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

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Overview

1. The Standard Model and its drawbacks

2. BSM models
   - Supersymmetry
   - The type-III Seesaw Model
   - The type-II Seesaw/Georgi-Machacek model

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   - Supersymmetry analysis
   - Type-III Seesaw analysis
   - Type-II Seesaw/Georgi-Machacek Model analysis

4. Conclusion

The Standard Model and its drawbacks

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 origin of neutrino mass
- The explanation of a DM candidate
- 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.

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.
   - 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 notion of *Practical Naturalness* states that

An Observable $\mathcal{O}$ is natural if all independent contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$.

The measure of Naturalness is the Electroweak fine-tuning parameter (Δ_{EW}) which is defined as

$$\Delta_{EW} = max_i |C_i|/(M_Z^2/2) \tag{1}$$

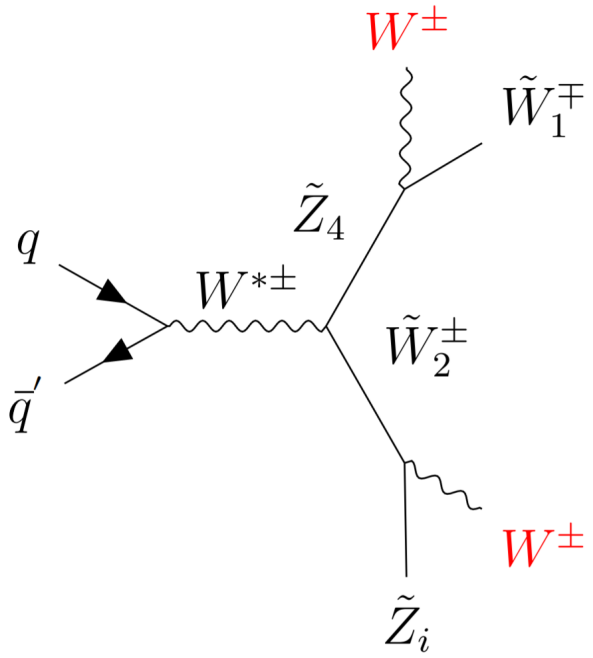
Where, C_i is any one of the parameters on the RHS of the following equation :

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{2}$$

A SUSY model is said to be natural if $\Delta_{EW} < 30$. This choice $\Delta_{EW} < 30$ is not ad-hoc, rather it arises from anthropic requirements for life to sustain.

Supersymmetry

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 following feynman diagram.



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.

Supersymmetry

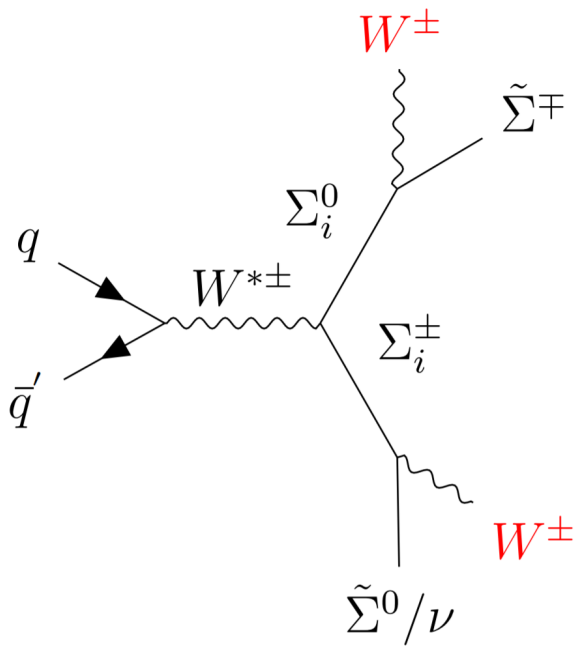
We have not assumed gaugino mass unification to compare this signal to the type-III seesaw model signal.

Our chosen benchmark point:

Input parameters:
$m_0 =$ 5000 GeV, $A_0 = -8000$ GeV, $\tan\beta =$ 12,
$M_1(\mathrm{GUT}) = M_3(\mathrm{GUT}) =$ 1250 GeV, $M_2(\mathrm{GUT}) =$ 895 GeV,
$\mu =$ 150 GeV , $m_A =$ 2500 GeV
which yields
$m_{\tilde{g}} =$ 2938.23 GeV, $m_{\tilde{t}_1} =$ 1820.48 GeV, $m_{\tilde{w}_2} =$ 762.9 GeV, $m_{\tilde{z}_4} =$ 775.41 GeV, $m_h =$ 125.09 GeV, $\Delta_{EW} =$ 29.6

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.



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.

The type-III Seesaw Model

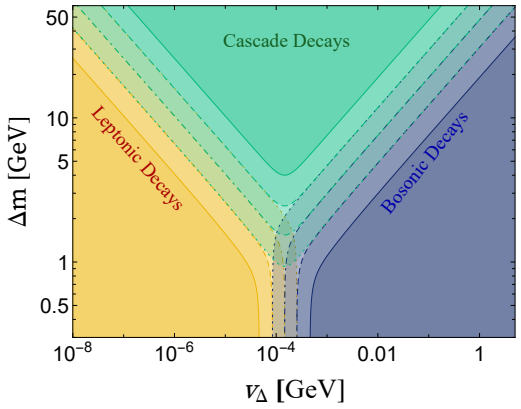
The lightest fermion triplet member $\tilde{\Sigma}^0$ of mass around a few hundred GeV can have lifetime long enough to escape detection and hence shows up as large $\not{E}_T$ in collider experiments.

arXiv: 1911.09037 by S. Jana, N. Okada, and D. Raut

$\tilde{\Sigma}^\pm$, being only a few MeV heavier than its neutral partner $\tilde{\Sigma}^0$ results in a disappearing track signature from $\tilde{\Sigma}^\pm$. Depending on experimental limits from several dedicated searches for the disappearing track signature, we set $m(\tilde{\Sigma}^\pm) = 670$ GeV in our chosen benchmark point. Therefore, we set the other two pairs of heavy fermions to have mass at 770 GeV, so that they primarily decay to a $W^\pm$ boson and a $\tilde{\Sigma}^{\pm,0}$, thereby leading to a clean SSdB $+ \not{E}_T$ signature.

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 $Y = 1$.

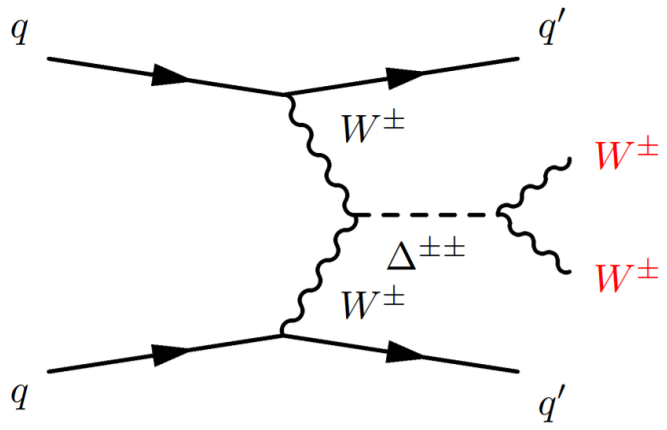


Decay phase diagram of doubly-charged scalar ($\Delta^{\pm\pm}$) with mass = 300 GeV. The solid, dashed, dot-dashed and dotted contours indicate 99%, 90%, 50% and 10% branching ratios respectively, for the bosonic, leptonic or cascade decays. The mass splitting Δm is defined in the main text.

Our chosen benchmark point: $m(\Delta^{\pm\pm}) = 300$ GeV, $\Delta m = 2$ GeV and $v_\Delta \sim 1$ GeV, where v_Δ is the VEV of Δ^0.

The type-II Seesaw/Georgi-Machacek model

Therefore, $\Delta^{\pm\pm}$ decays primarily to two same-sign W bosons via the following feynman diagram. 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.



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

Since, in type-II seesaw model $v_{\Delta} \lesssim 3$ GeV whereas in the GM model v_{Δ} can be as high as ~ 50 GeV, owing to the custodial symmetry breaking, in GM model the resonant production rate of $\Delta^{\pm\pm}$ can be much higher.

Signal and Background Evaluations

- For simulations, we have used `MadGraph5_aMC@NLO` for event generation, interfaced with `Pythia` 8.2 for parton showering and hadronization, followed by `Delphes` 3.4.2 for detector simulation where the default Delphes card is employed.
- We have used `Isajet` 7.88 to generate the Les Houches Accord (LHA) file for the NUHM2 signal and pass it through the above-mentioned simulation chain.
- We have used `Prospino` to derive the K-factors for the NUHM2 and the type-III seesaw signal. K-factors for the type-II/GM model signal and the SM BG processes have been obtained from an earlier analysis.

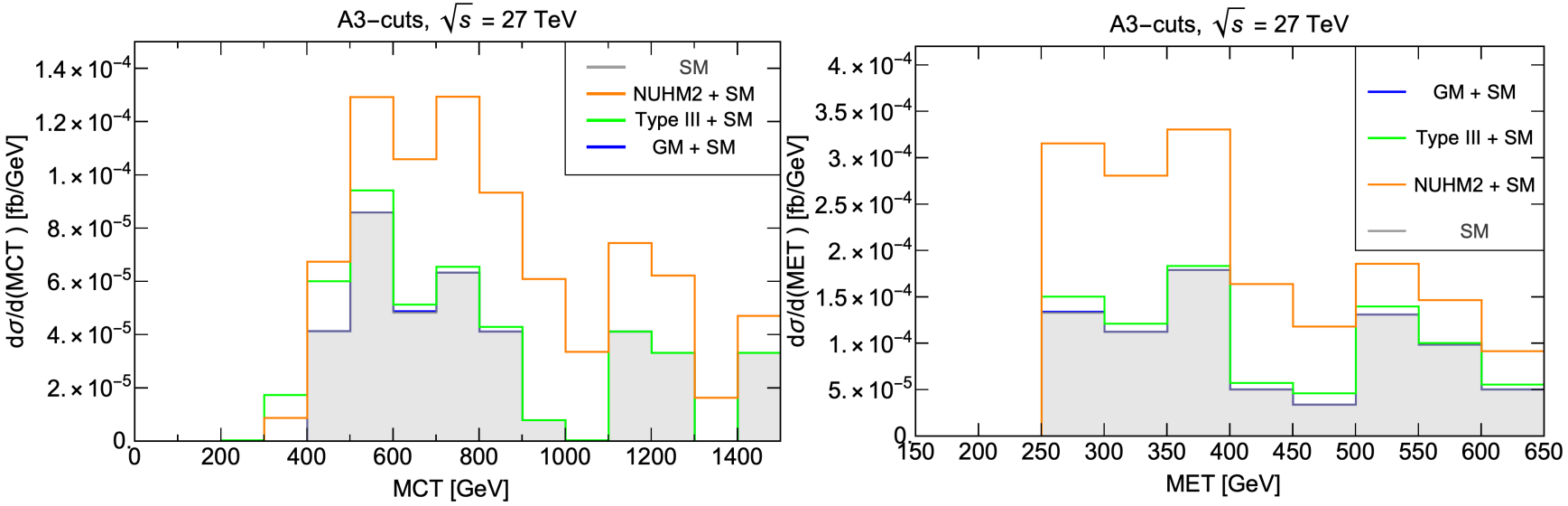
Supersymmetry analysis

Cuts used:

- Require exactly two same-sign isolated leptons, where the isolated leptons are defined as those with $p_T(\ell) > 10$ GeV and $\eta(\ell) < 2.5$.
- Veto events with any identified b-jet.
- Require $p_T(\ell_1) > 20$ GeV, where ℓ_1 denotes the leading lepton.
- Require $\not{E}_T > 250$ GeV.
- Require $m_{T_{\rm min}} > 200$ GeV.

At $\sqrt{s} = 27$ TeV, for an IL of 3 ab^{-1} (15 ab^{-1}), we obtain
$S/\sqrt{S+B} = 8.38\ (18.73)$ for the NUHM2 signal,
$S/\sqrt{S+B} = 1.3\ (2.91)$ for the type-III seesaw signal and
$S/\sqrt{S+B} = 0.015\ (0.03)$ for the GM model signal.

Supersymmetry analysis



(a) (b)

(a) MCT distribution and (b) $\not{E}_T$ distribution after the A3-cuts.

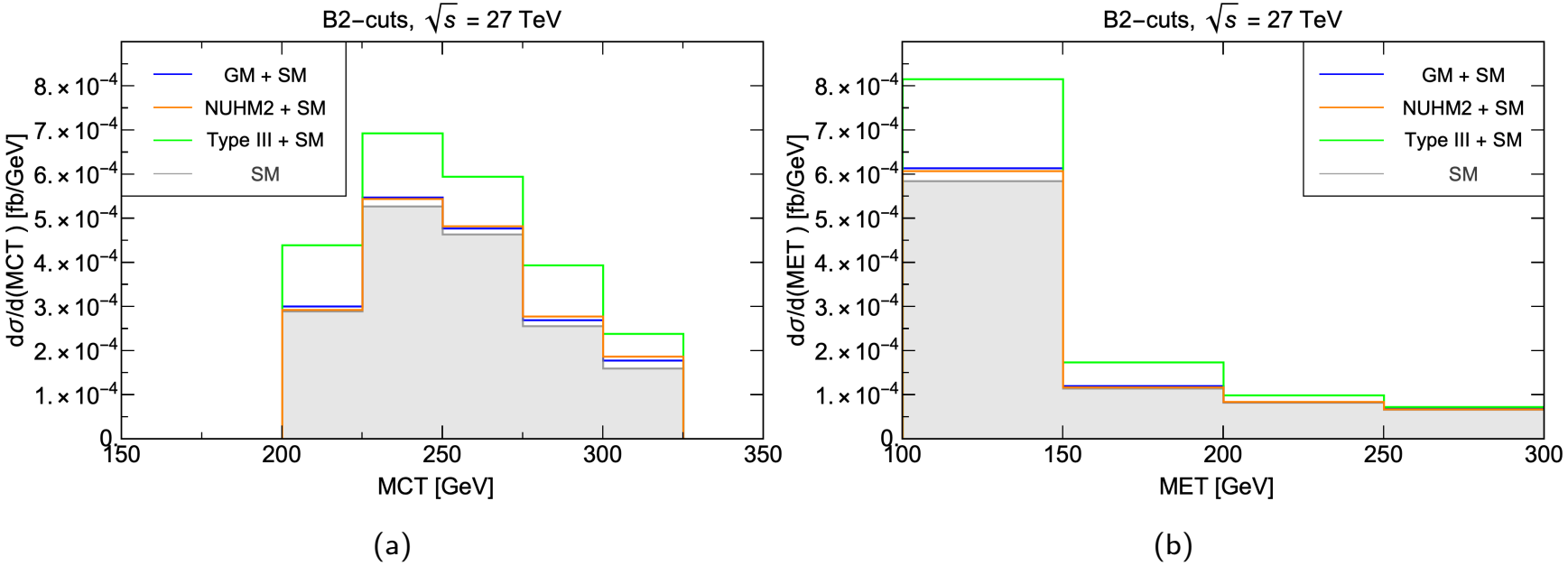
Type-III Seesaw analysis

Cuts used:

- Require exactly two same-sign isolated leptons, where the isolated leptons are defined as those with $p_T(\ell) > 10$ GeV and $\eta(\ell) < 2.5$.
- Veto events with any identified b-jet.
- Require $p_T(\ell_1) > 20$ GeV, where ℓ_1 denotes the leading lepton.
- Require njet ≤ 1.
- Require $\not{E}_T > 100$ GeV.
- Require 105 GeV $< m_{T_{\rm min}} <$ 195 GeV.
- Require 200 GeV $<$ MCT $<$ 325 GeV.

At $\sqrt{s} = 27$ TeV, for an IL of 3 ab^{-1} (15 ab^{-1}), we obtain
$S/\sqrt{S+B} = 3.74\ (8.36)$ for the type-III seesaw signal,
$S/\sqrt{S+B} = 0.6\ (1.3)$ for the NUHM2 signal and
$S/\sqrt{S+B} = 0.5\ (1.1)$ for the GM model signal.

Type-III Seesaw analysis



(a) MCT distribution and (b) $\not{E}_T$ distribution after the B2-cuts.

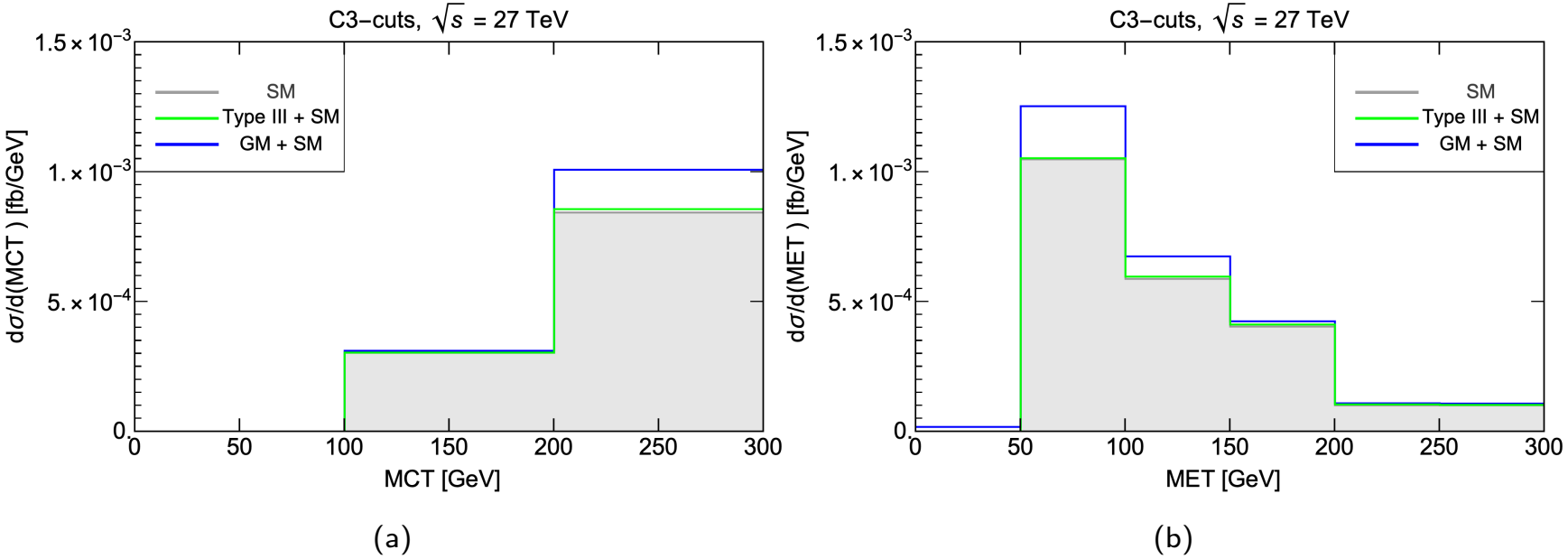
Type-II Seesaw/Georgi-Machacek Model analysis

Cuts used:

- Require exactly two same-sign isolated leptons, where the isolated leptons are defined as those with $p_T(\ell) > 10$ GeV and $\eta(\ell) < 2.5$.
- Veto events with any identified b-jet.
- Require $p_T(\ell_1) > 20$ GeV, where ℓ_1 denotes the leading lepton.
- Require MCT ≤ 300 GeV.
- Require njet ≥ 2.
- Require $\Delta\eta(j_1, j_2) > 5$.
- Require $m_{T_{\rm min}} > 105$ GeV.

At $\sqrt{s} = 27$ TeV, for an IL of 3 ab^{-1} (15 ab^{-1}), we obtain
$S/\sqrt{S+B} = 2.6\ (5.8)$ for the GM model signal,
$S/\sqrt{S+B} = 0.22\ (0.5)$ for the type-III seesaw signal, and
$S/\sqrt{S+B} = 0\ (0)$ for the NUHM2 signal.

Type-II Seesaw/Georgi-Machacek Model analysis



(a) MCT distribution and (b) $\not{E}_T$ distribution after C3-cuts.

Conclusion

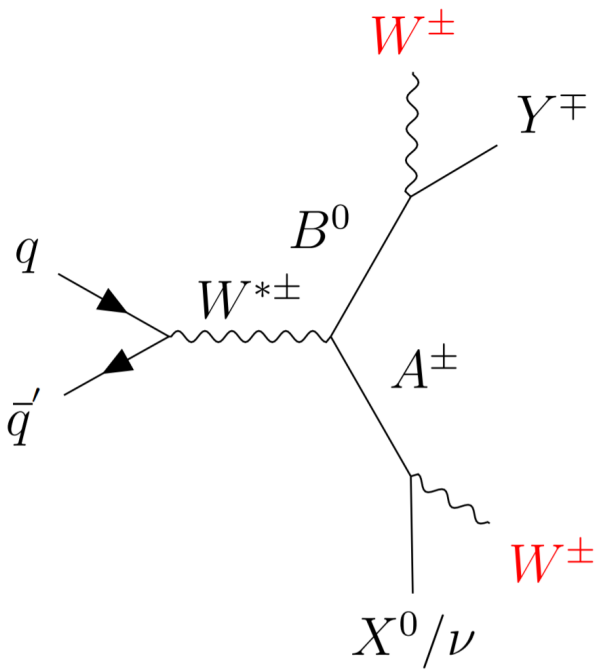
- Here, we focus on using the signature of SSdB + $\not{E}_T$ to search for new physics and study how various models with such a signature can be distinguished by imposing suitable cuts.
- We find that it is possible to observe such a unique signature in three well-motivated BSM scenarios, namely: (i) 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 $= 3ab^{-1}$.
- 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 $= 15ab^{-1}$ is needed.

Thank You

Questions ?

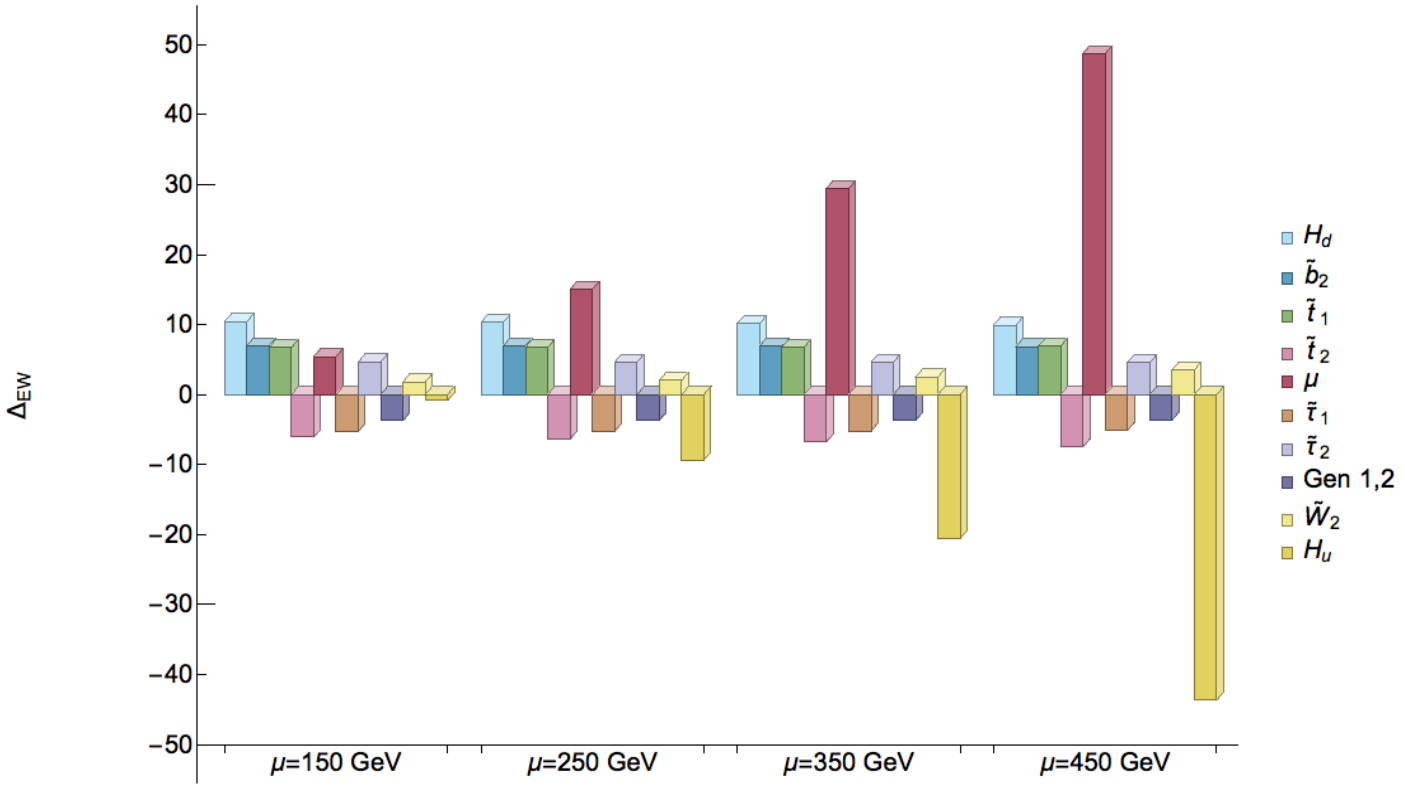
Back Up Slides

Generic diagram



A generic Feynman diagram for SSdB + $\not{E}_T$ production at the LHC in BSM models, where B^0, $A^{\pm}$, X^0 and $Y^{\pm}$ are new particles.

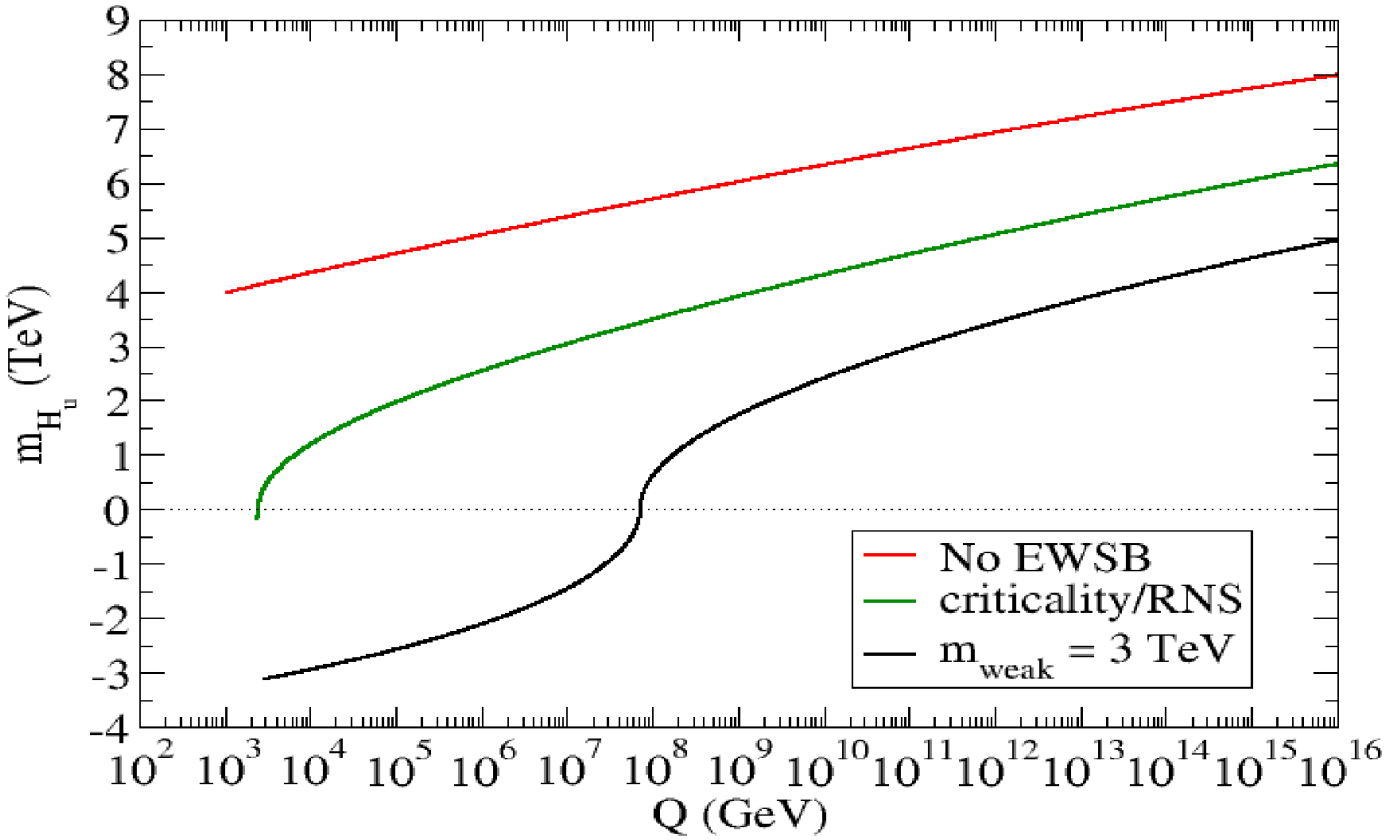
arXiv : 1702.06588 by H. Baer et. al.



3. Top ten contributions to Δ_{EW} from NUHM2 model benchmark points with $\mu = 150$, 250, 350 and 450 GeV.

$\Delta_{EW} < 30$ requires $\mu \sim$ 100-350 GeV.

arXiv : 1602.07697 by H. Baer et. al.



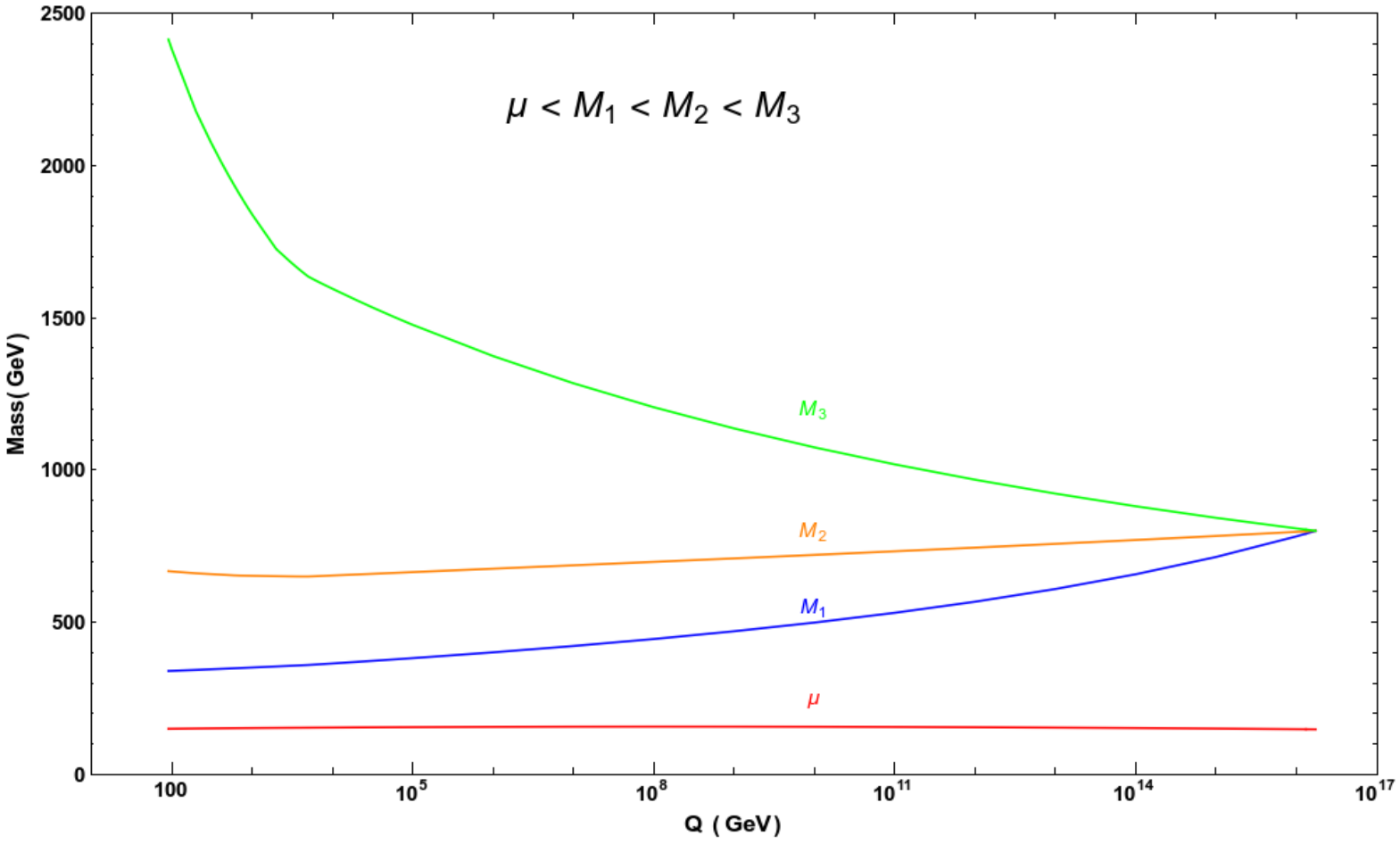
4. Evolution of the term $sign(m^2_{H_u})\sqrt{m^2_{H_u}}$ for the case of $No\ EWSB$, criticality as in RNS and $m_{weak} = 3$ TeV. Supersymmetric models with **radiatively-driven naturalness** enjoy modest electroweak fine-tuning while respecting LHC sparticle and Higgs mass constraints.

nNUHM2,3 Model

In the two- or three- extra parameter non-universal Higgs models, nNUHM2 or nNUHM3,

- The SSB parameters arise from tree level gravitational interactions of observable sector superfields with gauge singlet hidden sector fields. This mechanism is called **Gravity-mediated SUSY breaking**.
- The gaugino masses are unified to $m_{1/2}$, the matter scalar soft masses are unified to m_0 and the trilinear couplings are unified to A_0 at the GUT scale.
- In the NUHM3 model, it is further assumed that the third generation matter scalars are split from the first two generation $m_0(1,2) \neq m_0(3)$.
- The soft Higgs masses m_{H_u} and m_{H_d} are independent of m_0.Typically the parameter freedom in m_{H_u} and m_{H_d} is traded for the more convenient weak scale parameters μ and m_A.

NUHM2



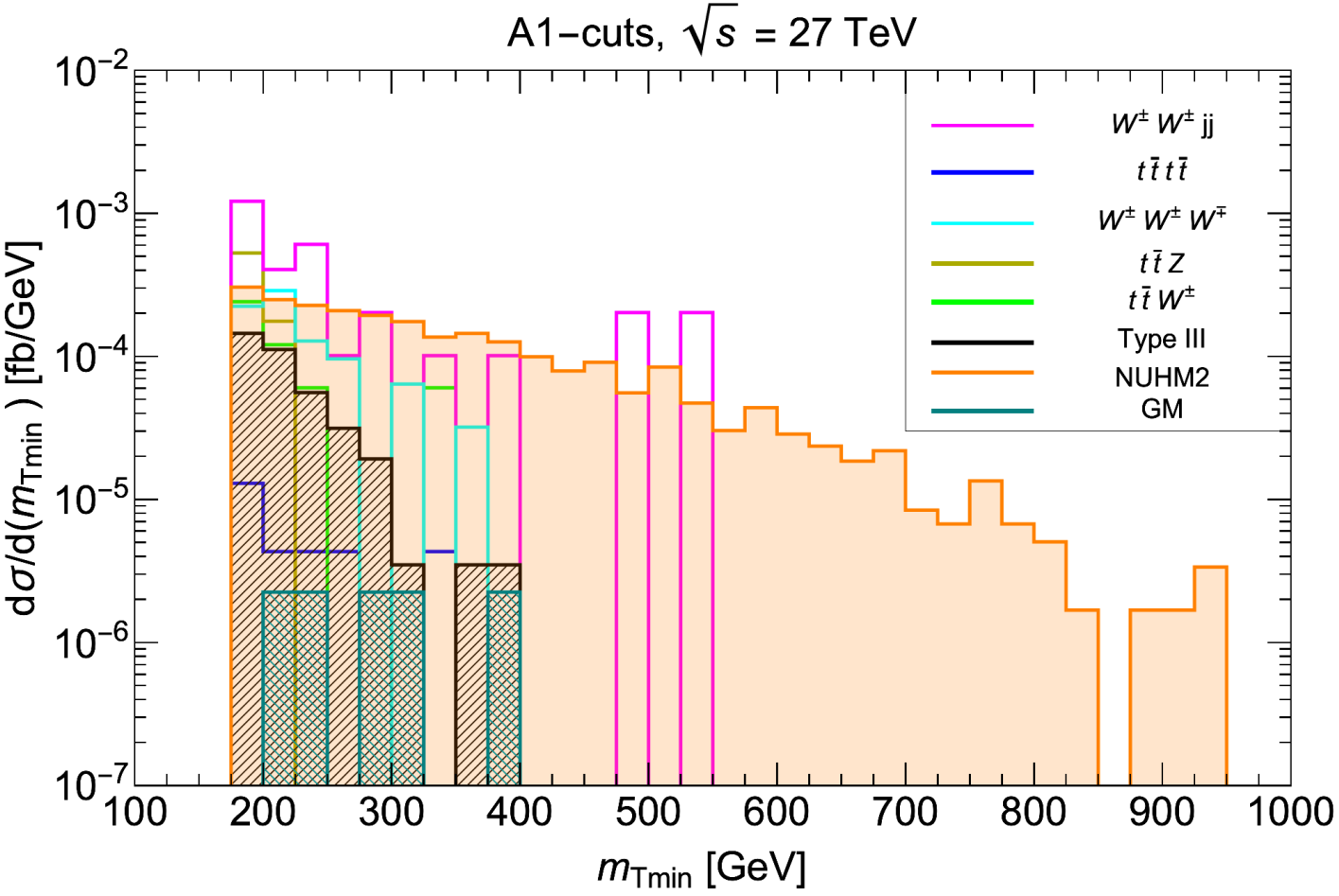
5. This hierarchy leads to a novel, rather clean same-sign diboson signature from wino pair production at hadron colliders.

$m_{T_{\mathrm{min}}}$

Minimum transverse mass ($m_{T_{\mathrm{min}}}$) is defined as:

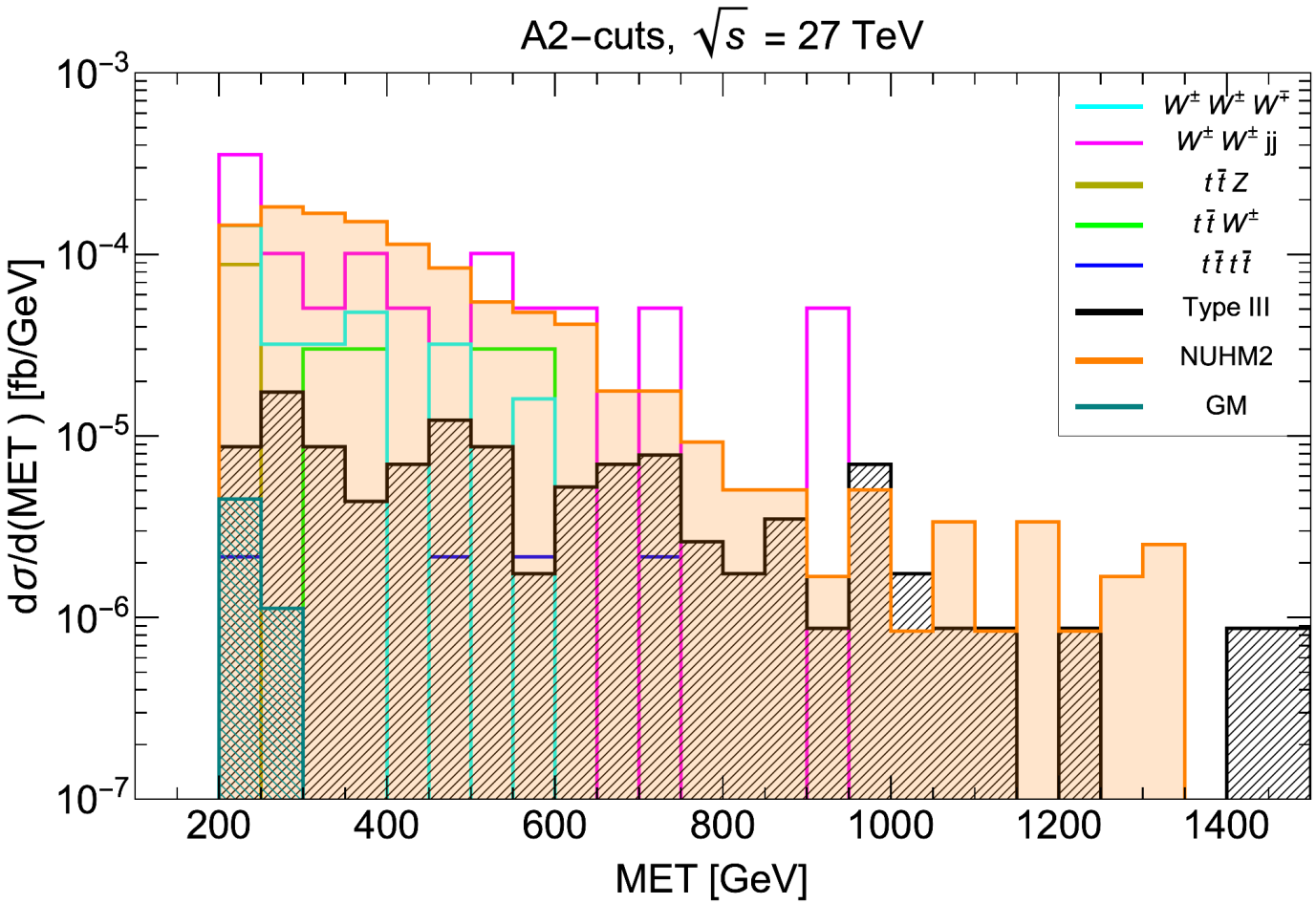
$$m_{T_{\mathrm{min}}} = \min(m_T(\ell_1, \not{E}_T), m_T(\ell_2, \not{E}_T)) \tag{3}$$

Supersymmetry analysis



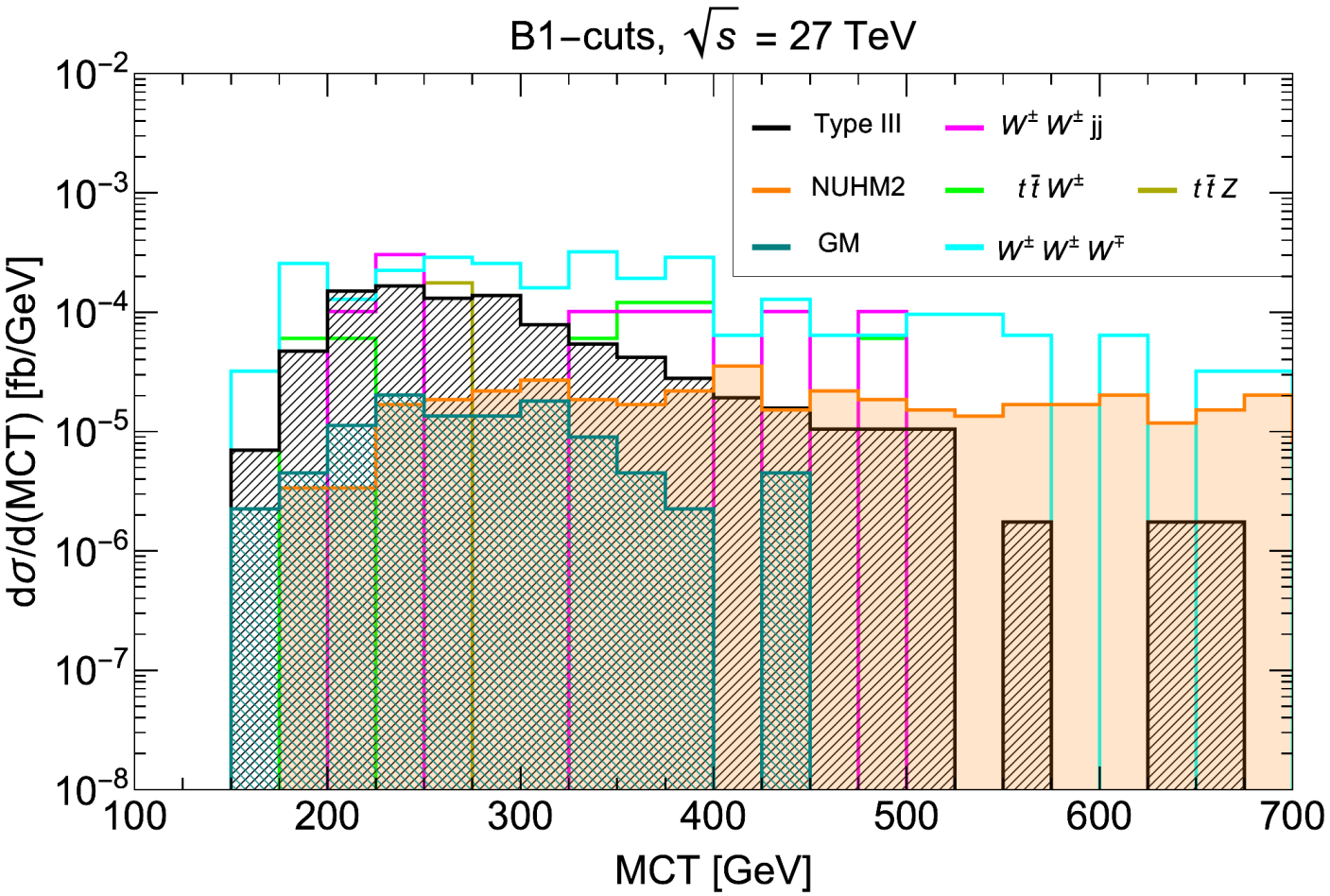
$m_{T_{\mathrm{min}}}$ distribution after A1-cuts.

Supersymmetry analysis



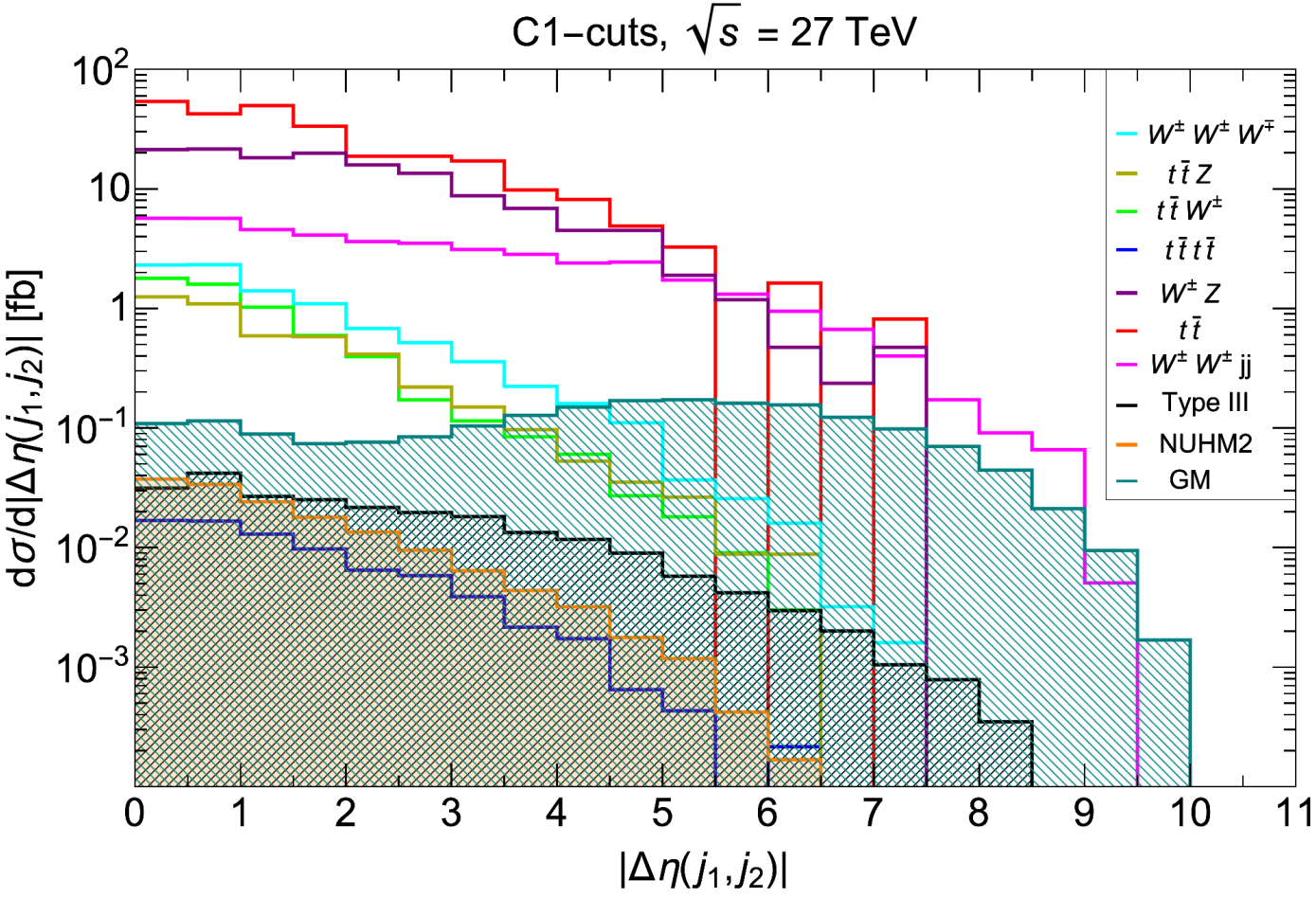
$\not{E}_T$ distribution after A2-cuts.

Type-III seesaw analysis



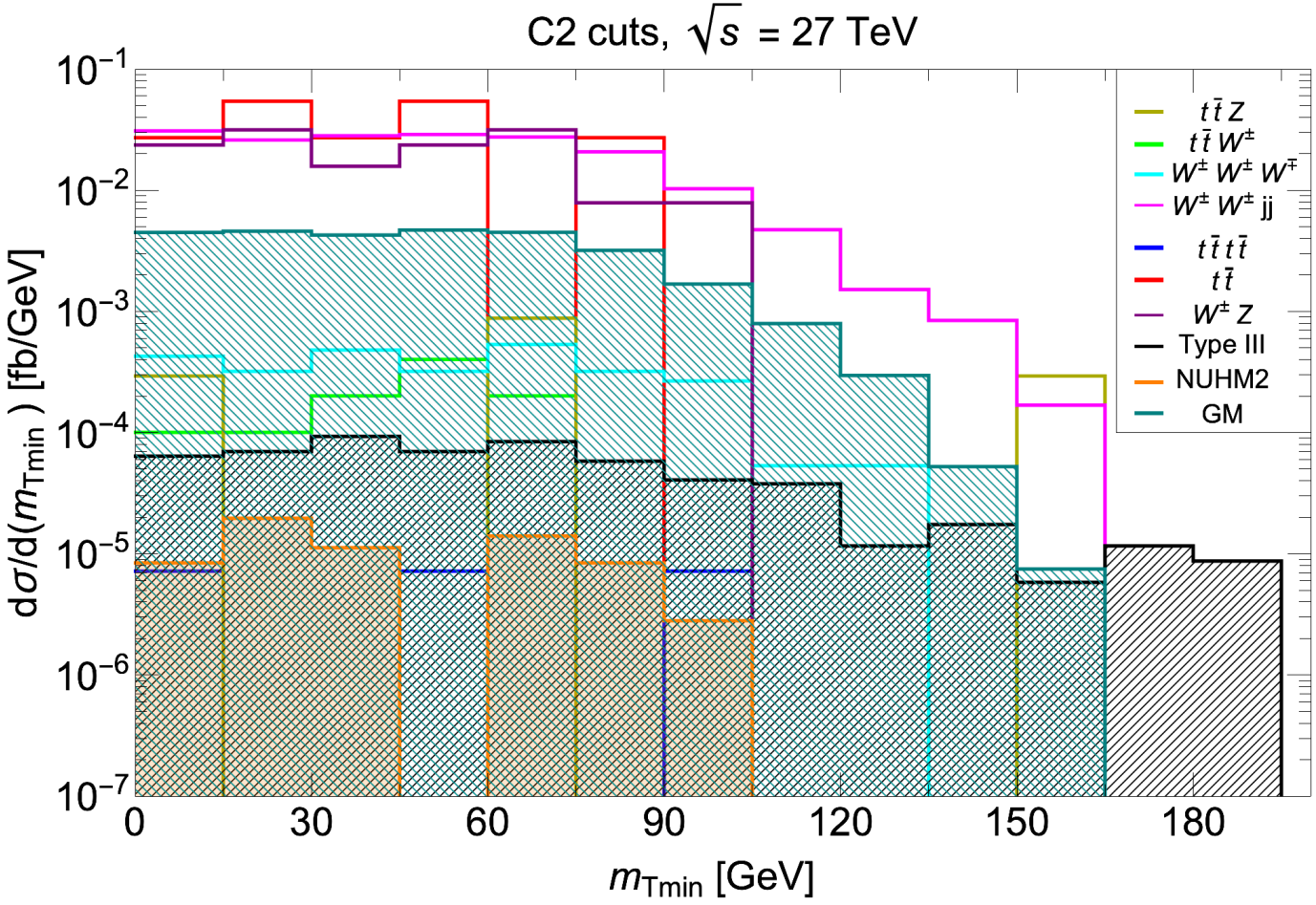
MCT distribution after B1-cuts.

Type-II seesaw/GM model analysis



$\Delta\eta(j_1, j_2)$ distribution after C1-cuts.

Type-II seesaw/GM model analysis



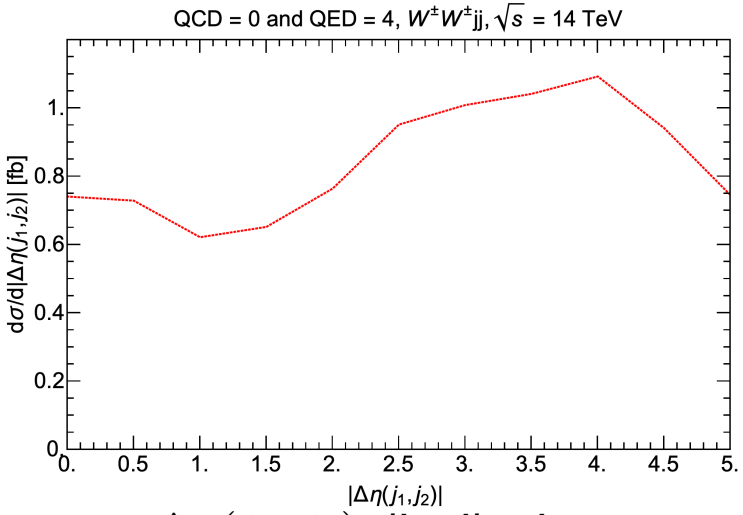
$m_{T_{\mathrm{min}}}$ distribution after C2-cuts.

$W^{\pm}W^{\pm}jj$ process in the SM

The $W^{\pm}W^{\pm}jj$ process in the SM includes two types of diagrams: 1. QCD $=$ 0 and QED $=$ 4 and 2. QCD $=$ 2 and QED $=$ 2. As can be seen in the following figure, we do get a peak at higher value of $\Delta\eta(j_1, j_2)$ for the QCD $=$ 0 and QED $=$ 4 diagrams after the following cuts:

- $p_T(\ell) > 20$ GeV, $\eta(\ell) < 2.5$, $\Delta R_{\ell\ell} > 0.3$
- $p_{T,miss} > 40$ GeV
- $p_T(j) > 30$ GeV, $\eta(j) < 4.5$, $\Delta R_{j\ell} > 0.3$

as depicted in Eur.Phys.J.C 78 (2018) 8, 671



$\Delta\eta(j_1, j_2)$ distribution.