Abstract: We perform a comprehensive study of SU(5), SO(10) and E(6) super-symmetric 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 ($g - 2$).
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 $\mu$ ($\text{sgn}(\mu)$) 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-PLANCK 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 $M_1, M_2, M_3$ are the gaugino masses corresponding to the $U(1)_Y, SU(2)_L, SU(3)_C$ gauge groups respectively. We scan the parameters $M^G_3, m^G_0, A_0, \tan \beta$ 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], and the dark matter relic density within 3-sigma of the WMAP-PLANCK [32, 33] measured band $0.112 < \Omega h^2 < 0.128$. In addition we have other constraints: within the allowed parameter space the contribution to the $B_s \rightarrow X_s \gamma$ [34], $B_s \rightarrow \mu^+ \mu^-$ [35] and the muon $(g - 2)$ [36] must satisfy the experimental bounds. We have also set the lower limit on the gluino mass ($m_\tilde{g}$) to be 1.4 TeV\textsuperscript{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 $(g - 2)$ [36]. 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 [37] and Super-CDMS [38] experiments and one model is ruled out by XENON100 [39].

\footnote{We define the GUT scale input of these parameters as $M^G_i$.}

\footnote{Though 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.}
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 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 framework 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 \(\mu\) (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 \(\eta\) is dimensionless parameter, \(M = M_{Pl}/\sqrt{8\pi}\) (reduced Planck mass). As \(F_{\mu\nu}\) transforms as adjoint of the unbroken GUT groups, \(\Phi\) 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:

\[
\begin{align*}
SU(5) & \Rightarrow (24 \otimes 24)_{sym} = 1 \oplus 24 \oplus 75 \oplus 200, \\
SO(10) & \Rightarrow (45 \otimes 45)_{sym} = 1 \oplus 54 \oplus 210 \oplus 770, \\
E(6) & \Rightarrow (78 \otimes 78)_{sym} = 1 \oplus 650 \oplus 2430, 
\end{align*}
\]

(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 [40–43]. 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: \(SU(5) \rightarrow SU(3) \otimes SU(2) \otimes U(1)\) 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 $SO(10)$: $SU(5) \otimes U(1), SU(4) \otimes SU(2) \otimes SU(2)$, and for $E(6)$ we have considered $SO(10)' \otimes U(1), SU(3) \otimes SU(3) \otimes SU(3), SU(6) \otimes SU(2)$. 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 $SU(5) \otimes U(1)$ is a maximal subgroup of $SO(10)$. In normal $SU(5)$ model the extra $U(1)$ does not contribute in $U(1)$ of SM, but in flipped $SU(5)$ model the hypercharge generator of SM is a linear combination 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.

| Model Number | $M_1 : M_2 : M_3$ (at $M_X$) | $M_1 : M_2 : M_3$ (at $M_{EW}$) | Model |
|--------------|-----------------------------|--------------------------------|-------|
| 1            | $-19/5 : 1 : 1$             | $-19/5 : 2 : 6$                | $SO(10) \xrightarrow{1.0/210} (SU(5) \otimes U(1))_{flipped}$ |
| 2            | $-3 : 1 : 1$                | $-3 : 2 : 6$                   | $E(6) \xrightarrow{1.1/2430,650} (SU(6) \otimes SU(2)_X)$ |
| 3            | $-13/5 : 1 : 1$             | $-13/5 : 2 : 6$                | $E(6) \xrightarrow{1.1/650} (SU(6) \otimes SU(2)_R)$ |
| 4            | $-22/5 : 1 : 1$             | $-22/5 : 2 : 6$                | $E(6) \xrightarrow{1.0/650} (SU(10) \otimes U(1))_{flipped}$ |
| 5            | $41/15 : 1 : 1$             | $41/15 : 2 : 6$                | $E(6) \xrightarrow{1.1/2440} (SU(6) \otimes SU(2)_R)$ |
| 6            | $122/5 : 1 : 1$             | $122/5 : 2 : 6$                | $E(6) \xrightarrow{1.0/2440} (SU(10) \otimes U(1))_{flipped}$ |
| 7            | $-101/10 : -3/2 : 1$        | $-101/10 : -3 : 6$             | $SO(10) \xrightarrow{24.0/770} (SU(5) \otimes U(1))_{flipped}$ |
| 8            | $77/5 : 1 : 1$              | $77/5 : 2 : 6$                 | $SO(10) \xrightarrow{1.0/770} (SU(5) \otimes U(1))_{flipped}$ |
| 9            | $10 : 2 : 1$                | $10 : 4 : 6$                   | $SO(10) \xrightarrow{20.0/770} SU(5)$ |

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

1. Higgs mass bound from LHC [31]

\[ 122 \, \text{GeV} < M_h < 127 \, \text{GeV} \]

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

| Model Number | \( M_1 : M_2 : M_3 \) (at \( M_Y \)) | \( M_1 : M_2 : M_3 \) (at \( M_{EW} \)) | Model |
|--------------|-------------------------------------|-------------------------------------|-------|
| 10           | \( 2 : 1 : 1 \)                    | \( 2 : 2 : 6 \)                    | \( E(6) \rightarrow (SO(6) \otimes SU(2)_R) \) |
| 11           | -5 : 3 : 1                         | -5 : 6 : 6                         | \( SO(10) \rightarrow SU(5) \) |
| 12           | 1 : 35/9 : 1                       | 1 : 70/9 : 6                       | \( E(6) \rightarrow (SU(6) \otimes SU(2)_L) \) |
| 13           | -1 : -5 : 1                        | 1 : -10 : 6                        | \( E(6) \rightarrow (SU(6) \otimes SU(2)_L) \) |
| 14           | -3/5 : 1 : 1                       | -3/5 : 2 : 6                       | \( E(6) \rightarrow (SO(6) \otimes SU(2)_R) \) |
| 15           | -1/5 : -1 : 1                      | -1/5 : -2 : 6                      | \( E(6) \rightarrow (SU(6) \otimes SU(2)_R) \) |
| 16           | 1/10 : 5/2 : 1                     | 1/10 : 5 : 6                       | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 17           | 1/10 : -3/2 : 1                    | 1/10 : -3 : 6                      | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 18           | 2/5 : 2 : 1                        | 2/5 : 4 : 6                        | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 19           | -1/5 : 3 : 1                       | -1/5 : 6 : 6                       | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 20           | 5/2 : -3/2 : 1                     | 5/2 : -3 : 6                       | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 21           | -1/5 : -3/2 : 1                    | -1/5 : -3 : 6                      | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 22           | -1/5 : 1 : 1                       | -1/5 : 2 : 6                       | \( E(6) \rightarrow (SO(10) \otimes U(1))_{\text{flipped}} \) |
| 23           | 19/10 : 5/2 : 1                    | 19/10 : 5 : 6                      | \( SO(10) \rightarrow (SU(4) \otimes SU(2)_R) \) |
| 24           | -1/2 : -3/2 : 1                    | -1/2 : -3 : 6                      | \( SO(10) \rightarrow (SU(5) \otimes U(1))_{\text{flipped}} \) |
| 25           | 7/10 : -3/2 : 1                    | 7/10 : -3 : 6                      | \( SO(10) \rightarrow (SU(5) \otimes U(1))_{\text{flipped}} \) |
2. Relic density constraint from WMAP-PLANCK data at $3\sigma$ [32, 33]

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

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

4. Branching fraction for $B_s \rightarrow X_s \gamma$ at $2\sigma$ [34]

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

5. Branching fraction for $B_s \rightarrow \mu^+ \mu^-$ at $2\sigma$ [44]

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

6. Ratio of branching fraction for $B_u \rightarrow \tau \nu_\tau$ in MSSM to that in SM at $3\sigma$ [45]

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

7. There is a discrepancy in anomalous muon magnetic moment, $a_\mu \equiv (g - 2)/2$, between experimental value [36] and SM prediction [46],

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

We compute the SUSY contribution to $a_\mu$ 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 $a_\mu^{SUSY} = 2.65 \times 10^{-10}$.

For our analysis we use the two-loop RGE code SUSpect [47] to obtain the weak scale SUSY particle spectrum. In addition we use the MicrOMEGAs code [48] 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:

$$m_0 \in [100, 2000] \text{ GeV},$$

$$M_3 \in [800, 2000] \text{ GeV},$$

$$\text{sgn}(\mu) \equiv +, -.$$ 

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 $A_0 = -1, 0, 1$ 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
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 ($g - 2$).

| Model no. | $M_1^G : M_2^G : M_3^G$ | $m_0$ (GeV) | $M_3^G$ (GeV) | $A_0$ (TeV) | $\tan \beta$ | sgn($\mu$) |
|-----------|----------------------|-------------|---------------|-------------|--------------|------------|
| 1         | $-\frac{1}{3} : 1 : 1$ | 182         | 2038          | $-1$        | 10           | $+$        |
| 2         | $-3 : 1 : 1$          | 100         | 1620          | $-1$        | 10           | $+$        |
| 3         | $-\frac{1}{3} : 1 : 1$ | 300         | 1320          | $-1$        | 10           | $+$        |
| 4         | $-\frac{2}{5} : 1 : 1$ | 130         | 2055          | $-1$        | 10           | $+$        |
| 5         | $\frac{11}{15} : 1 : 1$ | 300         | 1460          | $-1$        | 10           | $+$        |
| 6         | $10 : 2 : 1$          | 116         | 966           | $-1$        | 10           | $+$        |
| 7         | $\frac{3}{5} : 1 : 1$ | 1000        | 1190          | $-1$        | 10           | $+$        |
| 8         | $-\frac{1}{3} : 3 : 1$ | 2000        | 1650          | $-4$        | 40           | $+$        |
| 9         | $\frac{2}{5} : 2 : 1$ | 200         | 1119          | $-1$        | 10           | $+$        |
| 10        | $-5 : 3 : 1$          | 789         | 1719          | $-3.5$      | 10           | $+$        |
| 11        | $\frac{1}{3} : -\frac{3}{2} : 1$ | 1900     | 1740          | $-1$        | 10           | $-$        |
| 12        | $\frac{5}{2} : -\frac{1}{2} : 1$ | 150       | 1355          | $-1$        | 10           | $-$        |
| 13        | $-\frac{1}{2} : -\frac{3}{2} : 1$ | 506      | 800           | $-3.5$      | 20           | $-$        |

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 $\mu$ is chosen to be negative as that gives the a positive contribution to $(g - 2)$.

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[49]. 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.
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 $\sim 100–700$ 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 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.

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 LSP masses are almost degenerate with the wino LSP masses due to which the wino co-annihilation processes $\chi^0_1\chi^\mp_1 \rightarrow ZW^\pm, c\bar{s}, u\bar{d}$ and $\chi^-_1\chi^+_1 \rightarrow W^-W^+$ make as much contribution to the relic density in addition as the annihilation channel $\chi^0_1\chi^0_1 \rightarrow W^-W^+$. 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 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
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.

\[ M_{\text{LSP}} \sim 2 \text{ TeV} \, [50]. \]

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 Fig. 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, \(\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow \tilde{t}\tilde{b}; \tilde{\chi}_1^- \tilde{\chi}_1^+ \rightarrow \tilde{t}\tilde{t}, \tilde{b}\tilde{b}\) 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, \(\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{b}\tilde{b}\) and \(\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \tilde{b}\tilde{b}\) 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 Fig. 3 with the parameter space for different values of \(A_0\) being split further apart as compared to Figs. 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 \(\tilde{\chi}_1^0 \tilde{\tau}_1 \rightarrow A\tau; \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tau\bar{\tau}, AA; \tilde{\chi}_1^0 \tilde{\tau}_1 \rightarrow Z\tau\) 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...
Figure 3: Same as Fig. 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 m₀ is ∼ 1200 − 2000 GeV with M₁³ between ∼ 1300 − 1900 GeV for A₀ = 0 TeV, while for A₀ = 1 TeV, m₀ ranges between ∼ 1500 − 2000 GeV with M₁³ between ∼ 1500 − 1900 GeV and finally for A₀ = −1 TeV m₀ lies between ∼ 1000 − 2000 GeV and M₁³ between ∼ 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 A₀ = −1 TeV. For model 18(2/5 : 2 : 2) the allowed mass range for m₀ is ∼ 200 − 320 GeV and M₁³ ranges between ∼ 1100 − 1900 GeV. For model 22(−1/5 : 1 : 1) the allowed mass range for m₀ is ∼ 150 − 200 GeV while for M₁³ it is ∼ 1300 − 1950 GeV.

either the relic density is over abundant or ˜τ₁ becomes the LSP or the model is unphysical (tachyonic modes). For model 14, when m₀ ≤ 200 GeV ˜τ₁ is the LSP, and when m₀ > 200 GeV the relic density is over abundant with stau coannihilation dominating in the lower m₀ range while for m₀ > 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 m₀ ≲ 200 GeV, but the Higgs mass is lighter than the acceptable limit of 122 GeV. Whereas for m₀ ≳ 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 M₁³ > 1 TeV ˜τ₁ becomes the LSP. In model 16, for m₀ < 200 GeV the parameter space is unphysical, and for m₀ ≥ 200 the relic density is over abundant with the dominant annihilation channels into τ̄τ and bb. Model 17 is similar to model 15, however in case of model 17 the ˜τ₁ mass is below LEP limit for m₀ < 200 GeV. Model 21 is similar to model 18, but is ruled
**Bino Models**

| Model no. | 10 | 18 | 19 | 22 | 24 |
|-----------|----|----|----|----|----|
| $M_1^G : M_2^G : M_3^G$ | $\frac{9}{5} : 1 : 1$ | $\frac{2}{5} : 2 : 1$ | $-\frac{5}{3} : 1$ | $-\frac{1}{5} : 1 : 1$ | $-\frac{1}{2} : -\frac{3}{2} : 1$ |
| $\tilde{\chi}_1^0$ | 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 |
| $\mu$ | 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 |
| $\tilde{e}_{R, \tilde{R}}$ | 1271 | 259.4 | 797.3 | 184.6 | 528.0 |
| $\tilde{e}_{L, \tilde{L}}$ | 1303 | 1424 | 3316 | 861 | 926.6 |
| $\tilde{\mu}$ | 1847 | 1391 | 1559 | 1959 | 775.7 |
| $\tilde{t}_1$ | 2264 | 2258 | 4039 | 2398 | 1440 |
| $\tilde{t}_2$ | 2250 | 2049 | 3089 | 2386 | 1404 |
| $\tilde{b}_1$ | 2412 | 2249 | 4033 | 2465 | 1473 |
| $\tilde{b}_2$ | 2467 | 2069 | 3125 | 2480 | 1632 |
| $\tilde{u}_R$ | 2515 | 2482 | 4439 | 2606 | 1800 |
| $\tilde{u}_L$ | 123 | 123 | 125 | 122 | 124 |
| $M_H$ (Higgs) | 123 | 123 | 125 | 122 | 124 |
| $\Omega h^2$ | 0.12 | 0.11 | 0.12 | 0.11 | 0.12 |
| $\sigma_{\tilde{\mu}}^\text{SUSY}$ ($\times 10^{-10}$) | 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.

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 higgsinos dominated LSP the relic density is again overabundant with the main contribution to relic density coming from 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
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 Fig. 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 $M_G^3$ between ∼ 950 − 1550 GeV. For model 20(5/2 : −3/2 : 1) the allowed mass range for $m_0$ is ∼ 1850 − 2000 GeV with $M_G^3$ between ∼ 1400 − 2000 GeV. These models do not work for $A_0 = 0, 1$ TeV.

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 $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow ud, cs$. The NLSP mass is close to the LSP mass and the NLSP coannihilation $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow ud, cs$ also contributes to the relic density.

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 $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow t\bar{t}$; $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow b\bar{b}$ 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 $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow t\bar{t}$ 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.
Higgsino Models

| Model no. | 9     | 11    | 20  |
|-----------|-------|-------|-----|
| $M_1^G : M_2^G : M_3^G$ | $10 : 2 : 1$ | $-\frac{1}{5} : 3 : 1$ | $\frac{5}{7} : -\frac{3}{7} : 1$ |
| $\tilde{\chi}_1^0$ | 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 |
| $\mu$ | 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  |
| $\Omega h^2$ | 0.11  | 0.12  | 0.11 |
| $a_{\mu}^{SUSY} \times 10^{-10}$ | 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.

### 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 [39]. 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 Fig 7. While model 10 ($9/5 : 1 : 1$) which gives a $\sim 1$ TeV bino DM also easily evades the XENON100 bound as shown in Fig 6. In model 19 ($-5 : 3 : 1$) where the 159 GeV LSP is predominantly bino with
Figure 5: The direct detection spin independent proton-DM scattering cross section plotted with the constraint from XENON100 [39]. 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.

A higgsino mixture ($N_{11} = 0.826, N_{13} = 0.449, N_{14} = 0.338$) has a SI cross section $\sim 1.01 \times 10^{-8}\text{pb}$ 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 Fig 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 $\sim 7 \times 10^{-11}\text{pb}$ 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.
Figure 6: The direct detection spin independent proton-DM scattering cross section plotted with the constraint from XENON100 [39]. 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.

in Fig 5. These wino DM models may be within the reach of XENON1T [37] and Super-CDMS [38] experiments.

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 [51, 52] 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 [53, 54] so the largest \(\sigma_{\mu}^{SUSY} = 2.65 \times 10^{-10} [36, 46]\) comes from model 24 which has the lightest LSP (177 GeV bino) and slepton spectrum. In model 24 \((M_1^G : M_2^G : M_3^G = -1/2 : -3/2 : 1)\) it would have been easy to adjust the smuon mass (through \(m_{\tilde{G}_3}\)) 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. [55] in the context of Yukawa unification in \( SO(10) \), but in the benchmark models examined in [55] 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, 56] it is possible to explain muon \( (g - 2) \) from SUSY contributions along with the Planck-WMAP relic density [57]. It has been noted [58] 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 density and the smuon mass to fit muon \( (g - 2) \) using a single scalar representation for getting non-universal gaugino masses.

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 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 24 ($M_{G1} : M_{G2} : M_{G3} = -1/2 : -3/2 : 1$) 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 [39]. 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 [37] and Super-CDMS [38].

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 [43]. 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 [43] within a proper unification frame work. 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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