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Nonuniversal supergravity at the LHC: Prospects and discovery potential

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We explore supersymmetry (SUSY) parameter space with nonuniversal high scale parameters in a gravity mediated SUSY breaking (SUGRA) scenario that accommodates a Higgs mass of (125 ± 2) GeV while satisfying cold dark matter relic density and other low energy constraints. We indicate a few benchmark points consistent with different dark matter annihilation processes where third family squarks are lighter than the first two as a requirement to keep the Higgs mass within the limit. We show that bottom rich and leptonic final states have a better reach in such parameter space points and is the most likely scenario to discover SUSY at the upcoming run of LHC with center-of-mass energy 14 TeV.

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I. INTRODUCTION

Supersymmetry (SUSY) [1,2] has been under a scanner for the past 40 years or more. The ongoing Large Hadron Collider (LHC) has put strong bounds on the squark and gluino masses of minimal supersymmetric Standard Model (MSSM), particularly on minimal supergravity (mSUGRA) or constrained minimal supersymmetric Standard Model (CMSSM) [3], not seeing any of those supersymmetric particles. Still, the SUSY search in different forms is the most studied subject of particle physics research due to its unparalleled theoretical appeal and phenomenological implications.

Out of different SUSY-breaking schemes, mSUGRA has been the most popular due to its economy of parameters: the universal gaugino mass ($M_{1/2}$), the universal scalar mass (m_0), the universal trilinear coupling (A_0) all at the grand unified theory (GUT) scale, $\tan\beta$, the ratio of the vacuum expectation values of the two Higgses and the sign of SUSY-conserving Higgsino mass parameter μ. However, this framework has been highly constrained by direct and indirect search experiments [4–7], and nonuniversality in scalar [8–19] and gaugino masses [20–22] are gaining more importance to keep low-scale SUSY alive.

The recent discovery of the Higgs boson with $m_H \simeq 125$ GeV at LHC by the ATLAS and CMS Collaborations [23] has put a severe constraint on SUSY parameter space. SUSY Higgs gets a significant correction from the top squark (stop) loop, which increases with an increasing stop mixing and/or a stop mass scale. Therefore, to get a Higgs boson around 125 GeV, a significant stop mixing or a large stop mass scale is required. Large stop mixing results into large mass splitting in the stop sector and consequently gives rise to a lighter stop ($\tilde{t}_1$) in the mass spectrum. Hence, the Higgs boson mass at 125 GeV results in a SUSY mass spectrum with light third family scalars.

The light third family scalars but the relatively heavy first two families[1] favor SUSY discovery at future LHC runs given gluino ($\tilde{g}$) dominantly decays into top-stop pairs ($\tilde{g} \to t\tilde{t}_1$) and subsequently stop decays into the top neutralino or the b-chargino where $t \to bW^{\pm}$ gives rise to multiple b jets, leptons and large missing energy ($E_{\not T}$). Final states with multiple b jets and charged leptons, together with large missing energy, cut down the SM background much more than the usual SUSY signals with multijets plus a large missing energy, and both ATLAS and CMS experiments have achieved b-tagging efficiency 50% or more and have put bounds on SUSY from the available data [5].

Another important aspect of SUSY is the dark matter (DM); R-parity conservation yields a natural candidate, namely, the lightest supersymmetric particle (LSP). The DM relic density limits from WMAP [24] and PLANCK [25] can easily be satisfied in the nonuniversal gaugino and/or scalar mass scenarios where CMSSM is tightly constrained. For example, if the wino mass is smaller than the bino mass at the GUT scale ($M_2 \leq M_1$), we obtain wino dominated LSP yielding the correct abundance in a larger parameter space. Similarly, nonuniversality in the scalar sector may result in a Higgsino-like LSP (from nonuniversality in the Higgs sector) or a stau-LSP coannihilation (from nonuniversality in the soft SUSY breaking stau mass). We have systematically studied such nonuniversal gaugino and/or scalar mass scenarios and proposed benchmark points for collider studies at LHC with $E_{CM} = 14$ TeV.

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[1]Such scenarios have already been considered for studies in different contexts [8,9,10].

A vast amount of work has already been done in mSUGRA to discover SUSY at the LHC. However, because of the observed Higgs mass, and the dark matter constraint, the only region left in mSUGRA and accessible at the LHC is the stop coannihilation region (where the lighter top squark $\tilde{t}_1$ and the lightest neutralino $\tilde{\chi}_1^0$ annihilate to satisfy the dark matter constraint. However, in this parameter space, $\tilde{t}_1$ mass is very close to the $\tilde{\chi}_1^0$ mass giving rise to very little high p_T multijet activity from its decay [26]. A significant number of works have also been done by increasing the number of parameters, with nonuniversal gaugino masses and nonunversality in the scalar masses satisfying all the existing constraints [27]. However, we pinpoint that to survive the Higgs mass and dark matter constraint in the framework of gravity mediated supersymmetry breaking, a larger region of parameter space is available with specific nonuniversal gaugino and scalar mass patterns with a generic signature in bottom rich and bottom quark plus charged lepton rich final states with large missing energy, which with suitable cuts can be observed over the SM background at the 14 TeV LHC. We claim that these will be the most favorable final states at the 14 TeV LHC to discover SUSY or to put the strongest bounds on them.

The paper is organized as follows. In Sec. 2, we discuss the model under consideration and the selected benchmark points. We also review the dark matter constraints on the SUSY parameter space to motivate our benchmark points. In Sec. 3, we discuss the final states in which SUSY signals can be observed over the SM background, including the details of the collider simulation strategy and the numerical results at the 14 TeV LHC. We conclude in Sec. 4.

II. MODEL, CONSTRAINTS AND BENCHMARK POINTS

A. Constraints on SUSY models

The following measurements play a key role to constrain SUSY parameter space. We discuss their effect and motivate how that leads eventually to the benchmark points chosen in this article for SUSY searches at LHC.

(i) The main constraint on the SUSY parameter space after LHC 7/8 TeV data is that the CP-even Higgs mass is within [23]

$$123 \leq m_h \leq 127. \tag{1}$$

(ii) The branching ratio for $b \to s\gamma$ [6] which at the 3σ level is

$$2.13 \times 10^{-4} < \mathrm{Br}(b \to s\gamma) < 4.97 \times 10^{-4}. \tag{2}$$

(iii) We also take into account the constraint coming from the $B_s \to \mu^+\mu^-$ branching ratio which by LHCb observation [7] at 95% C.L. is given as

$$2 \times 10^{-9} < Br(B_s \to \mu^+\mu^-) < 4.7 \times 10^{-9}. \tag{3}$$

(iv) Parameters are fine-tuned in a way that it gives a correct cold dark matter relic abundance according to WMAP data [24], which at 3σ is

$$0.091 < \Omega_{\mathrm{CDM}} h^2 < 0.128, \tag{4}$$

where Ω_{CDM} is the dark matter relic density in units of the critical density and $h = 0.71 \pm 0.026$ is the reduced Hubble constant (namely, in units of $100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$).

To note here, the PLANCK constraints $0.112 \leq \Omega_{\mathrm{DM}} h^2 \leq 0.128$ [25] are more stringent and cut a significant amount of dark matter allowed SUSY parameter space. We choose our benchmark points satisfying PLANCK on top of WMAP.

In the following subsection, we discuss mainly the dark matter and Higgs mass constraints on SUSY parameter space as they have been the key for choosing our benchmark points.

B. Dark matter and Higgs mass on SUSY: Benchmark points

One of the main motivations for postulating R-parity conserving SUSY is the presence of a stable weakly interacting massive particle (WIMP) which can be a good cold dark matter. The lightest neutralino $\tilde{\chi}_1^0$ is most often the LSP and a good candidate for cold dark matter. In some regions of the parameter space, it has the annihilation cross section to SM particles yielding the correct relic abundance to satisfy WMAP/PLANCK [24,25].

In mSUGRA, $\tilde{\chi}_1^0$ is bino dominated in a large part of the parameter space. For a bino DM, the WIMP miracle occurs when they annihilate to leptons via a t-channel exchange of sleptons with mass in the 30–80 GeV range [28]. However, slepton masses that light were already discarded by direct slepton searches at LEP2 [29]. Therefore, after LEP2, some distinct parts of the mSUGRA parameter space that satisfies relic abundance are as follows:

(i) *The h-resonance region* [30] is characterized by $2m_{\tilde{\chi}_1^0} \sim m_h$ which occurs at low $m_{1/2}$. In this region, the $\tilde{\chi}_1^0$ annihilation cross section enhances due to the presence of a s-channel h resonance.

(ii) *The A-funnel region* [31] is where $2m_{\tilde{\chi}_1^0} \sim m_A$; A is the CP-odd Higgs boson. This region is characterized by large $\tan\beta \sim 50$.

(iii) *The hyperbolic branch/focus point (HB/FP) region* [32] is the parameter space where the large m_0 region corresponds to small μ and thus the Higgsino dominates $\tilde{\chi}_1^0$ and annihilates to WW, ZZ and Ah significantly.

(iv) *The stau coannihilation region* [33] arises if the neutralino LSP is nearly degenerate with the stau ($m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\tau}_1}$). In mSUGRA, this occurs at low m_0 and high $M_{1/2}$.

(v) *Stop coannihilation* [34] occurs in mSUGRA with some particular values of A_0, where a lighter stop ($\tilde{t}_1$) becomes nearly degenerate with the LSP.

After LHC data with the discovery of Higgs and exclusion limits on the squark/gluino masses, many of the above DM regions in mSUGRA are highly constrained. With 20.3 fb^{-1} integrated luminosity and $E_{CM} = 8$ TeV, ATLAS [35] and CMS [36] Collaborations have excluded equal squark and gluino masses below 1.7 TeV completely ruling out the h-resonance region, whereas the A-funnel, stau and stop coannihilation regions are partly excluded. Observation of the Higgs mass at about 125 GeV indicates large m_0 ($m_0 > 0.8$ TeV) and large A_0 ($|A_0| > 1.8 m_0$ for $m_0 < 5$ TeV) [37]. For $m_0 > 0.8$ TeV, stau coannihilation is viable only at very large $M_{1/2}$ values which makes the SUSY discovery at the collider very challenging. The HB/FP region remains unscathed by the LHC squark/gluino searches as it requires low μ at very large $m_0 \sim 3-10$ TeV for $A_0 = 0$. However, the Higgs mass at 125 GeV (requires a large $|A_0|$) pushes the region to much higher m_0 $\sim 10 - 50$ TeV values. A small part of stop coannihilation is the only region of the mSUGRA parameter space alive, having some possibilities of seeing at 14 TeV LHC.

Nonuniversality in the gaugino and/or scalar sector, on the other hand, can provide a lot more breathing space. The implications of a direct search bound from LHC on neutralino dark matter have been studied extensively. See, for example, [38–40]. In our analysis, we choose four benchmark points (BP) which are motivated from different LSP annihilation and coannihilation mechanisms and are consistent with all experimental limits:

(i) *BP1*: If $M_2 < M_1$ at the GUT scale and the electroweak (EW) scale, and $M_2 < \mu$ at the low scale, the LSP $\tilde{\chi}_1^0$ is wino dominated and then the lightest chargino is almost degenerate with LSP. Chargino coannihilation crucially controls the relic abundance in such a region of parameter space, apart from a larger wino component that itself increases the annihilation cross section. A large part of purely wino DM hence provides underabundance [41]. However, we scan the wino dominated parameter space where it is consistent with the relic abundance from WMAP. As an example, we have scanned the parameter space over M_1, M_2 and A_0 for $m_0 = 2000$ GeV, $M_3 = 500$ GeV $\tan\beta = 15$ and $\mu > 0$. The allowed values of M_2/M_1 as a function of A_0 are plotted in Fig. 1 for three different values $M_2 =$ 700, 800 and 900 GeV in red, blue and green, respectively. When we vary M_2 continuously, they merge into a continuous region. It is important to note in Fig. 1 the vertical high A_0 region is dominated by stop coannihilation as the stop becomes lighter with increasing A_0 and a small change in A_0 results in a big change in M_2/M_1 to keep the relic abundance within the proper limit. The horizontal part of the red, blue and green regions with smaller A_0, on the other hand, represent wino dominated dark matter with nearly degenerate chargino and coannihilation to yield the proper abundance. For example, with $M_2 = 700$ GeV, $|A_0| > 4000$ GeV is dominated by stop coannihilation and $|A_0| < 4000$ GeV characterizes wino DM. Our first benchmark point BP1 is a representative of this particular nonuniversal gaugino mass scenario $M_3 < M_2 < M_1$ with wino dominated DM. While gaugino mass nonuniversality has been used to obtain BP1, scalar masses are kept universal. Also note that gaugino nonuniversality with $M_3 < M_2 < M_1$ is obtained within the framework of SUSY-GUT in $SU(5)$ or $SO(10)$ [20,21] with the dimension five operator in the extension of the gauge kinetic function $f_{\alpha\beta}(\Phi^j)$,

$$\mathrm{Re} f_{\alpha\beta}(\phi) F^{\alpha}_{\mu\nu} F^{\beta\mu\nu} = \frac{\eta(\Phi^s)}{M} \mathrm{Tr}(F_{\mu\nu} \Phi^N F^{\mu\nu}), \quad (5)$$

where nonsinglet chiral superfields Φ^N belong to the symmetric product of the adjoint representation of the underlying gauge group as

$$SU(5){:}\ (24 \times 24)_{\mathrm{symm}} = 1 + 24 + 75 + 200,$$

$$SO(10){:}\ (45 \times 45)_{\mathrm{symm}} = 1 + 54 + 210 + 770. \quad (6)$$

Gaugino masses become nonuniversal if these nonsinglet Higgses are responsible for the GUT breaking. The 75 and 200 belonging to $SU(5)$ or 770[2] of $SO(10)$ yield the hierarchy of $M_3 < M_1, M_2$ shown in Table 1. The specific nonuniversal ratio(s) used in the scan can be motivated from GUT breaking with a linear combination of the aforementioned nonsinglet representations. The benchmark points are explicitly written in Table 2.

(ii) *BP2*: Our second benchmark point BP2 is motivated from the hyperbolic branch/focus point region of DM. As has already been mentioned, for mSUGRA, very large values $m_0 \sim 10 - 50$ TeV are required to make μ small such that LSP becomes predominantly a Higgsino that paves the way for correct relic abundance through annihilation to WW, ZZ and Ah final states. However, the introduction of nonuniversality in the scalar sector, in particular in the Higgs parameters m_{H_u} and m_{H_d} at the GUT scale, gives rise to small μ, even without going to such high scalar masses, making it accessible to collider events at LHC. Again, following our strategy to minimize the number of parameters to choose BP2, we kept all gaugino and other scalar masses universal at the high scale.

(iii) *BP3*: Our third benchmark point BP3 represents the stau coannihilation region exploiting nonuniversality

[2]For breaking through 770, we quote the result when it breaks through the Pati-Salam gauge group G_{422D} ($SU(4)_C \times SU(2)_L \times SU(2)_R$ with even D-parity and is assumed to break at the GUT scale itself.

in the scalar sector. We have used squark-slepton nonuniversality as well as nonuniversality in the family to make the third family slepton masses lighter than other scalars at the high scale. Although such scalar nonuniversality is mostly phenomenological, having impacts on CP and flavor changing neutral current issues, it can be motivated from string-inspired models with flavor dependent couplings to the modular fields [8,9]. In Table 2 we show all the inputs at high scale as well as the low-scale SUSY masses.

(iv) *MSG*: The mSUGRA benchmark point, named as *MSG* here, represents the stop coannihilation region of DM parameter space. In mSUGRA, stop coannihilation occurs at distinct nonzero values of $|A_0|$ in a narrow range, for particular values of m_0, $M_{1/2}$, $\tan\beta$, and $\mathrm{Sign}(\mu)$. The Higgs mass of 125 GeV can also be obtained in the whole $m_0 - M_{1/2}$ plane with $m_0 >$ 0.8 TeV for large A_0. Hence, a tiny region of m_0, $M_{1/2}$ and A_0 parameter space simultaneously satisfies the right Higgs mass and dark matter constraints.

However, the situation changes dramatically if we introduce nonuniversality in the gaugino sector. If we assume $M_3 < M_2 = M_1$, effectively adding one more parameter to mSUGRA, then the Higgs mass of 125 GeV can be satisfied in a larger range of A_0 values; while for a given A_0, dark matter density can be satisfied by varying $M_{1,2}$ appropriately through stop coannihilation.

In Fig. 2, we have presented a sample scan of such a four-dimensional parameter space m_0, M_3, $M_{1,2}$ and A_0, for $\tan\beta = 15$ and positive μ. The left panel shows a three-dimensional subset of the scan with M_3 (along the x axis), m_0 (along the y axis) and A_0 (color gradient), and on the right panel we have M_3 (along the x axis), m_0 (along the y axis) and $M_{1,2}$ (color gradient). For a given M_3 and m_0, there is a range of A_0 and $M_{1,2}$ which gives rise to the right relic abundance and Higgs mass. For simplicity, in Fig. 2, we consider the minimum possible values of A_0 and $M_{1,2}$ which are consistent with experimental constraints. As a result, the whole parameter space shown in the figure is allowed by dark matter and Higgs mass constraint. The white dots in Fig. 2 correspond to $M_3 = M_{1,2}$, i.e. mSUGRA points as a subspace of such gaugino nonuniversality. Our benchmark point MSG is represented by one of these white dots. We did not chose a nonuniversal benchmark point from this region as the collider signature is expected to be the same as the chosen MSG point.

For the renormalization group equation (RGE), we use the code SuSpect v2.3 [42] with $m_t = 173.2$ GeV, $m_b = 4.2$ GeV, $m_\tau = 1.777$ GeV and stick to two-loop RGE with radiative corrections to the gauginos and squarks. We use full one loop and dominant two loop corrections for the Higgs mass. We ensure radiative electroweak symmetry breaking to evaluate the Higgsino parameter μ at the low scale out of high scale inputs $m^2_{H_u}$ and $m^2_{H_d}$, and the electroweak symmetry breaking scale has been set at $\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, the default value in the code SuSpect. The low scale value of the strong coupling constant has been chosen at $\alpha_3(M_Z)^{\overline{MS}} = 0.1172$. We compute the cold dark matter relic density with the code micrOMEGAs3.1 [43].

III. COLLIDER SIMULATION AND RESULTS

Nonuniversal SUGRA points advocated in the earlier section can be seen at the future run of LHC in bottom rich and leptonic final states. This also serves as a major distinguishing feature from mSUGRA points surviving Higgs mass and dark matter constraints.

We first discuss the strategy for the simulation including the final state observables and the cuts employed therein, and then we discuss the numerical results in the next subsection.

A. Strategy for simulation

The spectrum generated by SuSpect, as described in the earlier section, at the benchmark points are fed into the event generator PYTHIA 6.4.16 [44] by the SLHA interface [45] for the simulation of a pp collision with center of mass energy 14 TeV for LHC.

The default parton distribution functions CTEQ5L [46], the QCD scale $\sqrt{\hat{s}}$ in PYTHIA, has been used. All possible SUSY processes (mainly $2 \to 2$) and decay chains consistent with the conserved R parity have been kept open with the initial and final state radiation on. We take hadronization into account using the fragmentation functions built in PYTHIA.

The main "physics objects" that are reconstructed in a collider, are the following:

(i) Isolated leptons identified from electrons and muons;
(ii) Hadronic jets formed after identifying isolated leptons;
(iii) Unclustered energy made of calorimeter clusters with $p_T > 0.5$ GeV (ATLAS) and $|\eta| < 5$, not associated with any of the above types of high-E_T objects (jets or isolated leptons).

We try to mimic the experimental reconstruction for these objects in PYTHIA as follows.

(i) *Isolated leptons* (ℓ): Isolated leptons are identified as electrons and muons with $p_T > 10$ GeV and $|\eta| < 2.5$. An isolated lepton is separated from another lepton by $\Delta R_{\ell\ell} \geq 0.2$, from jet (jets with $E_T > 20$ GeV) with $\Delta R_{\ell j} \geq 0.4$, while the energy deposit $\sum E_T$ due to low-E_T hadron activity around a lepton within $\Delta R \leq 0.2$ of the lepton axis should be ≤ 10 GeV. $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ is the separation in pseudorapidity and azimuthal angle plane. The smearing functions of isolated electrons, photons and muons are described below.

(ii) *Jets* (jet): Jets are formed with all the final state particles after removing the isolated leptons from the list with PYCELL, an inbuilt cluster routine in PYTHIA. The detector is assumed to stretch within the pseudorapidity range $|\eta|$ from -5 to $+5$ and is segmented in 100 pseudorapidity (η) bins and 64 azimuthal (ϕ) bins. The minimum E_T of each cell is considered as 0.5 GeV, while the minimum E_T for a cell to act as a jet initiator is taken as 2 GeV. All the partons within $\Delta R = 0.4$ from the jet initiator cell are considered for the jet formation, and the minimum $\sum_{\text{parton}} E_T{}^{\text{jet}}$ for a collected cell to be considered as a jet is taken to be 20 GeV. We have used the smearing function and parameters for jets that are used in PYCELL in PYTHIA.

(iii) *b jets*: We identify partonic b jets by a simple b-tagging algorithm with an efficiency of $\epsilon_b = 0.5$ for $p_T > 40$ GeV and $|\eta| < 2.5$ [47].

(iv) *Unclustered objects* ($Unc.O$): All the other final state particles, which are not isolated leptons and separated from jets by $\Delta R \geq 0.4$, are considered as unclustered objects. This clearly means all the particles (electron/photon/muon) with $0.5 < E_T < 10$ GeV and $|\eta| < 5$ (for muonlike track $|\eta| < 2.5$) and jets with $0.5 < E_T < 20$ GeV and $|\eta| < 5$, which are detected at the detector, are considered as unclustered objects.

(v) *Electron/photon energy resolution*:

$$\sigma(E)/E = a/\sqrt{E} \oplus b \oplus c/E, \tag{7}$$

where

$$a = 0.03\ [\text{GeV}^{1/2}], \quad b = 0.005 \quad \text{and}$$
$$c = 0.2\ [\text{GeV}] \quad \text{for } |\eta| < 1.5 \quad \text{and}$$
$$a = 0.055\ [\text{GeV}^{1/2}], \quad b = 0.005 \quad \text{and}$$
$$c = 0.6\ [\text{GeV}] \quad \text{for } 1.5 < |\eta| < 5.$$

$\oplus$ indicates addition in quadrature.

(vi) *Muon P_T resolution*:

$$\sigma(P_T)/P_T = a \quad \text{if } P_T < 100 \text{ GeV} \tag{8}$$

$$= a + b \log(P_T/\xi) \quad \text{if } P_T > 100 \text{ GeV}, \tag{9}$$

where

$$a = 0.008 \quad \text{and} \quad b = 0.037$$
$$\text{for } |\eta| < 1.5 = 0.02 = 0.05 \quad 1.5 < |\eta| < 2.5$$

and $\xi = 100$ GeV.

(vii) *Jet energy resolution*:

$$\sigma(E_T)/E_T = a/\sqrt{E_T}, \tag{10}$$

where $a = 0.55\ [\text{GeV}^{1/2}]$, default value used in PYCELL.

(viii) *Unclustered energy resolution*:

$$\sigma(E_T) = \alpha\sqrt{\Sigma_i E_T^{(\text{Unc}O)i}}, \tag{11}$$

where $\alpha \approx 0.55$. One should keep in mind that the x and y components of $E_T^{\text{Unc}O}$ need to be smeared independently with the same smearing parameter.

We sum vectorially the x and y components of the momenta separately for all visible objects to form visible transverse momentum $(p_T)_{\text{vis}}$,

$$(p_T)_{\text{vis}} = \sqrt{\left(\sum p_x\right)^2 + \left(\sum p_y\right)^2}, \tag{12}$$

where $\sum p_x = \sum (p_x)_{\text{iso}\ell} + \sum (p_x)_{\text{jet}} + \sum (p_x)_{\text{Unc}O}$ and similarly for $\sum p_y$. We identify $(p_T)_{\text{vis}}$ as missing energy $E_{\not T}$, sometimes referred as MET in the text,

$$E_{\not T} = (p_T)_{\text{vis}}. \tag{13}$$

We also define effective mass H_T as the scalar sum of transverse momenta of visible objects like lepton and jets with missing energy

$$H_T = \sum p_T{}^{\ell_i} + p_T{}^{\text{jets}} + E_{\not T}. \tag{14}$$

Effective mass cuts have really been useful to reduce the SM background for the signals, as we will see shortly.

We studied the benchmark points in multilepton final states as well as in the b-rich final states at $E_{CM} =$ 14 TeV at LHC with varying cuts. The channels we study are the following:

(i) Four b jets with inclusive lepton and jets ($4b$): $4b + X + E_{\not T}$. Here X implies any number of inclusive jets or leptons without any specific veto on that. Basic cuts applied here are $p_T{}^b > 40$ GeV, $E_{\not T} > 100$ GeV.

(ii) Four b jets with single lepton ($4b\ell$) : $4b + \ell + X + E_{\not T}$. Here X implies any number of inclusive jets without any specific veto on that. The lepton can have any charge $\pm$. Basic cuts applied here are $p_T{}^b > 40$ GeV, $p_T{}^\ell > 20$ GeV, $|\eta| < 2.5$, $E_{\not T} > 100$ GeV.

(iii) Two b jets with dilepton ($2b2\ell$): $2b + 2\ell + X + E_{\not T}$. Here X implies any number of inclusive jets without any specific veto on that. Leptons can have any charge $\pm$ (including the same and opposite signs). Basic cuts applied here are $p_T{}^b > 40$ GeV, $p_T{}^\ell > 20$ GeV, $|\eta| < 2.5$, $E_{\not T} > 100$ GeV.

(iv) Same sign dilepton with inclusive jets ($\ell^\pm\ell^\pm$): $\ell^\pm\ell^\pm + X + E_{\not T}$. The basic cuts applied are $E_{\not T} > 30$ GeV, $p_T{}^{\ell_1} > 40$ GeV and $p_T{}^{\ell_2} > 30$ GeV with $|\eta| < 2.5$.

(v) Trilepton with inclusive jets ($\ell^\pm\ell^\pm\ell^\pm$): $\ell^\pm\ell^\pm\ell^\pm + X + E_{\not T}$. Basic cuts $E_{\not T} > 30$ GeV, $p_T{}^{\ell_1} >$ 30 GeV, $p_T{}^{\ell_2} > 30$ GeV and $p_T{}^{\ell_3} > 20$ GeV with $|\eta| < 2.5$.

(vi) Four-lepton with inclusive jets ($\ell^\pm\ell^\pm\ell^\pm$): $\ell^\pm\ell^\pm\ell^\pm\ell^\pm + X + E_{\not T}$. For basic cuts no missing energy cut is employed, while lepton transverse momentum cuts are as follows: $p_T{}^{\ell_1} > 20$ GeV, $p_T{}^{\ell_2} >$ 20 GeV and $p_T{}^{\ell_3} > 20$ GeV and $p_T{}^{\ell_4} > 20$ GeV with $|\eta| < 2.5$.

ℓ stands for final state isolated electrons and/or muons as discussed above and $E_{T}\!\!\!\!/$ depicts the missing energy. The opposite-sign dilepton was not considered mainly because of the huge SM background from the $t\bar{t}$ process.

Apart from the basic cuts including a Z veto of $|M_Z - M_{\ell^+\ell^-}| \geq 15$ GeV on the same flavor opposite sign dilepton arising in $2b2l$, trilepton and four lepton final states, we apply the sum of the lepton p_T cut ($\sum {p_T}^{\ell_i}$) and the combination of the lepton p_T cut with MET, called modified effective mass cut $H_{T1} = \sum {p_T}^{\ell_i} + E_{T}\!\!\!\!/$ to the leptonic final states, and harder H_T cuts on b-rich final states, and we refer to them as follows:

(i) $C1$: $\sum {p_T}^{\ell_i} > 200$ GeV
(ii) $C2$: $\sum {p_T}^{\ell_i} > 400$ GeV
(iii) $C3$: $H_{T1} > 400$ GeV
(iv) $C4$: $H_{T1} > 500$ GeV
(v) $C1'$: $\sum {p_T}^{\ell_i} > 100$ GeV
(vi) $C2'$: $\sum {p_T}^{\ell_i} > 200$ GeV
(vii) $C3'$: $H_{T1} > 150$ GeV
(viii) $C4'$: $H_{T1} > 250$ GeV
(ix) $C5$: $H_T > 1000$ GeV, $E_{T}\!\!\!\!/ > 200$ GeV, ${p_T}^b > 60$ GeV.

We have generated dominant SM events from $t\bar{t}$ in PYTHIA for the same final states with the same cuts and multiplied the corresponding events in different channels by the proper K factor (1.59) to obtain the usually noted next to leading order and next to leading log resummed cross section at LHC [48]. The $b\bar{b}b\bar{b}$, $b\bar{b}b\bar{b}W/Z$ and $t\bar{t}b\bar{b}$ backgrounds have been calculated in MADGRAPH5 [49]. The cuts are motivated such that we reduce the background to a great extent as shown in the next subsection. Note that softer cuts $C1'$, $C2'$, $C3'$, $C4'$ have been used for the four lepton channel where the SM background is much smaller.

B. Numerical results

The main SUSY production cross sections for the benchmark points have been noted in Table III with the total cross section for all $2 \to 2$ SUSY processes. All the nonuniversal benchmark points have similar gluino production and third family stop production, while the mSUGRA point has a huge stop production due to the very light stop mass, and the total cross section for this point is also dominated by that. Although other benchmark points have sufficiently a large branching fraction of stop going to bottom chargino or stop neutralino, MSG has nothing in these channels as the stop is almost degenerate with the lightest neutralino; it only decays to $c\tilde{\chi}_1^0$ in loop. For MSG, $\tilde{\chi}_2^0$ decays to $\tilde{\chi}_1^0 h$ 95%, and the first chargino dominantly decays to $\tilde{t}_1\bar{b}$. Hence the $3b$ channel can be a better channel to look for such MSG points. As mSUGRA is only alive in such a region of parameter space for the sake of dark matter, all MSG points will be similar in this aspect. We also note that for BP1: $\tilde{\chi}_1^\pm$ decays into $\ell + \nu_\ell + \tilde{\chi}_1^0$ through off-shell sleptons in 33% while $\tilde{\chi}_2^0$ decays to the leptonic final state is only $\simeq 1\%$. BP2 has dominant production in electroweak gauginos. Associated production of the gluinos with neutralinos is also quite heavy. Here $\tilde{t}_1 \to t\tilde{\chi}_{2,3}^0$ branchings are also of the same order of $\tilde{t}_1 \to t\tilde{\chi}_1^0$. Although $\tilde{\chi}_2^0$ decays to the leptonic final state is 1%, $\tilde{\chi}_1^\pm$ decays into $\ell + \nu_\ell + \tilde{\chi}_1^0$ in 33%. Huge electroweak production will significantly contribute to leptonic final states for BP2. For BP3, chargino and neutralino decays to the tau-rich final state as a result of lighter stau. Hence, in addition to the standard leptons, channels with tau tagging can be better channels to look for this benchmark point.

The missing energy distribution of the benchmark points in bottom rich final states is shown in Fig. 3. The missing energy has been normalized to 1. The $4b$ and $4b\ell$ final states do not have a significant background; hence only signal events are shown. It occurs that the benchmark points have a similar missing energy pattern, while for $2b2\ell$, the $t\bar{t}$ background has a sharper peak at the low missing energy as can be expected. Similarly effective mass H_T distribution in bottom-rich final states is shown in Fig. 4. There is no significant difference between the benchmark points in terms of this distribution either. We can see for the $4b\ell$ channel (Fig 3, top right), the peaks of the distributions are a bit separated. For $2b2\ell$, background $t\bar{t}$ peaks at a much lower value while the signal events have a peak ≥ 1000 GeV. This gives us the opportunity to put a very hard effective mass H_T cut, which reduces the background to almost zero, while retaining the signal. The hard effective mass cut also helps to remove other hadronic and QCD backgrounds as shown in Table IV.

In summary, from Table IV, BP1, BP2 and BP3 have very good prospects of being discovered at LHC in $4b$, $4b\ell$ and $2b2\ell$ final states while the corresponding MSG point does not contribute at all in such final states. The main reason of this is clear from Table III. Although $\tilde{t}_1\tilde{t}_1^*$ production is huge for MSG, the stop being almost degenerate with LSP, it cannot decay to $t\tilde{\chi}_1^0$ or $b\tilde{\chi}_1^+$, and hence it does not produce any b jets. We might, however, see $3b$ events from electroweak production.

The SM backgrounds are negligible in bottom rich channels excepting $2b2\ell$, which suffers from a sufficiently large background from $t\bar{t}$ production. But, a heavy effective mass cut (H_T) eliminates this to a large extent, while retaining the signals. The effective mass distribution in Fig. 4 bears the testimony to the fact. We also note that SM background events were simulated with a very high number of events, such that each event carries a small weight, 0.01 fb of the cross section; hence, null events in the simulation correspond to the cross section less than that.

The missing energy and effective mass distribution for same-sign dilepton and trilepton events are shown in Figs. 5 and 6, respectively. Again all the benchmark points show a very similar distribution, while the $t\bar{t}$ can be reduced with a heavy H_{T_1} cut. All the leptonic event numbers for the benchmark points are shown in Table V.

Table V tells us that trilepton events are still good for all the benchmark points while the four-lepton channel is good for BP2 and BP3 only. We also need to note that the background for the four-lepton channel is negligible (the hadronically quiet part comes from $4W$ or ZZZ production). After the cuts they vanish almost completely. Similarly ZW, which contributes to the trilepton, reduces to a great extent after the Z veto. Hence, we did not quote those background events here. We also see that the $C2$ and $C4$ cuts reduce the $t\bar{t}$ background significantly. $C2$ kills the signal events to a great extent too; hence, $C4$ is a better choice to reduce background and retain signal. Hence, these leptonic final states are also good channels to study such benchmark points. The reason for BP2 having larger leptonic events comes also from huge electroweak gaugino productions as pointed out in Table III. Hence, a significant part of these leptonic final states should contain hadronically quiet lepton events. The minimal supergravity benchmark point does not contribute at all to the leptonic final states, the reason being simply understood as not having lighter stops to decay through top or sleptons leading to leptons. Hence, such mSUGRA points can only be studied in hadronic channels or perhaps $3b$ final states as mentioned earlier. After mSUGRA being alive only in the stop coannihilation region, this seems to be a generic feature for all mSUGRA parameter space points to obey Higgs mass and dark matter constraint. This, in turn, can help distinguish such nonuniversal frameworks from mSUGRA in LHC signature space.

IV. SUMMARY AND CONCLUSIONS

It is remarkable that a Higgs boson has been discovered with a mass $\simeq$125 GeV. In pure SM, theoretically there is no reason why its mass should be at the EW scale, or even if it is, why it is not much higher or lower than 125 GeV. (In fact, in pure SM, the best fit to the EW data prefers a much lower mass.) This gives us hope that some symmetry principle is there beyond the pure SM, and supersymmetry being the most natural candidate, because it solves the hierarchy problem, as well as it constrains the Higgs mass to be less than $\sim$135 GeV. In addition, supersymmetry has a natural candidate for the dark matter. However, the minimal version of the most desirable version of MSSM, mSUGRA, is in a very tight corner to satisfy all the existing experimental constraints, as well as being within the reach of LHC. We find that mSUGRA is still viable in the stop coannihilation region in which the classic SUSY signal (multijet plus missing E_T) is essentially unobservable beyond the SM background at the LHC. (The other allowed region such as hyperbolic/focus point has SUSY particle masses well beyond the reach of LHC.) However, if we relax a little bit from mSUGRA with nonuniversal gaugino and/or scalar masses, the situation becomes much more favorable to discover SUSY at the LHC.

In this work, we have shown that SUSY with nonuniversalities in gaugino or scalar masses within a high scale SUGRA setup can still be accessible at LHC with $E_{CM} = 14$ TeV. In particular, we show the consistency of the parameter space in different dark matter annihilation regions. Wino dominated LSP with chargino coannihilation can be achieved with gaugino mass nonuniversality with $M_3 < M_2 < M_1$. The hyperbolic branch/focus point region with Higgsino dominated LSP can be obtained easily with Higgs nonuniversality as BP2. Such parameter space automatically occurs with lighter gauginos, and hence they may dominate the production and leptonic final states at LHC. Stau coannihilation can occur with scalar nonuniversality while stop coannihilation can arise simply with high-scale gaugino nonuniversality with $M_3 < M_2 = M_1$. mSUGRA, though viable in only the stop coannihilation region, do not yield lepton or b-rich final states due to a lack of phase space for the stop to decay leptonically. There exists a reasonable region of parameter space in the nonuniversal scenario which not only satisfies all the existing constraints, but also can unravel SUSY in the bottom and lepton rich final states with third family squarks being lighter than the first two automatically. We have made detailed studies of three benchmark points in these allowed parameter spaces, and find that the SUSY signal in the bottom or bottom plus lepton-rich final state stands over the SM background with suitable cuts. We have also investigated pure leptonic final states with suitable cuts, and find some of these final states have viable prospects. Finally we also emphasize that with good luminosity in the upcoming 14 TeV LHC runs, these allowed parameter spaces can be ruled out easily, or we will discover SUSY.

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