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Investigating New Physics Models with Signature of Same-Sign Diboson+$\not{E}_T$

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We investigate the prospect of searching for new physics via the novel signature of same-sign diboson + $\not{E}_T$ at current and future LHC. We study three new physics models: (i) natural SUSY models, (ii) type-III seesaw model and (iii) type-II seesaw/Georgi-Machacek model. In the first two class of models, this signature arises due to the presence of a singly-charged particle which has lifetime long enough to escape detection, while in the third model this signature originates resonantly from a doubly-charged particle produced along with two forward jets that, most likely, would escape detection. We analyze in great detail the discovery prospects of the signal in these three classes of models in the current as well as the upcoming runs of the LHC (such as HL-LHC, HE-LHC and FCC-hh) by showing a distinction among these scenarios.

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1. Introduction

Despite the tremendous success of the Standard Model (SM) with the observation of the Higgs boson in 2012 [1, 2], the SM is incomplete in its current form. There are several reasons such as the higgs mass instability problem in the electroweak sector, the origin of neutrino masses, an understanding of dark matter, the origin of the matter-antimatter asymmetry in the Universe and several others to expect new physics beyond the Standard Model (BSM). Here, we investigate the novel signal of same-sign diboson (SSdB) + $\not{E}_T$ which is an interesting signal as it has negligibly small SM background. After a careful study, we find that it is possible to observe such a unique signature in three well-motivated BSM scenarios, namely: (i) natural supersymmetry models [3–9], (ii) type-III seesaw model [10], and (iii) type-II seesaw [11–14]/Georgi-Machacek model [15] , while still being consistent with the existing theoretical and experimental limits. This paper aim to point out possible BSM models that can be a potential source of such a novel signature, if seen in experiments. Since more than one BSM scenario qualify, thus a need to distinguish among them is called for and such a distinction can be accomplished by the use of different sets of cuts as discussed in Sec. 2. Finally, we conclude in Sec. 3.

2. SSdB + $\not{E}_T$ Signature from BSM Models

In this section, we briefly review the three BSM models and how they give rise to the SSdB + $\not{E}_T$ signature followed by devising suitable cuts to optimize the signals from each of the three BSM models against the SM background as well as the other two BSM scenarios. Each of the charged bosons in the final state are allowed to decay leptonically, leading to a same-sign dilepton (SSdL)+ $\not{E}_T$ final state. For simulations, we have used MadGraph5_aMC@NLO [16, 17] interfaced with Pythia 8.2 [18] followed by Delphes 3.4.2 [19] with the anti-k_T jet algorithm [20]. We have used Isajet 7.88 [21] to generate the Les Houches Accord (LHA) file for the NUHM2 signal and pass it through the above-mentioned simulation chain. We have used the K-factors for the signal and SM background processes as discussed in Ref. [22, 23].

2.1 Supersymmetry

Being a well-motivated BSM framework, supersymmetry (SUSY) provides an elegant solution to the Higgs mass hierarchy problem, accommodates a valid cold dark matter candidate, explains electroweak symmetry breaking, and features gauge coupling unification [24]. However, current LHC data indicate that $m_{\tilde{g}} > 2.2$ TeV [25, 26] and $m_{\tilde{t}_1} > 1.2$ TeV [26–28]. Such large lower bounds on the masses of sparticles question the naturalness of weak scale SUSY [29] based on the older notions of naturalness [30–32]. However, these earlier notions of naturalness can be updated to a more conservative electroweak naturalness measure, denoted by Δ_{EW} [33–36]. A SUSY model is said to be natural if $\Delta_{EW} < 30$. In such natural SUSY models, the lightest SUSY Particle (LSP) is almost purely higgsino-like. Assuming R-parity conservation, the LSP becomes a good dark matter candidate in the model and manifests as $\not{E}_T$ in collider experiments. Out of various natural SUSY models listed in Ref. [37], we choose the two extra parameter non-universal Higgs (NUHM2) model [3, 4] and generalized it so that gaugino mass unification [38] is not assumed. But the chosen benchmark point does satisfy the mass hierarchy: higssino mass parameter (μ) $\ll$ Wino mass parameter (M_2) essential to give rise to the SSdB + $\not{E}_T$ signature via Wino pair-production as pointed out in Ref. [23, 39]. The corresponding Feynman diagram is shown in Fig. 1. The final

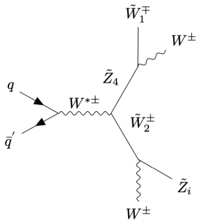

Figure 1: Feynman diagram for SSdB production at the LHC in SUSY models with light higgsinos ($\tilde{W}_1^{\mp}$ and $\tilde{Z}_i$ with $i = 1, 2$). Here $\tilde{Z}_4$ and $\tilde{W}_2^{\pm}$ in the intermediate step are winos.

set of cuts, namely the A3 (A3′)-cuts at $\sqrt{s} = 27(100)$ TeV, to extract the NUHM2 signal from the SM Backgrounds and to distinguish it from the other two signals were devised as: A3 (A3′)-cuts: SSdL, no b-jets, $p_T(\ell_1) > 20$ GeV, $\not{E}_T > 250(350)$ GeV, $m_{T_{\rm min}} > 200(325)$ GeV. After applying the A3 (A3′)-cuts at $\sqrt{s} = 27(100)$ TeV we obtain the significance for various signals as: NUHM2 : 8.06 (13.6) at $\mathcal{L} = 3$ ab^{-1} and 18.01(30.5) at $\mathcal{L} = 15$ ab^{-1}; Type III : 1.21 (1.5) at $\mathcal{L} = 3$ ab^{-1} and 2.71(3.3) at $\mathcal{L} = 15$ ab^{-1}; GM : 0.0135 (0.06) at $\mathcal{L} = 3$ ab^{-1} and 0.03(0.14) at $\mathcal{L} = 15$ ab^{-1}.

2.2 The type-III Seesaw Model

In the type-III seesaw model [10], which has been proposed to explain the tiny neutrino masses and mixings, the SM particle spectrum is extended by three generations of $SU(2)_L$ triplet fermions with hypercharge $Y = 0$, the lightest of which (denoted by $\tilde{\Sigma}$) has a lifetime long enough to escape detection [40], provided they have mass around a few hundred GeV and hence shows up as large $\not{E}_T$ in collider experiments. $\tilde{\Sigma}^{\pm}$, being only a few MeV heavier than its neutral partner $\tilde{\Sigma}^0$, travels a short distance before primarily decaying into $\tilde{\Sigma}^0$ and a charged pion of momentum low enough to be reconstructed as a track. This results in a disappearing track signature from $\tilde{\Sigma}^{\pm}$ as can also be seen in Ref. [40]. For simplicity, we set the other two generations of heavy fermions (denoted by Σ_i) to be almost degenerate. Hence, this model can also give rise to the novel signature of SSdB + $\not{E}_T$ via the process shown in Fig. 2. The final set of cuts, namely the B2 (B2′)-cuts at $\sqrt{s} = 27(100)$

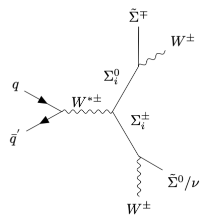

Figure 2: Feynman diagram for the SSdB + $\not{E}_T$ signature at the LHC in the type-III seesaw model, where $\tilde{\Sigma}^0$ and $\tilde{\Sigma}^{\pm}$ are members of the lightest fermionic triplets.

TeV, to extract the type-III Seesaw signal from the SM Backgrounds and to distinguish it from the other two signals were devised as : B2 (B2′)-cuts: SSdL, no b-jets, $p_T(\ell_1) > 20$ GeV, njet ≤ 1 + $\not{E}_T > 100(120)$ GeV + 105 GeV $< m_{T_{\rm min}} <$ 195 GeV + 200 GeV $<$ MCT $<$ 325(350) GeV. After applying the B2 (B2′)-cuts at $\sqrt{s} = 27(100)$ TeV we obtain the significance for various signals as follows: NUHM2 : 0.52 (0.8) at $\mathcal{L}$ = 3 ab^{-1} and 1.2(1.8) at $\mathcal{L}$ = 15 ab^{-1}; Type III : 3.5 (4.3) at $\mathcal{L}$ = 3 ab^{-1} and 7.8(9.6) at $\mathcal{L}$ = 15 ab^{-1} ; GM : 0.45 (1.4) at $\mathcal{L}$ = 3 ab^{-1} and 1.0(3.1) at $\mathcal{L}$ = 15 ab^{-1}.

2.3 Type-II seesaw/Georgi-Machacek model

The SSdB signature can originate from the decay of a doubly-charged scalar which appear in several BSM frameworks [11, 12, 14, 15, 41–57]. One such framework is the simplest type-II seesaw model [11–14] which introduces an $SU(2)_L$ triplet scalar $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$ with hypercharge $Y = 1$. Tiny neutrino masses are generated while the neutral component of the $SU(2)_L$ triplet, Δ^0, acquires a small VEV, v_Δ.

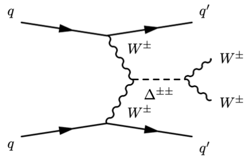

Figure 3: Feynman diagram for SSdB + forward jets production at LHC in the type-II seesaw models.

Here, we consider the scenario where Δ^{++}, produced via vector boson fusion as shown in Fig. 3, is the lightest among all members in the triplet fields. In this scenario, Δ^{++} can dominantly decay into same-sign dilepton (SSdL) ($\Delta^{\pm\pm} \to \ell^\pm\ell^\pm$) or SSdB ($\Delta^{\pm\pm} \to W^\pm W^\pm$), depending on the value of v_Δ [58–60]. We choose the benchmark point such that Δ^{++} dominantly decays into SSdB. The forward jets are most likely to escape detection and hence the resultant final state will mimic our signature of interest. However, due to a stringent T-parameter constraint [11–14, 61], the type-II seesaw model cannot give a sizeable cross section for this signature, whereas the GM model can, owing to the custodial symmetry [62–65]. The final set of cuts, namely the C3 (C3′)-cuts at $\sqrt{s}$ = 27(100) TeV, to extract the GM model signal from the SM Backgrounds and to distinguish it from the other two signals were devised as follows: C3 (C3′)-cuts: SSdL, no b-jets, $p_T(\ell_1) > 20$ GeV, MCT ≤ 300 GeV + njet ≥ 2, $\Delta\eta(j_1, j_2) > 5$, $\not{E}_T > 50$ GeV, $m_{T_{\rm min}} > 105$ (120) GeV After applying the C3 (C3′)-cuts at $\sqrt{s}$ = 27(100) TeV we obtain the significance for various signals as follows: NUHM2 : 0 (0.22) at $\mathcal{L}$ = 3 ab^{-1} and 0(0.48) at $\mathcal{L}$ = 15 ab^{-1}; Type III : 0.22 (1.23) at $\mathcal{L}$ = 3 ab^{-1} and 0.5(2.7) at $\mathcal{L}$ = 15 ab^{-1} ; GM : 2.5 (3.02) at $\mathcal{L}$ = 3 ab^{-1} and 5.5(6.75) at $\mathcal{L}$ = 15 ab^{-1}.

3. Conclusions

In this paper, our goal is to catalogue various BSM scenarios that can give rise to the SSdB+$\not{E}_T$ signature in experiments and extract these signals from SM background by imposing suitable cuts. Since more than one BSM scenario qualify, we also focus on devising suitable cuts to distinguish these BSM models from one another. We have analyzed three new physics models: the NUHM2 scenario of natural SUSY models, the type-III seesaw model, and the GM model. Assuming $\mathcal{L}$ = 15 ab^{-1} and $\sqrt{s}$ = 27 (100) TeV, the C3 (C3′)-cuts and the B2 (B2′)-cuts are needed to observe clean GM model and type-III seesaw model signals, respectively, at a level above 5σ significance. For the NUHM2 model, a clean signal at a level above 5σ significance can be seen with the A3 (A3′)-cuts for data collected from $\mathcal{L}$ = 3 ab^{-1} and $\sqrt{s}$ = 27 (100) TeV.

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