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Jet substructure shedding light on heavy Majorana neutrinos at the LHC

Arindam Das

School of Physics, KIAS, Seoul 02455, Korea E-mail: `arindam@kias.re.kr`

The existence of tiny neutrino masses and flavor mixings can be explained naturally in various seesaw models, many of which typically having additional Majorana type SM gauge singlet right handed neutrinos (N). If they are at around the electroweak scale and furnished with sizable mixings with light active neutrinos, they can be produced at high energy colliders, such as the Large Hadron Collider (LHC). A characteristic signature would be same sign lepton pairs, violating lepton number, together with light jets – $pp \to N\ell^{\pm}$, $N \to \ell^{\pm}W^{\mp}$, $W^{\mp} \to jj$. We propose a new search strategy utilising jet substructure techniques, observing that for a heavy right handed neutrino mass M_N much above $M_{W^{\pm}}$, the two jets coming out of the boosted $W^{\pm}$ may be interpreted as a single fat-jet (J). Hence, the distinguishing signal topology will be $\ell^{\pm}\ell^{\pm}J$. Performing a comprehensive study of the different signal regions along with complete background analysis, in tandem with detector level simulations, we compute statistical significance limits. We find that heavy neutrinos can be explored effectively for mass ranges 300 GeV $\leq M_N \leq$ 800 GeV and different light-heavy neutrino mixing $|V_{\mu N}|^2$. At the 13 TeV LHC with 3000 fb^{-1} integrated luminosity one can competently explore mixing angles much below present LHC limits, and moreover exceed bounds from electroweak precision data.

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1. Introduction

The experimental evidence for neutrino oscillations and lepton flavor mixings, from the various experiments, motivate extensions of the SM incorporating non-zero neutrino masses and mixings. After the pioneering realization of the unique $d = 5$ Weinberg operator within the SM with $\Delta L = 2$ lepton number violation ($L =$ Lepton number), it was realized that the very well known Seesaw mechanism could be the simplest idea to explain the smallness of the neutrino masses and flavor mixings. In many of these models, SM is extended by gauge singlet, Majorana type, heavy right handed neutrinos (RHNs). After electroweak (EW) symmetry breaking, the light Majorana neutrino masses are generated by, for instance, the so called type-I seesaw mechanism. At the 8 TeV LHC, with 20.3 fb^{-1} luminosity and 95% confidence limit (C. L.), ATLAS [1] has probed mixings for muon flavor down to a $|V_{\mu N}|^2$ of 3.5×10^{-3}, for $M_N = 100$ GeV. The limits further goes down to 2.9×10^{-3} for $M_N = 110$ GeV and then monotonically weakens with mass, up to $M_N = 500$ GeV. At $M_N = 500$ GeV the limits are $|V_{\mu N}|^2 = 4 \times 10^{-1}$. The limits are nearly two orders of magnitude weaker in the case of electron flavor mixings $|V_{eN}|^2$ at the 95% C. L. CMS has also studied the SSDL plus dijet signal and obtain the exclusion limits for $|V_{eN}|^2$ [2] and $|V_{\mu N}|^2$ [3]. Both studies are performed at the 8 TeV LHC with 19.7 fb^{-1} luminosity at 95% C. L. The limits for the mixed $e^\pm \mu^\pm + jj$ final state was also considered in [2]. CMS observed upper limits for $|V_{eN}|^2$ at 1.2×10^{-4} for $M_N = 40$ GeV, 2×10^{-2} for $M_N = 85$ GeV, 8×10^{-3} for $M_N = 130$ GeV and 1.2×10^{-2} for $M_N = 200$ GeV. Thus, the $|V_{eN}|^2$ limits were found to again weaken with M_N. Alternatively, RHNs may be excluded as large as $M_N = 480$ GeV, assuming the mixing is unity. The limits on $|V_{\mu N}|^2$ from the SSDL + dijet final state with μ flavor is probed down to 2×10^{-5} for $M_N = 40$ GeV, 4.5×10^{-3} for $M_N = 90$ GeV, 1.75×10^{-3} for $M_N = 125$ GeV and 7×10^{-3} for $M_N = 175$ GeV with $|V_{\mu N}|^2$ again weakening subsequently with M_N. For $M_N = 500$ GeV the limit is $|V_{\mu N}|^2 = 0.6$. In this paper we leverage boosted $W^\pm$ production from massive RHN, and its subsequent decay into a fat-jet in association with $\mu^\pm\mu^\pm$ pairs. The P_T of the $W^\pm$ scale as $P_T^W \sim (M_N^2 - M_W^2)/M_N$ and the separation between the hadronic decay products of $W^\pm$ scale as $\sim M_W/P_T^W$. Therefore, a natural region of focus may be the intermediate to heavy RHN mass range, say $M_N \geq 300$ GeV. In this mass range, the only other competent limit that exists comes from indirect EW precision data (EWPD). The EWPD limit is around $|V_{\mu N}|^2 = 0.009$ [5, 4, 6]. The boosted $W^\pm$ can produce a fat-jet when decays hadronically. For simplicity and clarity, we consider only the μ flavor for the SSDL. Moreover, μ detection efficiencies are better, compared to electrons and tau leptons. We place limits on $|V_{\mu N}|^2$ at the 13 TeV LHC, with 3000 fb $^{-1}$ luminosity, in the 300 GeV $\leq M_N \leq$ 800 GeV mass range which has been studied in [7].

2. Collider Analysis

To establish specific features and kinematic characteristics related to our RHN signal and backgrounds, we start by focusing on signal identification. Our prototypical signal is Same Flavour ($\mu^\pm$) SSDL, in association with a fat-jet (J). We adopt the selection criteria as :(i) muons $\mu^\pm$ are identified with a minimum transverse momentum $p_T^\mu > 10$ GeV and rapidity range $|\eta^\mu| < 2.4$, with a maximum efficiency of 95%. Efficiency decreases for p_T^μ above 1 TeV, (ii) only events with reconstructed di-muons having same sign are selected for further analysis, (iii) hard jets having

Cut	Signal for M_N			Background		
	300 GeV	500 GeV	700 GeV	WW+j	WZ+j	$WWZ+j$
Pre-selection + $\mu^{\pm}\mu^{\pm}+J$ $p_T^J > 100$ GeV	82.2+ 45.2 [100%]	36.6+23.4 [100%]	19.2+13.0 [100%]	2717.5+2597.0 [100%]	9881.3+7639.3 [100%]	252.1+240.4 [100%]
$p_T(\mu_{1,2}), m_{\mu\mu}$	79.5+ 39.8 [94%]	33.02+ 20.3 [88%]	15.6+9.2 [77%]	2255.7+2132.1 [83%]	5496.6+5074.1 [60%]	208.0+193.4 [82%]
$E_T^{\text{miss}} < 35$ GeV	66.3+27.4 [74%]	28.5 +18.1 [77%]	10.0+7.6 [55%]	260.8+163.2 [7.9%]	189.9+188.1 [2.2%]	24.2+ 19.6 [8.9%]
$p_T^J > 150$ GeV	35.1+20.6 [44%]	15.2+ 10.5 [58%]	8.3+6.0 [44%]	152.4+91.4 [4.5%]	36.5+ 27.2 [0.4%]	14.14+12.4 [5.3%]
$M_J > 50$ GeV	29.3+16.9 [36%]	20.9+ 10.2 [42%]	6.6+4.4 [34%]	34.0+26.6 [1.1%]	11.6+8.5 [0.1%]	6.6+5.0 [2.3%]
$\tau_{21}^J < 0.5$	26.7+13.7 [32%]	13.2+7.2 [34%]	5.4+2.8 [25%]	17.5+15.9 [0.6%]	5.9+5.2 [0.06%]	3.0+2.8 [1.2%]

Table 1: The effectiveness of different variables in minimizing backgrounds is illustrated in the form a cut flow. The two numbers correspond to expected events in $\mu^+\mu^+$ and $\mu^-\mu^-$ channels. We adopt a typical mixing angle $|V_{\mu N}| = 0.03$. The numbers are for an integrated luminosity of 3000fb^{-1}, at the 13 TeV LHC.

at least $p_T^j > 10\,\text{GeV}$ and $|\eta^j| < 2.4$ are identified, (iv) candidate fat-jets are to be identified with $R = 0.8$, Cambridge-Achen jet with $|\eta^J| < 2.4$, (v) we identify the hardest fat-jet with the $W^{\pm}$ candidate jet (J), and this is required to have $p_T^J > 100$ GeV. These basic selection criteria are like primary level cuts required for effective signal identification. The last requirement is to ensure robust fat-jet properties. The features of the boosted fat-jet are rather more prominent for large M_N; showing up emphatically for 300 GeV and above. Finally we introduce some additional event criteria and then illustrate various results by considering several signal benchmark points along with the SM backgrounds like $WW+j$, $WZ+j$ and $WWZ+j$. For final selection between the signal and background we list the final event selection criteria motivated by the kinematic distributions in [7]: (i) leading muon should have $p_T(\mu_1) > 20$ GeV and the next hardest muon must have $p_T(\mu_2) > 15$ GeV, (ii) minimum invariant mass for the same sign muon pair must satisfy $m_{\mu\mu} > 50$ GeV. This is easily satisfied for the signal events, and can control backgrounds with non-prompt muon pairs, (iii)lacking any missing particles for our signal, require $E_T^{\text{miss}} < 35$ GeV. This can control background events with large MET contributions, (iv) the hardest, reconstructed fat-jet must have a transverse momentum $p_T^J > 150$ GeV, (v) we also demand the invariant mass of the hardest, reconstructed fat-jet to satisfy the jet mass $M_J > 50$ GeV. In principle one may use a mass window around the $W^{\pm}$ mass, but we find that a simple lower bound suffices. (vi) we use the N-subjettiness ratio corresponding to the reconstructed fat-jet must satisfy $\tau_{21}^J < 0.5$. The corresponding cut flow for the signal and SM backgrounds are listed in Tab. 1

3. Conclusion

We compare our results with the current LHC bounds from the 13 TeV dilepton [9] and trilepton [10] searches and EWPD [5, 4, 6]. We find the RHNs can be probed up to 5-σ significance at the 13 TeV LHC using 3000 fb^{-1} using SSDL plus fat-jet [7]. better than the EWPD. A comprehensive analysis using the opposite sign same flavor dilepton plus fat jet has been performed in [8].

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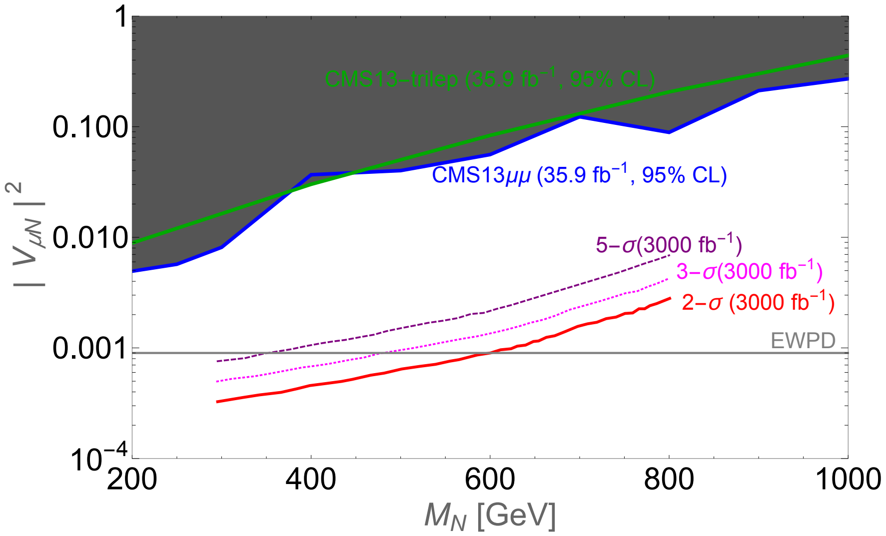

Figure 1: Comparison between current LHC limits ([9] and trilepton [10]) at the 13 TeV, EWPD [5, 4, 6] and calculated limits at the 13 TeV LHC with 3000 fb^{-1} luminosity at 2-σ, 3-σ and 5-σ significances using the cut based analysis.

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