij} l_{ij} \overline{L}_{Li} \Phi_2^* l_{Rj} + h.c.$$  \hspace{1cm} (2.1)

The $\Phi_1$ is in charge of the neutrino,

$$L^{\nu}_{\text{Yukawa}} = - m_N \overline{N}N - (Y_{i} l_{ij} \Phi_1^* N + h.c.),$$  \hspace{1cm} (2.2)

where the subscript $i = 1, 2, 3$ corresponds to the $e, \mu, \tau$ lepton doublets, respectively. In this model, $Y_i$ can be significantly amplified by a sizeable $\tan\beta \equiv \frac{v_2}{v_1}$, keeping the effective coupling with the standard-model Higgs boson $h_{SM}$ small.

3. Background Analysis and the Cut Flow

We identify the sterile neutrino jet finding out the high-energy-fraction muons in a jet. For the SM backgrounds, $b$-jet might fake the signal through the semi-leptonic decay of a $B$-meson. The main irreducible background is therefore $pp \rightarrow b\bar{b}l^+l^-$, $b \rightarrow B + X \rightarrow \mu + \nu + X$. We also considered the $pp \rightarrow jb + l^+l^-$ and $pp \rightarrow jj + l^+l^-$ processes, in which a non-$b$-jet can also produce a muon inside.
We also calculated the important reducible \( pp \rightarrow \tau \tau \rightarrow b \bar{b} t^+ t^- \) background. Considering the MET reconstruction efficiency and the large pile-up effect in the future, we will show both the results with and without this background, which two extreme cases are covered.

We select the signal events by some anti-mass window around the \( Z \)-boson mass, and the mass window around the \( H^{\pm} \) mass. Then a \( \mu \)-jet will be identified if it carries 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](image1.png)

**Figure 2**: Minimum \( \epsilon \) 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. \( pp \rightarrow \tau \tau \rightarrow \mu^+ \mu^- b \bar{b} \nu \nu \) contributions to the background are not taken into account.

![Figure 3](image2.png)

**Figure 3**: Minimum \( \epsilon \) 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. \( pp \rightarrow \tau \tau \rightarrow \mu^+ \mu^- b \bar{b} \nu \nu \) contributions are included.

In Fig. 2 and Fig. 3, we show the minimum efficiency, \( \epsilon \) in the 3 ab\(^{-1}\) integrated luminosity at the LHC for the “no-\( \tau \tau \)” and \( \tau \tau \) cases respectively, required to obtain a 5\( \sigma \) significance. The \( \epsilon \) 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

We have simulated the signal and backgrounds at a 13 TeV LHC for the production of a sterile neutrino with the mass $m_N < 100$ GeV within the framework of a ν-THDM. With the muon-jet tagging technique, the QCD jet backgrounds have been eliminated and in some regions of the parameter space, the proposed 3000 ab$^{-1}$ expected at the HL-LHC can be sensitive to the $\varepsilon \lesssim 0.01$ cases. The reducible $pp \to \bar{t}t$ may be crucial if the pile-up effects will not be improved.[11].

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