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

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arXiv: 2106.03888. Published in: Phys.Rev.D 105 (2022) 5, 5

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Introduction

Till today, though, the Standard Model (SM) is the most celebrated and established theory, there are several reasons to expect new physics beyond SM. Some of these are as follows :

- The Higgs mass instability problem in the EW sector
- The origin of neutrino mass
- Dark Matter
- The origin of the matter-antimatter asymmetry in the Universe

and several others.

At the LHC, we have not seen any clear new physics signal yet. Here, we focus on the novel signal of same-sign diboson (SSdB) + $\not{E}_T$.
Since this signature has very small SM background, observing it would be a clear indication of BSM physics. The main essence of this work is to point out those BSM models which can possibly be responsible for such a signature, if seen in experiments.

SM Backgrounds: $t\bar{t}$, $t\bar{t}t\bar{t}$, $t\bar{t}W^{\pm}$, $t\bar{t}Z$, $W^{\pm}W^{\pm}jj$, $W^{\pm}W^{\pm}W^{\mp}$, $W^{\pm}Z$, ZZ, $W^{\pm}W^{\mp}Z$ and $W^{\pm}ZZ$.

Potential BSM models $\Longrightarrow$ SSdB + $\not{E}_T$

1. Supersymmetry
   - Each SM field is elevated to a superfield containing both fermionic and bosonic components.
   - Solves Higgs mass hierarchy problem and accommodates a valid cold dark matter candidate.
2. The type-III Seesaw Model
   - The SM particle spectrum is extended by three generations of $SU(2)_L$ triplet fermions with hypercharge $Y = 0$.
   - Explains the tiny neutrino masses and mixings.
3. The type-II Seesaw/Georgi-Machacek (GM) model
   - The SM particle spectrum is extended by at least one $SU(2)_L$ triplet scalar with hypercharge $Y = 1$.
   - The GM model contains an additional real $SU(2)_L$ triplet scalar.
   - Generates Majorana neutrino mass at tree level.

Supersymmetry

$m_{sparticles} >> m_{SMparticles}$
LHC Limits : $m_{\tilde{g}} > 2.2$ **TeV,** $m_{\tilde{t}_1} > 1.1$ **TeV $\Longrightarrow$ Is SUSY Unnatural?** The measure of Naturalness is the Electroweak fine-tuning parameter (Δ_{EW}) which is defined as $\Delta_{EW} = max_i|C_i|/(M_Z^2/2)$ Where, C_i is any one of the parameters on the RHS of $M_Z^2/2 \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2})$ A SUSY model is said to be natural if $\Delta_{EW} < 30$. We choose a natural SUSY model, namely NUHM2 and generalized it so that gaugino mass unification is not assumed. Though gaugino mass unification is not assumed, the benchmark point that we chose satisfies the mass hierarchy $\mu \ll M_2$ essential to give rise to the SSdB + $\not{E}_T$ signature via the feynman diagram shown in Fig. 1.

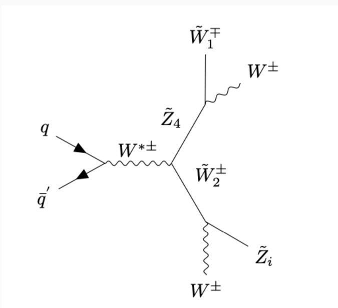

Fig. 1: SSdB production at the LHC in SUSY models with light higgsinos ($\tilde{W}_1^{\pm}$ and $\tilde{Z}_i$ with $i = 1, 2$). Here $\tilde{Z}_4$ and $\tilde{W}_2^{\pm}$ in the intermediate step are winos.

The final 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 follows:
A3 (A3')-cuts: SSdL, no b-jets, $p_T(\ell_1) > 20$ GeV, $\not{E}_T > 250(350)$ GeV, $m_{T_{\min}} > 200(325)$ GeV.
After applying the A3 (A3')-cuts at $\sqrt{s} = 27(100)$ TeV we obtain the significance for various signals as follows:
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}

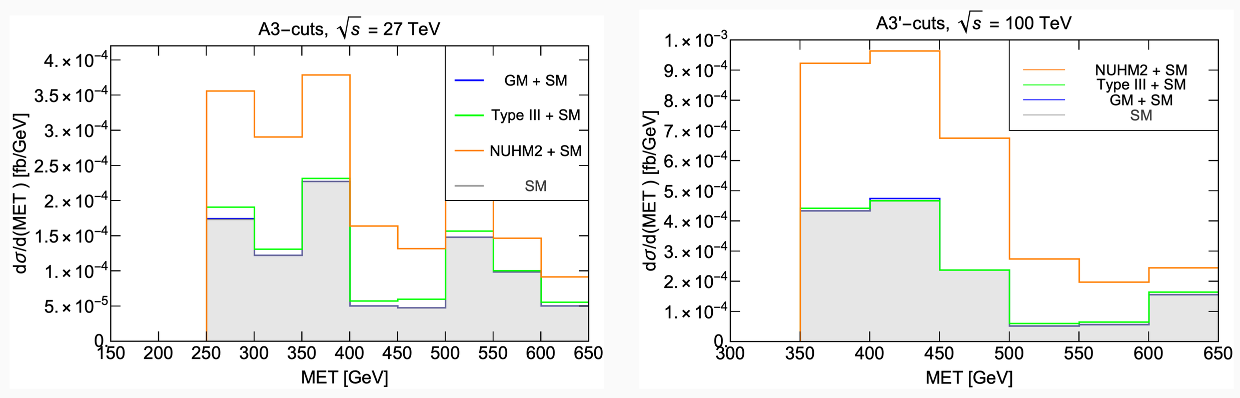

Fig. 2: $\not{E}_T$ distribution after (a) A3-cuts at $\sqrt{s} = 27$ TeV and (b) A3'-cuts at $\sqrt{s} = 100$ TeV.

The type-III Seesaw Model

We consider three generations of $SU(2)_L$ triplet fermions such that the heavier two generations are mass degenerate. Thus the heavier of these fermions can decay into the lighter one via the following feynman diagram and hence give rise to the SSdB + $\not{E}_T$ signature.

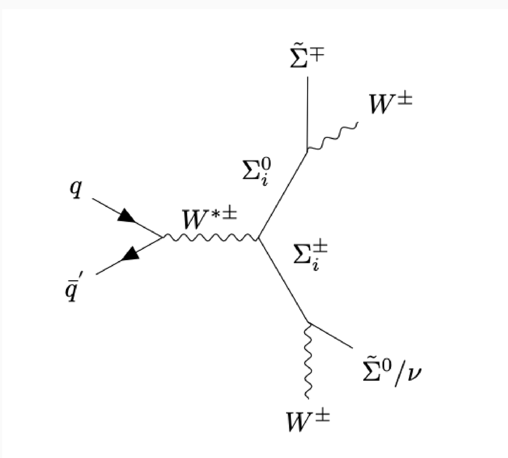

Fig. 3: SSdB + $\not{E}_T$ signature at the LHC in the type-III seesaw model, where $\tilde{\Sigma}^0$ and $\tilde{\Sigma}^{\pm}$ are members of the lightest fermionic triplets.

The final set of cuts, namely the B2 (B2')-cuts at $\sqrt{s} = 27(100)$ 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 $< m_{T_{\min}} <$ 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}

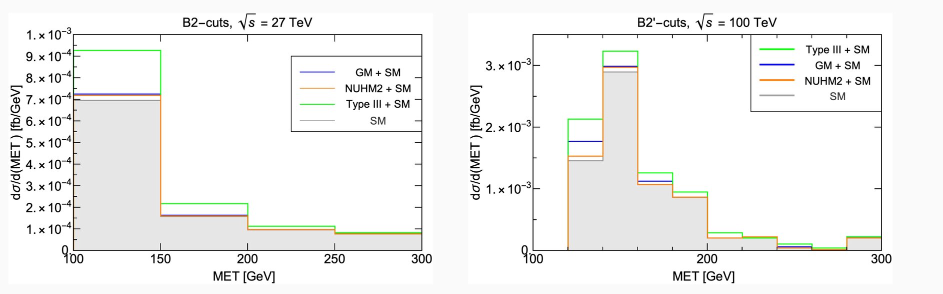

Fig. 4: $\not{E}_T$ distribution after (a) B2-cuts at $\sqrt{s} = 27$ TeV and (b) B2'-cuts at $\sqrt{s} = 100$ TeV.

The type-II Seesaw/Georgi-Machacek model

In this scenario, the SSdB signature originates from the decay of a doubly-charged scalar. In the type-II Seesaw model, beside the SM spectrum, present is an $SU(2)_L$ triplet scalar $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$ with hypercharge $Y = 1$. The accompanying jets, being forward, are most likely to escape detection. Then assuming leptonic decay of the W bosons, the final state mimics the signature of our interest.

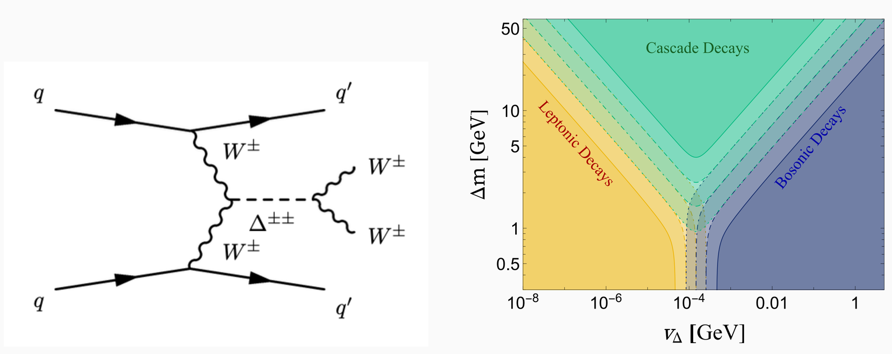

Fig. 5: (a)SSdB + forward jets production at LHC in the type-II seesaw models.(b)Decay phase diagram of doubly-charged scalar ($\Delta^{\pm\pm}$) with mass = 300 GeV.

Since, in type-II seesaw model $v_\Delta \leq 3$ GeV whereas in the GM model v_Δ can be as high as ~ 50 GeV, owing to the custodial symmetry, in GM model the resonant production rate of $\Delta^{\pm\pm}$ can be much higher. So, we will be using GM model with v_Δ = 10 GeV.

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, $m_{T_{\min}} > 105$ (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}

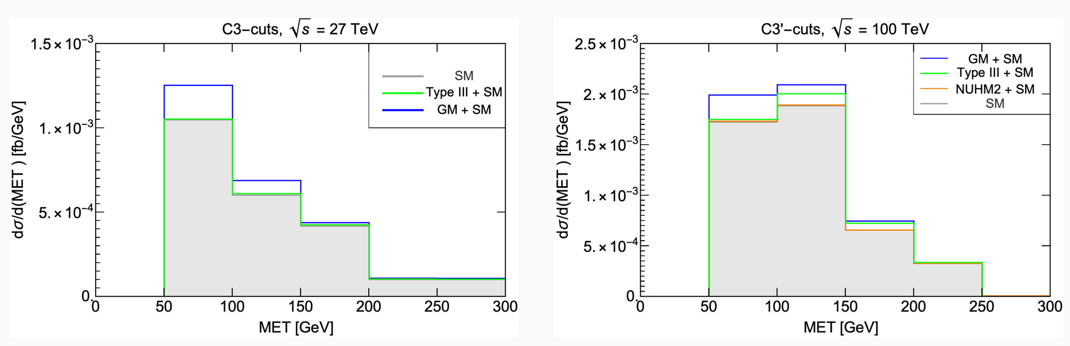

Fig. 6: $\not{E}_T$ distribution after (a) C3-cuts at $\sqrt{s} = 27$ TeV and (b) C3'-cuts at $\sqrt{s} = 100$ TeV.

Conclusion

- Here, we focus on using the signature of SSdB + $\not{E}_T$ to search for new physics and study how various models with such a signature can be distinguished by imposing suitable cuts. We find that it is possible to observe such a unique signature in three well-motivated BSM scenarios, namely: (i) NUHM2 model (ii) type-III seesaw model and (iii) type-II seesaw/Georgi-Machacek model, while still being consistent with the existing theoretical and experimental limits.
- For the NUHM2 model we were able to obtain significance above 5σ for our chosen benchmark point with $\sqrt{s} = 27$ TeV and IL $= 3$ ab^{-1}. For obtaining significance above 5σ for our chosen benchmark point in type-III seesaw model and GM model at $\sqrt{s} = 27$ TeV an IL $= 15$ ab^{-1} is needed.