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Non-universal gaugino mass GUT models in the light of dark matter and LHC constraints

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ABSTRACT: We perform a comprehensive study of SU(5), SO(10) and E(6) supersymmetric GUT models where the gaugino masses are generated through the F-term breaking vacuum expectation values of the non-singlet scalar fields. In these models the gauginos are non-universal at the GUT scale unlike in the mSUGRA scenario. We discuss the properties of the LSP which is stable and a viable candidate for cold dark matter. We look for the GUT scale parameter space that leads to the the lightest SM like Higgs mass in the range of 122–127 GeV compatible with the observations at ATLAS and CMS, the relic density in the allowed range of WMAP-PLANCK and compatible with other constraints from colliders and direct detection experiments. We scan universal scalar (m_0^G), trilinear coupling A_0 and SU(3)_C gaugino mass (M_3^G) as the independent free parameters for these models. Based on the gaugino mass ratios at the GUT scale, we classify 25 SUSY GUT models and find that of these only 13 models satisfy the dark matter and collider constraints. Out of these 13 models there is only one model where there is a sizeable SUSY contribution to muon ($g-2$).

KEYWORDS: Supersymmetry Phenomenology

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Contents

1	Introduction	1
2	SUSY GUT and non-universal gauginos	2
3	Results	4
3.1	Relic density and collider constraints	4
3.2	Direct detection constraints	11
4	Muon ($g - 2$)	13
5	Conclusions	15

1 Introduction

Supersymmetry (SUSY) is an aesthetically appealing model which provides a natural mechanism to stabilise the Higgs mass and solves the gauge hierarchy problem of the Standard Model. The general Supersymmetric Standard Model at the electroweak scale has more than a hundred parameters which make the predictability of such models questionable. An economical Supersymmetric Standard Model can be constructed which contains only a few free parameters known as the constrained Minimal Supersymmetric Standard Model (cMSSM), which relates to the high scale minimal supergravity models (mSUGRA) through renormalisation groups. In mSUGRA there are only 5 parameters: universal scalar mass m_0 , universal gaugino mass $M_{1/2}$, $\tan\beta$, sign of μ ($sgn(\mu)$) and universal tri-linear couplings A_0 . The lightest supersymmetric particle (LSP) is mostly bino-like. But the recent LHC data is ruling out most of its parameter space for obtaining the WMAP-PANCK measured relic density of bino as cold dark matter. But it is not necessary to have all the gauginos unified at the unification scale.

It has been noted in [1–7] that in Supersymmetric Grand Unified Theories (SUSY GUTs) the boundary conditions at the high scale itself can be different than that in mSUGRA. The gaugino masses can be non-universal at the GUT scale itself. The renormalisation group evolutions (RGEs) further change their ratios at the electroweak scale and thus the phenomenology of such models can be completely different compared to mSUGRA. But these non-universalities in SUSY GUT models are completely determined from the group theoretic structure of the symmetry breaking scalar fields. In [1–7] these non-universal gaugino mass ratios were first calculated for SU(5) group with 24-, 75-, and 200- dimensional scalar fields. Later in [8–11] the non-universal gaugino mass ratios are presented for all possible breaking patterns having all possible scalar fields for SO(10), and E(6) GUT gauge groups.

These non-universal models are clear departure from mSUGRA in the boundary conditions. Thus different non-universalities lead to different kind of LSP scenarios. Some recent papers has partly grabbed the impact of non-universality feature in either minimal or non-minimal version of models in the context of dark matter search, see for example [10, 12–30].

In this paper we have encapsulated the parameter space for all models (25) arising from different GUT gauge groups, like SU(5), SO(10), and E(6) and the symmetry breaking patterns from all the possible scalar representations which can break the F-term and gauge symmetries as well. These give rise to different mass ratios of the three gauginos at the GUT scale. Here we have considered only those models for which all of them are non-zero at the unification scale.

Running the masses down to the electroweak scale we get the ratios $M_1 : M_2 : M_3$ for different models which are quite distinct from the mSUGRA relation $1 : 2 : 6.7$ at electroweak scale. Here M_1, M_2, M_3 ,¹ are the gaugino masses corresponding to the $U(1)_Y, SU(2)_L, SU(3)_C$ gauge groups respectively. We scan the parameters $M_3^G, m_0^G, A_0, \tan\beta$ and test the range of parameters for each model which give the lightest Higgs mass in the range $122 \text{ GeV} < M_h < 127 \text{ GeV}$ [31, 32], and the dark matter relic density within 3-sigma of the WMAP-PLANCK [33, 34] measured band $0.112 < \Omega h^2 < 0.128$. In addition we have other constraints: within the allowed parameter space the contribution to the $B_s \rightarrow X_s \gamma$ [35], $B_s \rightarrow \mu^+ \mu^-$ [36] and the muon $(g-2)$ [37–39] must satisfy the experimental bounds. We have also set the lower limit on the gluino mass ($m_{\tilde{g}}$) to be 1.4 TeV.² Once these criterion are satisfied we compute the best fit value for the SUSY contribution to muon $(g-2)$ within the parameter space of the models constrained by the other experimental limits.

Of the 25 models examined we find that only 13 models satisfy the collider and dark matter experimental constraints and we find however that none of these 13 models explain the experimental value of muon $(g-2)$ [37–39]. The other 12 models are mainly ruled out when we impose light Higgs mass and 3-sigma relic density constraints together. The largest contribution to muon $(g-2)$ comes from the the models where the gaugino mass ratio at GUT scale is $M_1 : M_2 : M_3 \equiv -1/2 : -3/2 : 1$ and this model has a bino like dark matter with mass 177 GeV.

There are five wino, five bino and three higgsino dark matter models which give the WMAP-PLANCK relic density. Some of the models can be probed by the XENON1T [40] and Super-CDMS [41] experiments and one model is ruled out by XENON100 [42].

2 SUSY GUT and non-universal gauginos

Supersymmetry and Grand Unified Theory both have different motivations to be suitable theories beyond the Standard Model. Supersymmetry justifies the gauge hierarchy problem and predicts many other superpartners of SM particles. In R-parity conserving SUSY theories LSP is stable and can be a viable cold dark matter candidate. Here we will focus

¹We define the GUT scale input of these parameters as M_i^G .

²Though it is not playing any crucial role in our analysis as within the parameter space allowed by the other constraints $m_{\tilde{g}}$ is more than 1.8 TeV or so.

only on the neutralino LSPs. Within this framework SUSY is expected to explain the observed relics of the Universe. Added with these nice outcomes the extra feature of this theory in the GUT framework is very encouraging. SUSY improves the gauge coupling unification in most of the GUT models. Thus SUSY GUT models are phenomenologically interesting and motivating.

The GUT symmetry is broken when a non-singlet direction under that gauge group acquires vacuum expectation value. In SUSY GUT unified frame work most of the couplings (masses) are degenerate at the unification scale. In its minimal form all the gauginos and scalars are universal respectively. The other free parameters are tri-linear coupling (A_0) which is also universal, $\tan \beta$ (ratio of the vacuum expectation values, vev , of two Higgs doublets), and sign of μ (Higgs parameter). But we can have other possibilities, like gauginos or scalars are non-universal at the High scale themselves when we work under SUSY GUT framework. The scalars that cause the GUT symmetry breaking may develop a F-term breaking vev . Thus GUT and supersymmetry are broken via a single scalar but through the $vevs$ in different directions. The gauge kinetic term can be recast in a much simpler form as: $\frac{\eta}{M} Tr(F_{\mu\nu} \Phi F^{\mu\nu})$ where η is dimensionless parameter, $M = M_{Pl}/\sqrt{8\pi}$ (reduced Planck mass). As $F_{\mu\nu}$ transforms as adjoint of the unbroken GUT groups, Φ belongs to the symmetric product of the two adjoints.

In this paper we have worked on SU(5), SO(10), E(6) GUT groups, thus the choices of scalars are as following:

$$\begin{aligned} \text{SU}(5) &\Rightarrow (24 \otimes 24)_{\text{sym}} = 1 \oplus 24 \oplus 75 \oplus 200, \\ \text{SO}(10) &\Rightarrow (45 \otimes 45)_{\text{sym}} = 1 \oplus 54 \oplus 210 \oplus 770, \\ \text{E}(6) &\Rightarrow (78 \otimes 78)_{\text{sym}} = 1 \oplus 650 \oplus 2430, \end{aligned} \tag{2.1}$$

where 24, 45, 78 are the dimensions of the adjoint representations of SU(5), SO(10), E(6) respectively.

It has been noted earlier that these operators also change the gauge coupling unification conditions at the high scale and in many cases it improves the unifications, see for example [43–46]. As these scalars are non-singlet, their vev treat the SM gauginos in different footing. Thus the SM gauge fields, i.e. the gauge couplings are scaled differently. These types of operators can inject non-universality in the gaugino masses.

In SU(5) models with only possible breaking pattern: $\text{SU}(5) \rightarrow \text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)$ the scalar fields of 24, 75 and 200 dimensions lead to three different set of non-universal gaugino mass ratios. But as the ranks of SO(10) and E(6) are larger than that of the SM there are more than one possible breaking patterns of these GUT symmetry groups. We have noted the gaugino mass ratios for the following intermediate breaking patterns of SO(10): $\text{SU}(5) \otimes \text{U}(1)$, $\text{SU}(4) \otimes \text{SU}(2) \otimes \text{SU}(2)$, and for E(6) we have considered $\text{SO}(10)' \otimes \text{U}(1)$, $\text{SU}(3) \otimes \text{SU}(3) \otimes \text{SU}(3)$, $\text{SU}(6) \otimes \text{SU}(2)$. Though the group theoretic structures are similar in few cases but as the SM symmetry is realised in different ways the non-universal gaugino mass ratios are different for those models. For example $\text{SU}(5) \otimes \text{U}(1)$ is a maximal subgroup of SO(10). In normal SU(5) model the extra U(1) does not contribute in $\text{U}(1)_Y$ of SM, but in flipped SU(5) model the hypercharge generator of SM is a linear combination

Model Number	$M_1 : M_2 : M_3$ (at M_X)	$M_1 : M_2 : M_3$ (at M_{EW})	Model
1	$-19/5 : 1 : 1$	$-19/5 : 2 : 6$	$SO(10) \xrightarrow{(1,0) \subset 210} (SU(5) \otimes U(1))_{\text{flipped}}$
2	$-3 : 1 : 1$	$-3 : 2 : 6$	$E(6) \xrightarrow{(189,1) \subset 2430,650} (SU(6) \otimes SU(2)_X)$
3	$-13/5 : 1 : 1$	$-13/5 : 2 : 6$	$E(6) \xrightarrow{(1,1) \subset 650} (SU(6) \otimes SU(2)_R)$
4	$-22/5 : 1 : 1$	$-22/5 : 2 : 6$	$E(6) \xrightarrow{(1,0) \subset 650} (SO(10) \otimes U(1))_{\text{flipped}}$
5	$41/15 : 1 : 1$	$41/15 : 2 : 6$	$E(6) \xrightarrow{(1,1) \subset 2430} (SU(6) \otimes SU(2)_R)$
6	$122/5 : 1 : 1$	$122/5 : 2 : 6$	$E(6) \xrightarrow{(1,0) \subset 2430} (SO(10) \otimes U(1))_{\text{flipped}}$
7	$-101/10 : -3/2 : 1$	$-101/10 : -3 : 6$	$SO(10) \xrightarrow{(24,0) \subset 770} (SU(5) \otimes U(1))_{\text{flipped}}$
8	$77/5 : 1 : 1$	$77/5 : 2 : 6$	$SO(10) \xrightarrow{(1,0) \subset 770} (SU(5) \otimes U(1))_{\text{flipped}}$
9	$10 : 2 : 1$	$10 : 4 : 6$	$SO(10) \xrightarrow{(200) \subset 770} SU(5)$

Table 1. Ratios of gaugino masses that lead to $M_1 > M_2$ at $EWSB(M_{EW})$ Scale.

of this $U(1)$ and another Abelian group coming from $SU(5)$. In these two cases the ratio of the gaugino masses at the GUT scale are different from each other. Here we have tabulated 24 different types of non-universal gaugino mass ratios discarding the possibility of one of the gauginos has zero mass at the high scale. It is very interesting to note that unlike the mSUGRA scenario here we can have either $M_1 > M_2$ or $M_1 < M_2$ and even $M_1 \simeq M_2$ at the electroweak scale. Thus where in mSUGRA we have mostly bino-like Lightest Supersymmetric Particle (LSP), in these SUSY-GUT frame work because of the non-universality one can have purely bino- or wino- or higgsino- dominated LSP or a mixed one also.

Here we briefly mention our model identifications depending on the GUT groups, choices of scalar fields and symmetry breaking patterns, see tables 1 and 2. Here we would like to pass a remark that while calculating these gaugino mass ratios for different models it has been assumed that all the intermediate symmetry scales are same as the unification (GUT) scale, i.e., the GUT symmetry is broken to the SM gauge group at the unification scale itself.

3 Results

We examine the different non-universal gaugino mass models in the light of relic density, direct detections and collider bounds. We have classified all the models in three categories depending on the compositions of the LSPs: bino-dominated, wino-dominated, and higgsino-dominated.

3.1 Relic density and collider constraints

We have used the following constraints in our analysis and determine which of the 25 models arising from non-singlet Higgs pass these tests:

Model Number	$M_1 : M_2 : M_3$ (at M_X)	$M_1 : M_2 : M_3$ (at M_{EW})	Model
10	$\frac{9}{5} : 1 : 1$	$\frac{9}{5} : 2 : 6$	$E(6) \xrightarrow{(405,1) \subset 2430} (SU(6) \otimes SU(2)_R)$
11	$-5 : 3 : 1$	$-5 : 6 : 6$	$SO(10) \xrightarrow{(75) \subset 770} SU(5)$
12	$1 : 35/9 : 1$	$1 : 70/9 : 6$	$E(6) \xrightarrow{(1,1) \subset 2430} (SU(6) \otimes SU(2)_L)$
13	$1 : -5 : 1$	$1 : -10 : 6$	$E(6) \xrightarrow{(1,1) \subset 650} (SU(6) \otimes SU(2)_L)$
14	$-3/5 : 1 : 1$	$-3/5 : 2 : 6$	$E(6) \xrightarrow{(189,1) \subset 650, 2430} (SU(6) \otimes SU(2)_R)$
15	$-1/5 : -1 : 1$	$-1/5 : -2 : 6$	$E(6) \xrightarrow{(35,1) \subset 650} (SU(6) \otimes SU(2)_R)$
16	$1/10 : 5/2 : 1$	$1/10 : 5 : 6$	$E(6) \xrightarrow{(770,0) \subset 2430} (SO(10) \otimes U(1))_{\text{flipped}}$
17	$1/10 : -3/2 : 1$	$1/10 : -3 : 6$	$E(6) \xrightarrow{(54,0) \subset 650} (SO(10) \otimes U(1))_{\text{flipped}}$
18	$2/5 : 2 : 1$	$2/5 : 4 : 6$	$E(6) \xrightarrow{(770,0) \subset 2430} (SO(10) \otimes U(1))_{\text{flipped}}$ $(SO(10) \otimes U(1))_{\text{flipped}} \xrightarrow{(200) \subset 770} SU(5)$
19	$-1/5 : 3 : 1$	$-1/5 : 6 : 6$	$E(6) \xrightarrow{(210,0), (770,0) \subset 650, 2430} (SO(10) \otimes U(1))_{\text{flipped}}$ $(SO(10) \otimes U(1))_{\text{flipped}} \xrightarrow{(75) \subset 210, 770} SU(5)$
20	$5/2 : -3/2 : 1$	$5/2 : -3 : 6$	$E(6) \xrightarrow{(770,0) \subset 2430} (SO(10) \otimes U(1))_{\text{flipped}}$ $(SO(10) \otimes U(1))_{\text{flipped}} \xrightarrow{(24) \subset 770} SU(5)$
21	$-1/5 : -3/2 : 1$	$-1/5 : -3 : 6$	$E(6) \xrightarrow{(210,0) \subset 650, 2430} (SO(10) \otimes U(1))_{\text{flipped}}$ $(SO(10) \otimes U(1))_{\text{flipped}} \xrightarrow{(24) \subset 210} SU(5)$
22	$-1/5 : 1 : 1$	$-1/5 : 2 : 6$	$E(6) \xrightarrow{(210,0) \subset 650, 2430} (SO(10) \otimes U(1))_{\text{flipped}}$ $(SO(10) \otimes U(1))_{\text{flipped}} \xrightarrow{(1) \subset 210} SU(5)$
23	$19/10 : 5/2 : 1$	$19/10 : 5 : 6$	$SO(10) \xrightarrow{(1,1) \subset 770} (SU(4) \otimes SU(2)_R)$
24	$-1/2 : -3/2 : 1$	$-1/2 : -3 : 6$	$SO(10) \xrightarrow{(24) \subset 54, 210, 770} SU(5)$ $SO(10) \xrightarrow{(24,0) \subset 54} (SU(5) \otimes U(1))_{\text{flipped}}$ $SO(10) \xrightarrow{(1,1) \subset 54} (SU(4) \otimes SU(2)_R)$
25	$7/10 : -3/2 : 1$	$7/10 : -3 : 6$	$SO(10) \xrightarrow{(24,0) \subset 210} (SU(5) \otimes U(1))_{\text{flipped}}$

Table 2. Ratios of gaugino masses that lead to $M_1 < M_2$ at EWSB(M_{EW}) Scale.

1. Higgs mass bound from LHC [31, 32]

$$122 \text{ GeV} < M_h < 127 \text{ GeV}$$

2. Relic density constraint from WMAP-PANCK data at 3σ [33, 34]

$$0.1118 < \Omega h^2 < 0.1280$$

3. Gluino mass ($m_{\tilde{g}}$) $> 1.4 \text{ TeV}$.

4. Branching fraction for $B_s \rightarrow X_s \gamma$ at 2σ [35]

$$3.05 \times 10^{-4} < \text{BR}(B_s \rightarrow X_s \gamma) < 4.05 \times 10^{-4}$$

5. Branching fraction for $B_s \rightarrow \mu^+ \mu^-$ at 2σ [47]

$$0.8 \times 10^{-4} < \text{BR}(B_s \rightarrow \mu^+ \mu^-) < 6.2 \times 10^{-4}$$

6. Ratio of branching fraction for $B_u \rightarrow \tau \nu_\tau$ in MSSM to that in SM at 3σ [48, 49]

$$0.46 < \frac{\text{BR}(B_u \rightarrow \tau \nu_\tau)_{\text{MSSM}}}{\text{BR}(B_u \rightarrow \tau \nu_\tau)_{\text{SM}}} < 1.78$$

7. There is a discrepancy in anomalous muon magnetic moment, $a_\mu \equiv (g-2)/2$, between experimental value [37–39] and SM prediction [50],

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10}$$

We compute the SUSY contribution to a_μ for each of the models which satisfies the other criterion listed above. We find only one model where there is a substantial SUSY contribution with $a_\mu^{\text{SUSY}} = 2.65 \times 10^{-10}$.

For our analysis we use the two-loop RGE code **SuSpect** [51] to obtain the weak scale SUSY particle spectrum. In addition we use the MicrOMEGAs code [52] to evaluate low energy constraints like $B_s \rightarrow \mu^+ \mu^-$, $B_s \rightarrow X_s \gamma$, muon $(g-2)$ and relic density. The parameter scan performed in this analysis takes the following ranges of parameters:

$$\begin{aligned} m_0 &\in [100, 2000] \text{ GeV}, \\ M_3^G &\in [800, 2000] \text{ GeV}, \\ \text{sgn}(\mu) &\equiv +, -. \end{aligned}$$

Here we define M_3 as M_3^G at GUT scale and other gaugino masses M_1, M_2 are set by the gaugino mass ratios at that scale. We have performed our analysis for three different choices of tri-linear coupling $A_0 = -1, 0, 1 \text{ TeV}$. We have chosen $\tan \beta = 10$ unless mentioned otherwise.

We see that for large A_0 the $\tilde{\tau}$ mass becomes very large thereby precluding the stau-coannihilation channel and as a result the relic density which depends on the stau coannihilation becomes too large (this holds for light bino DM and applies to model 24 only). Also very large $\tan \beta$ leads to conflict with the $B_s \rightarrow \mu^+ \mu^-$ constraint since the SUSY contribution to this process goes as $O(\tan^6 \beta)$.

In table 2, model 24 which has a gaugino mass ratio of $-1/2 : -3/2 : 1$ having a bino LSP at low scale, is compatible with all the low energy constraints considered in this work. But it is mainly dependent on the stau coannihilation channel for achieving the correct relic density which means that one has to choose m_0 such that $\tilde{\tau}$ mass is quasi degenerate with the LSP mass. The sign of μ is chosen to be negative as that gives the a positive contribution to $(g-2)$.

Model no.	$M_1^G : M_2^G : M_3^G$	m_0 (GeV)	M_3^G (GeV)	A_0 (TeV)	$\tan \beta$	$\text{sgn}(\mu)$
1	$-\frac{19}{5} : 1 : 1$	182	2038	-1	10	+
2	$-3 : 1 : 1$	100	1620	-1	10	+
3	$-\frac{13}{5} : 1 : 1$	300	1320	-1	10	+
4	$-\frac{22}{5} : 1 : 1$	130	2055	-1	10	+
5	$\frac{41}{15} : 1 : 1$	300	1460	-1	10	+
9	$10 : 2 : 1$	116	966	-1	10	+
10	$\frac{9}{5} : 1 : 1$	1000	1190	-1	10	+
11	$-\frac{1}{5} : 3 : 1$	2000	1650	-4	40	+
18	$\frac{2}{5} : 2 : 1$	200	1119	-1	10	+
19	$-5 : 3 : 1$	789	1719	-3.5	10	+
20	$\frac{5}{2} : -\frac{3}{2} : 1$	1900	1740	-1	10	-
22	$-\frac{1}{5} : 1 : 1$	150	1355	-1	10	-
24	$-\frac{1}{2} : -\frac{3}{2} : 1$	506	800	-3.5	20	-

Table 3. Input parameters at GUT scale for the benchmark point chosen for each of the 13 models. We choose the parameters such that in each case we get a maximal contribution from SUSY to muon ($g - 2$).

Also in table 2, model 20 which has the gaugino mass ratio $5/2 : -3/2 : 1$ having a higgsino dominated LSP is compatible with all the low energy constraints but only for $A_0 = -1$ TeV.

We show the mass spectrum for wino models in table 4, bino models in table 5 and higgsino models in table 6 which satisfy all the low energy constraints listed in the beginning of the section. These are models 1 – 5, 9 – 11, 18 – 20, 22 and 24 as given in tables 1 and 2. The input parameters for each of the benchmark scenarios are shown in table 3. The non-universal gaugino models 11 and 19 have been examined in ref. [53]. For models 11, 19 and 24 the parameter space which satisfies all the constraints is restricted in the neighbourhood of the values shown in the benchmark table.

Wino DM. In models 2($-3 : 1 : 1$), 3($-13/5 : 1 : 1$) and 5 ($41/15 : 1 : 1$) the LSP is a wino with mass 1323 GeV, 1073 GeV and 1189 GeV respectively. In all three models the chargino masses are almost degenerate with the wino LSP masses due to which the chargino co-annihilation processes $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow ZW^+, c\bar{s}, u\bar{d}$ and $\tilde{\chi}_1^- \tilde{\chi}_1^+ \rightarrow W^- W^+$ make as much contribution to the relic density in addition as the annihilation channel $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^- W^+$. These models come closest to being probed in the direct detection experiments as discussed in section 3.2. In addition models 1($-19/5 : 1 : 1$) and 4($-22/5 : 1 : 1$) also show a valid parameter space for $M_3 = 2000 - 2400$ GeV, this is because of the well known

Wino Models

Model no.	1	2	3	4	5
$M_1^G : M_2^G : M_3^G$	$-\frac{19}{5} : 1 : 1$	$-3 : 1 : 1$	$-\frac{13}{5} : 1 : 1$	$-\frac{22}{5} : 1 : 1$	$\frac{41}{15} : 1 : 1$
$\tilde{\chi}_1^0$	1673	1323	1073	1688	1189
$\tilde{\chi}_2^0$	2160	1852	1514	2120	1739
$\tilde{\chi}_3^0$	2167	1861	1606	2129	1824
$\tilde{\chi}_4^0$	3490	2174	1609	4071	1842
$\tilde{\chi}_1^+$	1673	1323	1073	1688	1189
$\tilde{\chi}_2^+$	2168	1862	1606	2129	1829
M_1	3538	2202	1544	4129	1776
M_2	1632	1292	1049	1647	1160
M_3	4144	3344	2761	4175	3028
μ	2149	1847	2024	2108	1818
$\tilde{g}$	4262	3431	2835	4305	3105
$\tilde{\tau}_1$	1897	1344	1076	2080	1195
$\tilde{\tau}_2$	2835	1782	1293	3306	1482
$\tilde{e}_R, \tilde{\mu}_R$	2846	1790	1300	3318	1494
$\tilde{e}_L, \tilde{\mu}_L$	1905	1349	1081	2089	1203
$\tilde{t}_1$	3330	2554	2056	3441	2218
$\tilde{t}_2$	3519	2841	2364	3585	2563
$\tilde{b}_1$	3488	2822	2344	3503	2544
$\tilde{b}_2$	3717	2972	2467	3785	2699
$\tilde{u}_R$	4078	3160	2586	4255	2839
$\tilde{u}_L$	3834	3093	2574	3871	2816
M_h (Higgs)	124	123	123	124	124
Ωh^2	0.11	0.11	0.11	0.11	0.113
$a_\mu^{\text{SUSY}} (\times 10^{-10})$	0.3	0.46	0.65	0.28	0.66

Table 4. The SUSY mass spectrum for a chosen benchmark point as suggested in table 3 for each of the wino models which satisfy all the low energy constraints. In addition we also mention the Higgs mass and the relic density in each case. All masses are in GeV.

result that the correct relic density for wino LSP models is achieved at by wino annihilation to W pair by a t-channel chargino exchange with $M_{\text{LSP}} \sim 2 \text{ TeV}$ [54].

Of all the wino models only model 8(77/5 : 1 : 1) does not have any valid parameter space for the region that we scan. Here, for $M_3^G \lesssim 1600 \text{ GeV}$ the relic density is under abundant while for $M_3^G \gtrsim 1600$ there is no EWSB.

We have noted that if we allow the larger parameter space for M_3^G , models 1 and 4 allows some parameter space which is consistent with the constraints that we have imposed in our study. It is interesting to mention that for these models to be compatible with the

correct relic density, M_3^G needs to be more than 2 TeV in both cases, see figure 2. We have not extended M_3^G value beyond 2 TeV for other models as they already qualify to be allowed models for smaller ranges of parameters.

Bino DM. There are three models which have bino LSP as the DM but with very different benchmark spectrum. In model 10 (9/5 : 1 : 1) the DM is a 934 GeV bino LSP. The chargino mass is close to the LSP mass and chargino coannihilation processes, $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow t\bar{t}$; $\tilde{\chi}_1^- \tilde{\chi}_1^+ \rightarrow t\bar{t}, b\bar{b}$ are important for relic density. In addition the Next to Lightest Supersymmetric Particle (NLSP) mass is close at 970 GeV and the NLSP coannihilation processes, $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow b\bar{b}$ and $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow b\bar{b}$ makes a significant contribution to the DM annihilation. As a result, the parameters A_t and A_b significantly affect the parameter space for achieving the correct relic density. This is seen in the top panel of figure 3 with the parameter space for different values of A_0 being split further apart as compared to figures 1 and 2.

In model 19 (−5 : 3 : 1) the LSP is predominantly bino with higgsino mixture ($N_{11} = 0.826, N_{13} = 0.449, N_{14} = 0.338$) of mass 159 GeV. The processes $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+W^-, ZZ$ contribute to the relic density.

In model 24 (−1/2 : −3/2 : 1) the LSP is a bino of mass 178 GeV and the main annihilation channel is the stau coannihilation $\tilde{\chi}_1^0 \tilde{\tau} \rightarrow A\tau$; $\tilde{\tau}\tilde{\tau} \rightarrow \tau\bar{\tau}, AA$; $\tilde{\chi}_1^0 \tilde{\tau} \rightarrow Z\tau$ which are all an order of magnitude larger than the annihilation channel $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tau\bar{\tau}$. The stau coannihilation channels are boosted up by taking the stau mass 184.5 GeV close to the LSP mass. In addition the models 18 and 22 also show a very small parameter space in the stau coannihilation region. These two models in particular require that the $\tilde{\tau}_1$ mass be taken very close to the LSP mass (within 5 GeV) and in that sense are more fine tuned than the rest of the successful models.

The bino models which do not work in our parameter scan are models 14, 15, 16, 17, 18, 21, 22, 23 and 25 with their ratios as given in table 2. For these models either the relic density is over abundant or $\tilde{\tau}_1$ becomes the LSP or the model is unphysical (tachyonic modes). For model 14, when $m_0 \leq 200$ GeV $\tilde{\tau}_1$ is the LSP, and when $m_0 > 200$ GeV the relic density is over abundant with stau coannihilation dominating in the lower m_0 range while for $m_0 > 500$ GeV the dominant contribution to relic density coming from leptonic channel which is suppressed. In model 15 the correct relic density is achieved through stau coannihilation for $m_0 \lesssim 200$ GeV, but the Higgs mass is lighter than the acceptable limit of 122 GeV. Whereas for $m_0 \gtrsim 200$ GeV the Higgs mass is in the acceptable range for most of the parameter space but the relic density becomes overabundant with annihilation to leptons dominating the relic density contribution. In addition for $M_3^G > 1$ TeV $\tilde{\tau}_1$ becomes the LSP. In model 16, for $m_0 < 200$ GeV the parameter space is unphysical, and for $m_0 \geq 200$ the relic density is over abundant with the dominant annihilation channels into $\tau\bar{\tau}$ and $b\bar{b}$. Model 17 is similar to model 15, however in case of model 17 the $\tilde{\tau}_1$ mass is below LEP limit for $m_0 < 200$ GeV. Model 21 is similar to model 18, but is ruled out because of the higgs mass constraint. For model 22, at low m_0 values below 400 GeV the LSP is $\tilde{\tau}_1$. At higher values of m_0 the bino LSP which gives overabundant relic density crosses over to higgsino dominated LSP as M_3 increases. For the region with higgsino dominated LSP the relic density is again overabundant with the main contribution to relic density coming from

Figure 1. The allowed parameter space satisfying all the low energy constraints as listed in the text except muon $(g-2)$ for heavy wino DM models with the GUT scale the gaugino mass ratios as mentioned on top of each panel. The choice of other parameters are $\tan\beta = 10$, $\text{sgn}(\mu) \equiv +ve$ (positive). For model 2 $(-3 : 1 : 1)$ the allowed mass range for m_0 is $\sim 100 - 700$ GeV for $A_0 = 0, 1$ TeV with M_3^G ranging from $\sim 1600 - 2000$ GeV, whereas for $A_0 = -1$ TeV, m_0 ranges between $\sim 100 - 750$ GeV with M_3^G between $\sim 1550 - 2000$ GeV. For model 3 $(-13/5 : 1 : 1)$ the allowed mass range for m_0 is $\sim 300 - 900$ GeV with M_3^G between $\sim 1400 - 2000$ GeV for $A_0 = 0, -1$ TeV, but for $A_0 = 1$ TeV, m_0 ranges between $\sim 400 - 800$ GeV with M_3^G between $\sim 1600 - 2000$ GeV. For model 5 $(41/15 : 1 : 1)$ the allowed mass range for m_0 is $\sim 200 - 900$ GeV with M_3^G between $\sim 1300 - 2000$ GeV for $A_0 = 0, -1$ TeV, but for $A_0 = 1$ TeV, m_0 ranges between $\sim 300 - 800$ GeV with M_3^G between $\sim 1450 - 2000$ GeV.

coannihilation channel. Model 25 behaves similar to model 22, however for low m_0 values below 300 GeV the correct relic density is achieved through stau coannihilation however the higgs mass constraint is not satisfied. While for higher values of m_0 beyond 300 – 400 GeV, the higgs mass constraint does get satisfied but the relic density remains overabundant even in stau-coannihilation region of the parameter space.

Higgsino DM. In model 9 $(10 : 2 : 1)$ the LSP is a higgsino and the relic density is via the chargino coannihilation processes $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow u \bar{d}, c \bar{s}$. The NLSP mass is close to the LSP mass and the NLSP coannihilation $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow u \bar{d}, c \bar{s}$ also contributes to the relic density.

Figure 2. The allowed parameter space for heavy wino models 1 ($-19/5 : 1 : 1$) and 4 ($-22/5 : 1 : 1$) shown in the left and right panels respectively. We extend the scan range for M_3^G upto 3 TeV for these two models. The allowed mass range for M_3^G lies between $\sim 2.0 - 2.4$ TeV while for m_0 it covers the entire range of our scan from 100 – 2000 GeV.

In model 11 ($-1/5 : 3 : 1$) the LSP is a higgsino with mass 1015 GeV and the relic density is via the same chargino coannihilation processes as in model 9 including the NLSP coannihilation contribution.

In model 20 ($5/2 : -3/2 : 1$) the LSP is a higgsino of mass 1507 GeV and the contributions to the relic density are due to the chargino coannihilation $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow t\bar{b}$; $\tilde{\chi}_1^- \tilde{\chi}_1^+ \rightarrow t\bar{t}$, $b\bar{b}$ in addition to the main annihilation channel $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow b\bar{b}$, $t\bar{t}$. The NLSP mass is close to the LSP mass and the NLSP coannihilation $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow t\bar{b}$ also contributes to the relic density. This model gives the correct relic density for $A_0 \sim -1$ TeV.

The failed higgsino models are models 6 ($122/5 : 1 : 1$), 7 ($-101/10 : -3/2 : 1$), 12 ($1 : 35/9 : 1$) and 13 ($1 : -5 : 1$). All of these models fail because the spectrum is unphysical or the higgs sector is unstable. In model 6 for $m_0 \leq 1200$ GeV the spectrum contains tachyonic modes, while for $m_0 \geq 1200$ GeV there is no EWSB and as M_3 increases one again encounters tachyonic modes in the spectrum. In model 7 the relic density is under abundant for $M_3^G < 1.3$ TeV while for higher values of M_3^G there is no EWSB. Model 12 behaves very similar to model 6 and so fails for the same reasons. For model 13, there is no EWSB below a certain value of M_3 for a given m_0 , and this value increases with m_0 . Above this value of M_3 some of the scalar modes are tachyonic.

3.2 Direct detection constraints

The elastic scattering of neutralinos with nucleons which results in spin-independent cross section is by Higgs exchange. The Higgs coupling to the lightest neutralino depends upon the product of the higgsino and the gaugino fraction of the neutralino. Pure bino DM therefore easily evade the direct detection limits from XENON100 [42]. In model 24 ($5/2 : -3/2 : 1$) with a 176 GeV bino DM evades the XENON100 bound but may be probed in Xenon 1000 as shown in figure 7. While model 10 ($9/5 : 1 : 1$) which gives a ~ 1 TeV bino DM also easily evades the XENON100 bound as shown in figure 6. In model

Figure 3. Same as figure 1 but for heavy bino DM models $10(9/5 : 1 : 1)$, $18(2/5 : 2 : 2)$ and $22(-1/5 : 1 : 1)$. As before all low energy constraints except muon $(g - 2)$ are satisfied. For model $10(9/5 : 1 : 1)$ shown in the top panel, the allowed mass range for m_0 is $\sim 1200 - 2000$ GeV with M_3^G between $\sim 1300 - 1900$ GeV for $A_0 = 0$ TeV, while for $A_0 = 1$ TeV, m_0 ranges between $\sim 1500 - 2000$ GeV with M_3^G between $\sim 1500 - 1900$ GeV and finally for $A_0 = -1$ TeV m_0 lies between $\sim 1000 - 2000$ GeV and M_3^G between $\sim 1300 - 2000$ GeV. The models $18(2/5 : 2 : 2)$ and $22(-1/5 : 1 : 1)$ shown in the bottom left and right panels respectively, have a small parameter space and are more fine-tuned than the other models studied here. We show the result for $A_0 = -1$ TeV. For model $18(2/5 : 2 : 2)$ the allowed mass range for m_0 is $\sim 200 - 320$ GeV and M_3^G ranges between $\sim 1100 - 1900$ GeV. For model $22(-1/5 : 1 : 1)$ the allowed mass range for m_0 is $\sim 150 - 200$ GeV while for M_3^G it is $\sim 1300 - 1950$ GeV.

19 $(-5 : 3 : 1)$ where the 159 GeV LSP is predominantly bino with a higgsino mixture ($N_{11} = 0.826, N_{13} = 0.449, N_{14} = 0.338$) has a SI cross section $\sim 1.01 \times 10^{-8}$ pb and is incompatible with the XENON100 exclusion limits.

The Spin Independent (SI) cross section for model 20 $(5/2 : -3/2 : 1)$ which is a 1.5 TeV higgsino DM also evades the XENON100 bound easily as shown in figure 6 as the gaugino fraction is small. Similarly model 11 $(-1/5 : 3 : 1)$ with a 1 TeV wino DM has a SI cross section $\sim 7 \times 10^{-11}$ pb and evades the XENON100 bound.

The three wino dark matter models 2 $(-3 : 1 : 1)$, 3 $(-13/5 : 1 : 1)$ and 5 $(41/15 : 1 : 1)$ with a small mixing of higgsino have larger SI cross sections as shown in figure 5. These wino DM models may be within the reach of XENON1T [40] and Super-CDMS [41] experiments.

Bino Models					
Model no.	10	18	19	22	24
$M_1^G : M_2^G : M_3^G$	$\frac{9}{5} : 1 : 1$	$\frac{2}{5} : 2 : 1$	$-5 : 3 : 1$	$-\frac{1}{5} : 1 : 1$	$-\frac{1}{2} : -\frac{3}{2} : 1$
$\tilde{\chi}_1^0$	934.3	188.6	159.2	131.2	177.6
$\tilde{\chi}_2^0$	970.4	1252	202.6	1103	976.4
$\tilde{\chi}_3^0$	1551	1259	219.6	1696	1523
$\tilde{\chi}_4^0$	1558	1828	4219	1699	1528
$\tilde{\chi}_1^+$	970.1	1252	1999	1103	976.4
$\tilde{\chi}_2^+$	1557	1828	4219	1699	1528
M_1	943.6	190.1	174.4	133.2	177.9
M_2	943.1	1803	4194	1076	981.4
M_3	2497	2344	3494	2824	1771
μ	1545	1251	1943	1691	1521
$\tilde{g}$	2596	2420	3644	2883	1805
$\tilde{\tau}_1$	1253	195.3	740.6	139.1	184.5
$\tilde{\tau}_2$	1301	1419	3310	857.6	861.2
$\tilde{e}_R, \tilde{\mu}_R$	1271	259.4	797.3	184.6	528.0
$\tilde{e}_L, \tilde{\mu}_L$	1303	1424	3316	861	926.6
$\tilde{t}_1$	1847	1391	1559	1959	775.7
$\tilde{t}_2$	2264	2258	4039	2398	1440
$\tilde{b}_1$	2250	2049	3089	2386	1404
$\tilde{b}_2$	2412	2249	4033	2465	1473
$\tilde{u}_R$	2467	2069	3125	2480	1632
$\tilde{u}_L$	2515	2482	4439	2606	1800
M_h (Higgs)	123	123	125	122	124
Ωh^2	0.12	0.11	0.12	0.11	0.12
$a_\mu^{\text{SUSY}} (\times 10^{-10})$	0.79	0.16	0.28	1.0	2.65

Table 5. The SUSY mass spectrum for a chosen benchmark point as suggested in table 3 for each of the bino models which satisfy all the low energy constraints. In addition we also mention the Higgs mass and the relic density in each case. All masses are in GeV.

4 Muon ($g - 2$)

It has long been recognised that to explain the discrepancy between experiment and SM prediction for muon anomalous magnetic moment from a SUSY contribution would require a light mass spectrum on the gauginos and the sleptons [55, 56] which would put a severe restriction on the SUSY models.

The SUSY contribution to muon ($g - 2$) for light binos is through the bino-smuon loop [57, 58] so the largest $a_\mu^{\text{SUSY}} = 2.65 \times 10^{-10}$ [37–39, 50] comes from model 24 which has the lightest LSP (177 GeV bino) and slepton spectrum. In model 24 ($M_1^G : M_2^G :$

Figure 4. The allowed parameter space satisfying the low energy constraints except muon ($g - 2$) for heavy higgsino DM models 9(10 : 2 : 1) and model 20(5/2 : -3/2 : 1). All parameters are chosen as in figure 1 except $A_0 = -1$ TeV. For model 9(10 : 2 : 1) the allowed mass range for m_0 spans the entire range of scan from 100 – 2000 GeV with M_3^G between $\sim 950 - 1550$ GeV. For model 20(5/2 : -3/2 : 1) the allowed mass range for m_0 is $\sim 1850 - 2000$ GeV with M_3^G between $\sim 1400 - 2000$ GeV. These models do not work for $A_0 = 0, 1$ TeV.

$M_3^G = -1/2 : -3/2 : 1$) it would have been easy to adjust the smuon mass (through m_0^G) and the bino mass through M_3^G (as M_1^G is related to M_3^G) to get a much larger contribution to muon ($g - 2$). However the relic density of bino DM in model 24 depends on the stau coannihilation which has to be close to the bino DM mass of 177 GeV which is again determined by the universal scalar mass m_0 . So demanding the correct relic density results in a less than optimum contribution to the muon ($g - 2$) in this model. In table 2 one can note that the gaugino mass ratio referred to here as model 24, can arise from three possible breaking patterns of SO(10), each of them through a different intermediate symmetry group. It will be interesting to see if we distinguish intermediate scale separately than the unification scale then muon ($g - 2$) is further improved or not. We have kept this issue for our further publication. The gaugino mass ratio of model 24 has been studied in ref. [59] in the context of Yukawa unification in SO(10), but in the benchmark models examined in [59] the SUSY contribution to muon $g - 2$ is an order of magnitude smaller than the benchmark parameters for model 24 shown in table 5.

In this paper we have chosen a single non-singlet scalar for giving masses to the gauginos. By choosing a the gaugino masses to arise from more than one scalar representation like 1+24, 1+75 and 1+200 of SU(5) [14, 16, 60] it is possible to explain muon ($g - 2$) from SUSY contributions along with the Planck-WMAP relic density [61]. It has been noted [62] that in a mSUGRA model the gaugino mass ratio $M_1 : M_2 : M_3 = 1 : 1 : 10$ at the GUT scale gives the required muon ($g - 2$), but in this paper we see that this gaugino ratio does not arise from any of the GUT breaking patterns if one considers one non-singlet Higgs representation for generating the gaugino masses.

If one were to have non-universal scalar masses [27, 28] it may be possible to adjust the stau mass to control the relic relic density and the smuon mass to fit muon ($g - 2$) using a single scalar representation for getting non-universal gaugino masses.

Higgsino Models

Model no.	9	11	20
$M_1^G : M_2^G : M_3^G$	10 : 2 : 1	$-\frac{1}{5} : 3 : 1$	$\frac{5}{2} : -\frac{3}{2} : 1$
$\tilde{\chi}_1^0$	1006	1015	1507
$\tilde{\chi}_2^0$	1013	1016	1510
$\tilde{\chi}_3^0$	1584	3791	1958
$\tilde{\chi}_4^0$	4258	4093	2230
$\tilde{\chi}_1^+$	1007	1015	1507
$\tilde{\chi}_2^+$	1584	4093	2230
M_1	4294	3797	1969
M_2	1549	4051	2175
M_3	2023	3361	3570
μ	1002	1000	1495
$\tilde{g}$	2164	3585	3772
$\tilde{\tau}_1$	2138	3181	2455
$\tilde{\tau}_2$	3537	3779	2619
$\tilde{e}_R, \tilde{\mu}_R$	3554	3620	2473
$\tilde{e}_L, \tilde{\mu}_L$	2152	3181	2628
$\tilde{t}_1$	1767	2309	2910
$\tilde{t}_2$	2254	3716	3625
$\tilde{b}_1$	1782	2812	3617
$\tilde{b}_2$	2125	3726	3656
$\tilde{u}_R$	2945	4051	3785
$\tilde{u}_L$	2226	4662	3988
M_h (Higgs)	124	127	122
Ωh^2	0.11	0.12	0.11
$a_\mu^{\text{SUSY}} (\times 10^{-10})$	0.44	0.47	0.24

Table 6. The SUSY mass spectrum for a chosen benchmark point as suggested in table 3 for each of the higgsino models which satisfy all the low energy constraints. In addition we also mention the Higgs mass and the relic density in each case. All masses are in GeV.

5 Conclusions

In this paper we have exhaustively analysed all possible non-universal gaugino mass models that arise from SU(5), SO(10), E(6) SUSY GUT models. The underlying assumption is that the full gauge symmetry is broken to the SM symmetry group at the GUT scale itself, i.e., the intermediate scales are same as the GUT scale. We have considered all these models in its minimal versions, i.e., we have not probed the effect of the presence of multiple non-singlet scalars. If one considers that the contribution to the effective gaugino mass ratios are outcome of the contributions from more than one scalar field with the

Figure 5. The direct detection spin independent proton-DM scattering cross section plotted with the constraint from XENON100 [42]. These plots show selected points for the heavy wino models satisfying all the low energy constraints considered here, except for muon ($g-2$). These heavy wino models satisfy the XENON100 constraint.

introduction of one or more free parameters, the the unique group theoretic characteristics of the models are lost. Thus we restrict ourselves to the minimal versions (from the point of number of free parameters) of the non-universal gaugino models. We have shown different models predict different kind of LSP compositions. Thus the contributions to the relic density from such models are discriminated. We have performed a comparative study among such models using the collider constraints, lightest Higgs mass and the relic density. We also emphasise the importance of muon ($g-2$) and briefly argue why model

Figure 6. The direct detection spin independent proton-DM scattering cross section plotted with the constraint from XENON100 [42]. These plots show selected points for bino models satisfying all the low energy constraints considered here, except for muon ($g - 2$). These bino models satisfy the XENON100 constraint.

Figure 7. The direct detection spin independent proton-DM scattering cross section plotted with the constraint from XENON100 [42]. These plots show selected points for the heavy higgsino models satisfying all the low energy constraints considered here, except for muon ($g - 2$). These heavy higgsino models satisfies the XENON100 constraint.

24 ($M_1^G : M_2^G : M_3^G = -1/2 : -3/2 : 1$) is the best candidate among other models in the context of muon ($g - 2$) contribution. We also check the status of bino-, wino-, and higgsino- dominated models in the context of Direct detection constraints. The model 19 ($-5 : 3 : 1$) is ruled out by XENON100 [42]. The three models 2($-3 : 1 : 1$), 3($-13/5 : 1 : 1$)

and $5(41/5 : 1 : 1)$ where the dark matter is a TeV scale wino can be probed in upcoming direct detection experiments like XENON1T [40] and Super-CDMS [41].

Finally we would like to comment on the impact of the insertions of the intermediate scales. In supersymmetric grand unified theories in case of one step breaking the usual trend of the intermediate scale is to lie around the unification scale, see [46]. Thus we expect that the ratios at the GUT scale will not change visibly by the new set of RGEs from intermediate scale to the unification scale. But in case of two step symmetry breaking the second intermediate scale can as low as 100 TeV [46] within a proper unification framework. If the second intermediate scale is low enough then a new set of RGEs will change the gaugino mass ratios at the GUT scale widely. We are looking into this issue in detail and postpone and will present the results in a future publication.

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