Split sfermion families, Yukawa unification and muon $g - 2$

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Abstract: We consider two distinct classes of Yukawa unified supersymmetric SO(10) models with non-universal and universal soft supersymmetry breaking (SSB) gaugino masses at $M_{\rm GUT}$. In both cases, we assume that the third family SSB sfermion masses at $M_{\rm GUT}$ are different from the corresponding sfermion masses of the first two families (which are equal). For the SO(10) model with essentially arbitrary (non-universal) gaugino masses at $M_{\rm GUT}$, it is shown that t-b-τ Yukawa coupling unification is compatible, among other things, with the 125 GeV Higgs boson mass, the WMAP relic dark matter density, and with the resolution of the apparent muon $g-2$ anomaly. The colored sparticles in this case all turn out to be quite heavy, of order 5 TeV or more, but the sleptons (smuon and stau) can be very light, of order 200 GeV or so. For the SO(10) model with universal gaugino masses and NUHM2 boundary conditions, the muon $g-2$ anomaly cannot be resolved. However, the gluino in this class of models is not too heavy, $\lesssim 3$ TeV, and therefore may be found at the LHC.

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Contents

1 Introduction

Even though supersymmetric particles have not yet been observed, low scale supersymmetry (SUSY) remains at the forefront of beyond the Standard Model (SM) physics scenarios. In addition to resolving the gauge hierarchy problem and accommodating radiative electroweak symmetry breaking (REWSB), SUSY also provides a compelling dark matter candidate (the lightest supersymmetric particle (LSP)). Contrary to the non-supersymmetric case, the three gauge couplings naturally unify [1–5] around 10^{16} GeV (M_{GUT}), which therefore provides an additional reason to suspect that SUSY may be found soon, hopefully at LHC 14.

It is well known that gauge coupling unification does not significantly constrain the sparticle spectrum. On the other hand, imposing t-b-τ Yukawa coupling unification condition at M_{GUT} [6–8] can place significant constraints on the supersymmetric spectrum in order to fit the top, bottom and tau masses. These constraints are quite severe [9–19], especially after the discovery of a SM like Higgs boson with mass, $m_h \simeq 125 - 126$ GeV [20, 21].

The constraints from t-b-τ Yukawa coupling unification depend on the particular boundary conditions at M_{GUT} for the soft supersymmetry breaking (SSB) parameters [22]. To be more precise, t-b-τ Yukawa unification is successfully realized if the threshold corrections to the bottom quark mass are suitably large and have the correct sign. The dominant contributions arise from loop corrections involving the gluino ($m_{\tilde{g}}$), the third generation sfermions and the SSB trilinear interactions [22]. On the other hand, a 125 GeV light CP-even Higgs boson mass also requires large radiative corrections, and the dominant contributions in this case also arise from third generation sfermions and trilinear SSB scalar interaction [23–28]. Thus, t-b-τ Yukawa unification and the 125 GeV light CP even Higgs boson together strongly constrain the gluino and third generation sfermion masses as well as the trilinear SSB couplings. (For a recent discussion regarding the top quark mass and related issues in low scale supersymmetric models, see ref. [29])

We consider two choices for the minimal set of SSB parameters at $M_{\rm GUT}$ which can lead to t-b-τ Yukawa unification. The first case has universal SSB gaugino mass terms but non-universal Higgs SSB terms, $m_{H_u}^2 \neq m_{H_d}^2$ [30, 31]. Here m_{H_u,H_d} denote the up/down type Higgs SSB masses. In this case t-b-τ Yukawa unification can be realized if the gluino mass ($M_{\tilde{g}}$) is much smaller than the sbottom quark mass ($m_{\tilde{b}}$), and the stop trilinear SSB term (A_t) is larger than the stop mass ($m_{\tilde{t}}$). To realize a 125 GeV light CP even Higgs boson in this scenario we require $M_{\tilde{g}} \leq 3\,{\rm TeV}$ and $m_{\tilde{b}} \geq 10\,{\rm TeV}$. This also yields bounds on the fundamental SSB parameters, namely, $m_0 \gtrsim 10\,{\rm TeV}$ and $M_{1/2} \lesssim 1\,{\rm TeV}$ [9–11]. Here m_0 and $M_{1/2}$ are GUT scale universal SSB mass terms for the sfermions and gauginos, respectively.

The second class of SO(10) models have universal SSB Higgs mass^2 term ($m_{H_u}^2 = m_{H_d}^2$), whereas the gaugino SSB masses are non-universal at $M_{\rm GUT}$ [32–35]. In this scenario the desired supersymmetric threshold corrections to t-b-τ Yukawa couplings can be realized with $M_{\tilde{g}} \gtrsim m_{\tilde{b}}$ [12–17]. For a particular choice of SSB gaugino masses ($M_1 : M_2 : M_3 = 1 : 3 : -2$) at $M_{\rm GUT}$, which can be derived in the framework of SO(10) GUT, it was shown [18, 19] that the CP-even SM-like Higgs boson mass $m_h \approx 125\,{\rm GeV}$ can be predicted from t-b-τ YU. This result does not change much in terms of the Higgs mass prediction if we relax t-b-τ YU up to 10% [18, 19]. For this case, 10% or better t-b-τ Yukawa unification consistent with all constraints (including the Higgs boson mass) requires $m_0 \gtrsim 1\,{\rm TeV}$ and $m_{1/2} \gtrsim 1\,{\rm TeV}$ [18, 19]. The colored sparticle spectrum does not change much [12–17] if we consider different mass relations among the gauginos at $M_{\rm GUT}$, but the sleptons can be light. Again it leads to heavy first and second generation squarks which are beyond the reach of LHC 14 [36].

In both the above mentioned scenarios the sfermions were all assumed to have universal masses at $M_{\rm GUT}$. The main motivation for this assumption is based on the constraints obtained from flavor-changing neutral current (FCNC) processes [37]. It was shown in ref. [38] that constraints from FCNC processes, for the case when third generation sfermion masses are split from masses of the first and second generations, are very mild and easily satisfied. It therefore allows for significantly lighter first two family sfermions, while keeping the third generation sfermions relatively heavy. We adopt this approach in this paper and we will show that it is possible to have t-b-τ YU with LHC accessible first and second generation sfermions.

Another motivation for considering split sfermion families is related to the deviation of the observed muon anomalous magnetic moment $a_\mu = (g-2)_\mu/2$ (muon $g-2$) from its SM prediction [39, 40]

$$\Delta a_\mu \equiv a_\mu(\exp) - a_\mu({\rm SM}) = (28.6 \pm 8.0) \times 10^{-10}. \tag{1.1}$$

If supersymmetry is to provide a resolution of this discrepancy, the smuon and gaugino (bino or wino) SSB masses should not be much heavier than a few hundred GeV. On the other hand, as we mentioned above, t-b-τ YU requires [9–19] the sleptons to be around a TeV or above, if universality among sfermion masses is assumed at $M_{\rm GUT}$. Our analysis in the following sections show that the non-universal gaugino case with split family sfermions can resolve the $g-2$ discrepancy and also realize t-b-τ Yukawa unification, while staying consistent with all current experimental data.

We note that recently there have been several attempts to resolve the discrepancy within the MSSM framework assuming non-universal SSB mass terms at $M_{\rm GUT}$ for gauginos [41–43] or sfermions [38, 44].

The outline for the rest of the paper is as follows. In section 2 we summarize the scanning procedure and the experimental constraints applied in our analysis. In sections 3 and 4 we present the results for supersymmetric SO(10) models with non-universal and universal gaugino masses, respectively. Tables with benchmark points for both cases are also presented, and section 5 contains our conclusions.

2 Phenomenological constraints and scanning procedure

We employ the ISAJET 7.84 package [48] to perform random scans over the parameter space. In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to $M_{\rm GUT}$ via the MSSM renormalization group equations (RGEs) in the $\overline{DR}$ regularization scheme. We do not strictly enforce the unification condition $g_3 = g_1 = g_2$ at $M_{\rm GUT}$, since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [49–51]. With the boundary conditions given at $M_{\rm GUT}$, all the SSB parameters, along with the gauge and third family Yukawa couplings, are evolved back to the weak scale $M_{\rm Z}$.

In evaluating the Yukawa couplings the SUSY threshold corrections [52] are taken into account at a common scale $M_S = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. The entire parameter set is iteratively run between $M_{\rm Z}$ and $M_{\rm GUT}$ using the full 2-loop RGEs until a stable solution is obtained. To better account for the leading-log corrections, one-loop step-beta functions are adopted for the gauge and Yukawa couplings, and the SSB scalar mass parameters m_i are extracted from RGEs at appropriate scales $m_i = m_i(m_i)$. The RGE-improved 1-loop effective potential is minimized at an optimized scale M_S, which effectively accounts for the leading 2-loop corrections. Full 1-loop radiative corrections are incorporated for all sparticle masses.

We implement the following random scanning procedure: a uniform and logarithmic distribution of random points is first generated in the given parameter space. The function RNORMX [72, 73] is then employed to generate a Gaussian distribution around each point in the parameter space. The data points collected all satisfy the requirement of radiative electroweak symmetry breaking (REWSB) [58–62], with the neutralino in each case being the LSP. After collecting the data, we impose the mass bounds on all the particles [53] and use the IsaTools package [65, 66] to implement the various phenomenological constraints. We successively apply the following experimental constraints on the data that we acquire from ISAJET 7.84:

$$123 \text{ GeV} \le m_h \le 127 \text{ GeV} \quad [20, 21]$$
$$0.8 \times 10^{-9} \le BR(B_s \to \mu^+ \mu^-) \quad \le 6.2 \times 10^{-9} \ (2\sigma) \quad [54]$$
$$2.99 \times 10^{-4} \le BR(b \to s\gamma) \quad \le 3.87 \times 10^{-4} \ (2\sigma) \quad [55]$$
$$0.15 \le \frac{BR(B_u \to \tau\nu_\tau)_{\rm MSSM}}{BR(B_u \to \tau\nu_\tau)_{\rm SM}} \quad \le 2.41 \ (3\sigma). \quad [55]$$

We also implement the following mass bounds on the sparticle masses:

$$m_{\tilde{g}} \gtrsim 1.4 \text{ TeV (for } m_{\tilde{g}} \sim m_{\tilde{q}}) \quad [63, 64]$$
$$m_{\tilde{g}} \gtrsim 1 \text{ TeV (for } m_{\tilde{g}} \ll m_{\tilde{q}}) \quad [63, 64]$$
$$M_A \gtrsim 700 \text{ GeV (for } \tan\beta \simeq 48). \quad [57]$$

Here $m_{\tilde{g}}$, $m_{\tilde{q}}$, M_A respectively stand for the gluino, 1st/2nd generation squarks and the CP odd Higgs boson masses.

3   SO(10) with non-universal gauginos masses

In this section we present the sparticle spectroscopy of Yukawa unified SO(10) with non-universal gaugino masses at M_{GUT}. The sfermions of the first and second families are assigned a common SSB mass term $m_{16_{1,2}}$, while the third generation sfermions have a universal SSB mass term m_{16_3}. We also employ universal SSB mass term for the MSSM Higgs bosons, $m^2_{H_u} = m^2_{H_d} \equiv m^2_{10}$. As mentioned earlier, gauge coupling unification is one of the nice features of low scale supersymmetry and indicates that the SM gauge symmetry is embedded within a a simple gauge group with rank ≥ 4. In this case the MSSM gauginos are contained within a single vector multiplet. To retain gauge coupling unification and at the same time have non-universal gaugino masses at M_{GUT}, one way is to employ [74–76] non-singlet F-terms, compatible with the underlying GUT. Non-universal gauginos can also be generated from the F-term with a linear combination of two distinct fields of different dimensions [77]. We can also consider two distinct sources for supersymmetry breaking [78]. Since there are many possibilities for realizing non-universal gaugino masses with either fixed or arbitrary mass ratios, we employ independent masses for the three MSSM gauginos in our study. In this case our analysis will cover a variety of scenarios with non-universal gaugino masses and split sfermion families in the presence of t-b-τ Yukawa unification.

We have performed random scans in the fundamental parameter space of the model with ranges of the parameters given as follows:

$$0 \leq m_{16_{1,2}} \leq 1 \text{ TeV}$$
$$0 \leq m_{16_3} \leq 5 \text{ TeV}$$
$$-1 \leq M_1 \leq 0 \text{ TeV}$$
$$-1 \leq M_2 \leq 0 \text{ TeV}$$
$$0 \leq M_3 \leq 5 \text{ TeV}$$
$$-3 \leq A_0/m_3 \leq 3$$
$$35 \leq \tan\beta \leq 55$$
$$0 \leq m_{10} \leq 5 \text{ TeV}$$
$$\mu < 0 \tag{3.1}$$

In figure 1 we show the results in the $R_{tb\tau} - M_3$, $R_{tb\tau} - M_2$, $R_{tb\tau} - m_{16_{1,2}}$ and $m_{16_3} - m_{16_{1,2}}$ planes. *Gray* points are consistent with REWSB and neutralino LSP. *Green* points form a subset of the *gray* ones and satisfy sparticles and Higgs mass bounds and all other constraints described in section 2. *Yellow* points are a subset of the *green* points
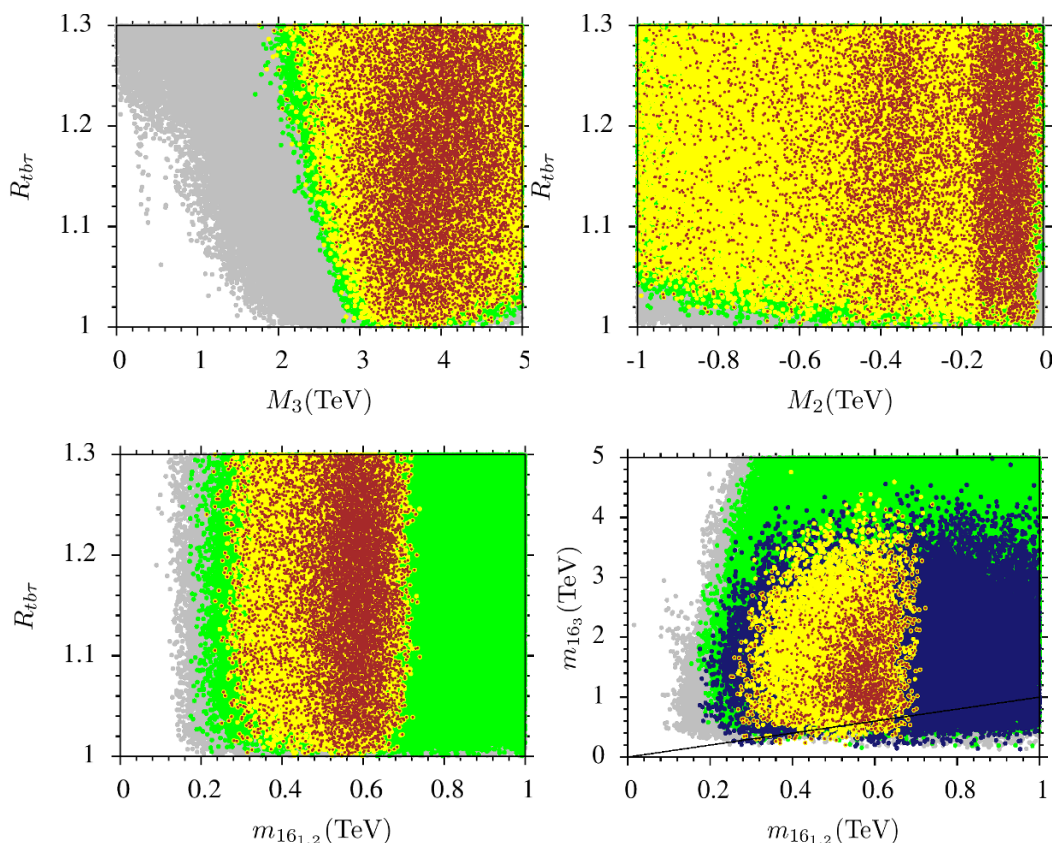
Figure 1. Plots in the $R_{tb\tau} - M_3$, $R_{tb\tau} - M_3$, $R_{tb\tau} - m_{16_{1,2}}$ and $m_{16_3} - m_{16_{1,2}}$ planes. *Gray* points are consistent with REWSB and neutralino LSP. *Green* points form a subset of the *gray* points and satisfy the sparticle and Higgs mass bounds, as well as all other constraints described in section 2. *Yellow* points are a subset of the *green* points and satisfy the Δa_μ constraint in eq. (1.1). *Brown* points belong to a subset of *yellow* points and satisfy bound on the LSP neutralino relic abundance, $0.001 \leq \Omega h^2 \leq 1$. In the $m_{16_3} - m_{16_{1,2}}$ panel, in addition, *blue* points are a subset of the *green* ones and satisfy $R_{tb\tau} < 1.1$ and *yellow*. The *yellow* region is a subset of the blue region, while *brown* is subset of *yellow* with the definition of the colors mentioned above.

satisfy the muon $g - 2$ constraint given in eq. (1.1). *Brown* points are a subset of *yellow* points and satisfy the following neutralino relic abundance constraint, $0.001 \leq \Omega h^2 \leq 1$. We have chosen to display our results for a wider range of Ωh^2 keeping in mind that one can always find points which are compatible with the current WMAP range for relic abundance with dedicated scans within the *brown* regions. In the $m_{16_3} - m_{16_{1,2}}$ plane, in addition, the *blue* points are a subset of the *green* ones and satisfy $R_{tb\tau} < 1.1$. In this panel the *yellow* region is a subset of the blue, and *brown* is a subset of the *yellow* region with the color definitions the same as mentioned above.

From the $R_{tb\tau} - M_3$ plane we see that just from the REWSB condition (*gray* points), we cannot have $M_3 \lesssim 1\,\text{TeV}$ (or equivalently $m_{\tilde{g}} \lesssim 3\,\text{TeV}$) if we demand t-b-τ Yukawa unification better than 10%. The reasons for such a heavy gluino mass are the combined effects from REWSB and the necessity for appropriate threshold corrections for t-b-τ Yukawa uni-
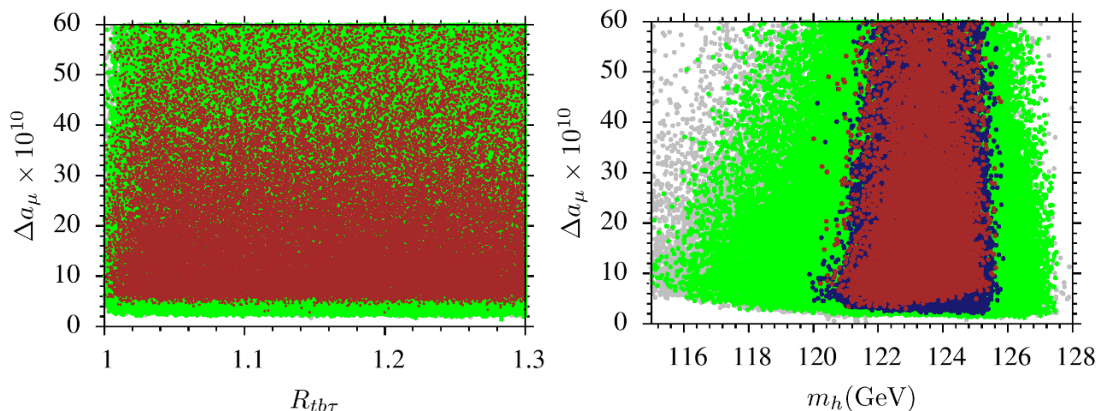
Figure 2. Plots in the $\Delta a_\mu - R_{tb\tau}$ and $\Delta a_\mu - m_h$ planes. *Gray* points are consistent with REWSB and neutralino LSP. *Green* points form a subset of the *gray* points and satisfy the sparticle and Higgs mass bounds, as well as all other constraints described in section 2. *Brown* points belong to a subset of *green* points and satisfy the bound for LSP relic abundance, $0.001 \leq \Omega h^2 \leq 1$. In the $\Delta a_\mu - m_h$ panel *blue* points are subset of the *green* ones and satisfy $R_{tb\tau} < 1.1$. *Brown* points are subset of *blue* points and have the same definition as above.

fication [19]. If we apply the current experimental constraint, the lower mass bound on the gluino changes drastically (*green* points). In particular, t-b-τ Yukawa unification better than 10% requires that $M_3 \gtrsim 2.5$ TeV. This bound is mostly dictated from the Higgs mass constraint (123 GeV $\leq m_h \leq$ 127 GeV), the reason being that for t-b-τ Yukawa unification with non-universal and opposite sign gaugino masses, the following condition is usually satisfied: $A_t/M_S < 1$ [19]. On the other hand, it is known [79] that the light CP even Higgs boson mass receives significant contribution from the A_t term if $A_t/M_S \gtrsim 1$. We can therefore conclude that there is no significant contribution from finite corrections to the CP even Higgs boson mass if we require almost perfect Yukawa unification and the Higgs mass is mostly generated from logarithmic corrections involving the stop quark. It was also shown in [19] that the stop quark mass in this case has to be $\gtrsim 5$ TeV in order to satisfy the Higgs mass bound. Another constraint from Yukawa unification, namely, $M_3 > m_{16_3}$, implies that the stop quark mass is mostly determined from radiative corrections from the gluino. This, therefore, is the reason why the gluino mass affects the Higgs mass bound so strongly for t-b-τ Yukawa unification better than 10%. The *yellow* points show that in this scenario supersymmetry can easily provide the desired contribution to the muon $g-2$ anomaly. We will show later that there are several channels that can generate the correct relic abundance for neutralino dark matter, displayed by the *brown* points.

In the $R_{tb\tau} - M_2$ plane we observe a very mild constraint on the parameter M_2 from t-b-τ Yukawa unification and all current experimental data including muon $g-2$ anomaly and dark matter relic abundance. The same conclusion applies to M_1 which is the reason we do not display results in terms of M_1 here.

Since the Higgs mass bound and t-b-τ Yukawa unification condition only affects the third generations squarks, the first and second generation sfermions can be as light as
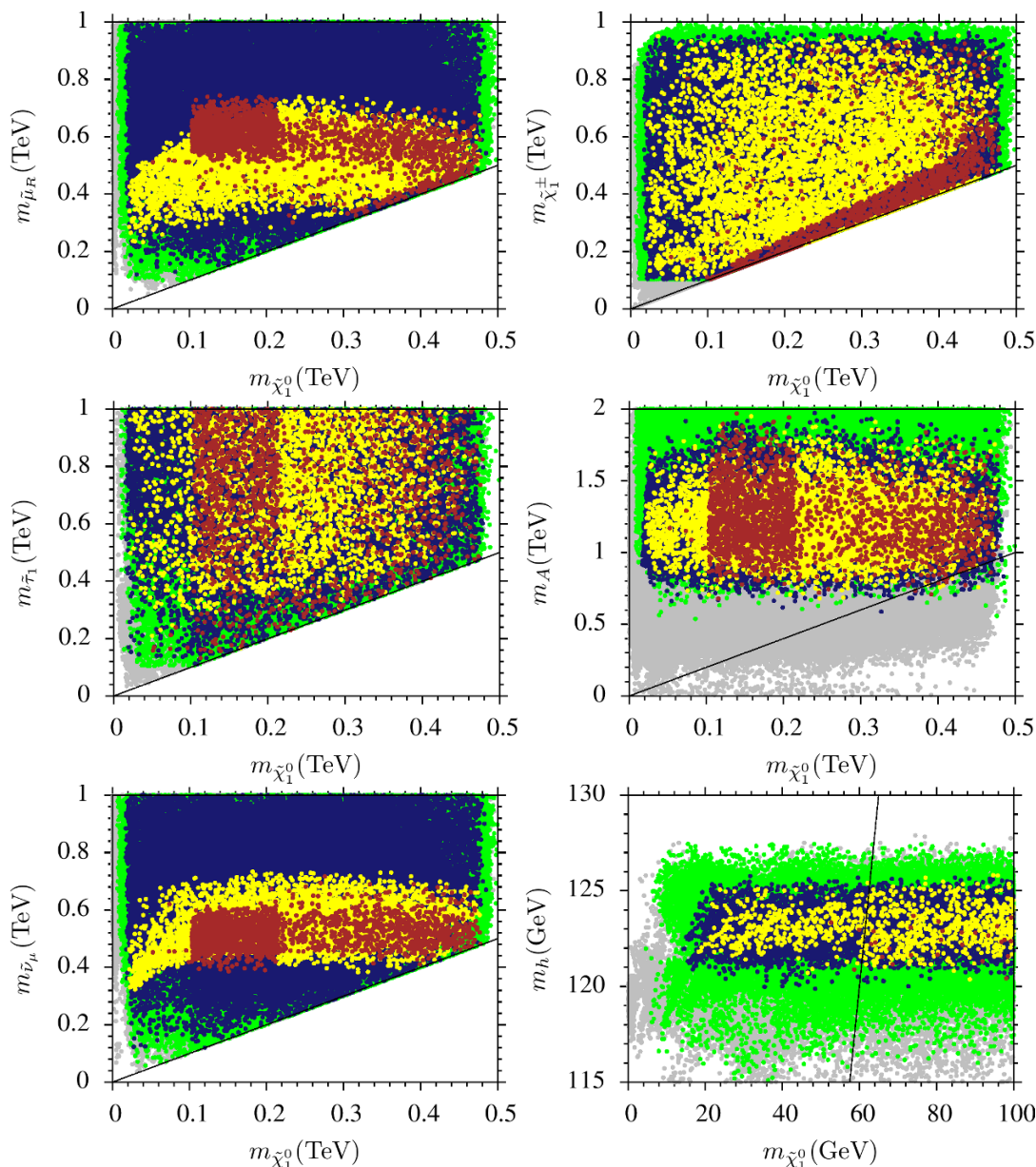
Figure 3. Color coding same as in the $m_{16_3} - m_{16_{1,2}}$ panel in figure 1.

100 GeV, as seen from the $R_{tb\tau} - m_{16_{1,2}}$ plane (*gray* points). The current experimental data (including the limit $m_{\tilde{q}} \gtrsim 1.5$ TeV) does not significantly change the lower bound on $m_{16_{1,2}}$. The reason is that here the gluino and wino masses are independent of each other and a large gluino mass ($m_{\tilde{g}} > 5$ TeV) automatically pushes the squark masses to a few TeV despite the low initial value $m_{16_{1,2}}$ at $M_{\rm GUT}$. This allows for low values of $m_{16_{1,2}}$ while still being consistent with all experimental results. After applying the muon $g - 2$ constraint we obtain 0.3 TeV $\lesssim m_{16_{1,2}} \lesssim 0.7$ TeV. Again, *brown* points show that the correct relic abundance is easily achieved once the muon $g - 2$ constraint is applied.

From the $m_{16_3} - m_{16_{1,2}}$ plane we learn that it is possible to have solutions consistent with muon $g - 2$ anomaly when $m_{16_3} = m_{16_{1,2}}$ with arbitrary and opposite sign gaugino
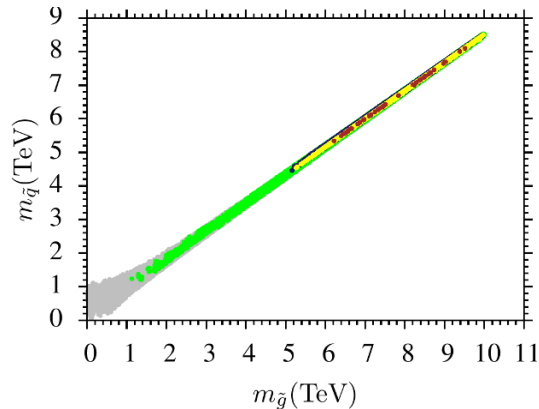
Figure 4. Color coding same as in the $m_{16_3} - m_{16_{1,2}}$ panel in figure 1.

mass ratios at M_{GUT} (see *yellow* points which are subset of *blue* points showing 10% or better t-b-τ Yukawa unification). We find that in this case $M_3 > 3 \cdot M_2$ needs to be satisfied at M_{GUT}. We also see that the solution consistent with muon $g-2$ anomaly mostly occurs for $m_{16_3} > m_{16_{1,2}}$.

In figure 2 we show the results in the $\Delta a_\mu - R_{tb\tau}$ and $\Delta a_\mu - m_h$ planes. *Gray* points are consistent with REWSB and neutralino LSP. *Green* points form a subset of the *gray* points and satisfy the sparticles, Higgs mass bound and all other constraints described in section 2. *Brown* points are a subset of the *green* points and satisfy the following bound on the neutralino relic abundance: $0.001 \leq \Omega h^2 \leq 1$. In the $\Delta a_\mu - m_h$ panel, the *blue* points are a subset of the *green* ones and satisfy $R_{tb\tau} < 1.1$. In this plane the *brown* points are a subset of the *blue* ones with the same definition mentioned above. We can see from the $\Delta a_\mu - R_{tb\tau}$ plane that a notable region of the parameter space simultaneously yields perfect t-b-τ Yukawa unification along with the desired contribution to the muon $g-2$ anomaly, while satisfying all experimental constraints described in in section 2.

The $\Delta a_\mu - m_h$ panel shows that it is possible to have a $125\,\text{GeV}$ light CP-even Higgs boson consistent with the desired contribution to the muon $g-2$ anomaly. The desired contribution to the muon $g-2$ anomaly and a $125\,\text{GeV}$ Higgs cannot be easily attained for a broad class of low scale supersymmetric model. For instance, it was shown in [80] that with universal SSB gaugino and sfermion masses at M_{GUT}, it is very hard to simultaneously have a $125\,\text{GeV}$ Higgs boson mass and the desired Δa_μ within 1σ deviation from its theoretical value. In our case this is easily achieved and is also compatible with good t-b-τ Yukawa unification (*blue* points).

In figure 3 we present our results in $m_{\tilde{\mu}_R} - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$, $m_A - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\nu}_\mu} - m_{\tilde{\chi}_1^0}$ and $m_h - m_{\tilde{\chi}_1^0}$ planes in order to show the different channels contributing to yield the correct neutralino dark matter relic abundance. We see that all the channels are consistent with the desired contribution to muon $g-2$ anomaly. We also observe that the slepton mass in this scenario can be around $200\,\text{GeV}$, and so there is hope that it can be tested at the LHC. The results in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane exhibit bino-wino and bino-higgsino mixed dark matter scenarios. The $m_h - m_{\tilde{\chi}_1^0}$ panel shows the presence of light Higgs and Z-resonance neutralino dark matter solutions, consistent with Yukawa unification. The

	Point 1	Point 2	Point 3	Point 4	Point 5
$m_{16_{1,2}}$	375.9	353.2	639	450.7	620.6
m_{16_3}	2257	562.9	3113	1634	3580
M_1	-981.9	-821.8	-526.8	-739.2	-699.1
M_2	-701.8	-640.6	-266.5	-389.9	-372.4
M_3	4299	3589	4305	3685	4771
$\tan\beta$	51.5	51.1	50.7	51.4	50.7
A_0/m_{16_3}	-2.06	-0.73	-1.62	1.87	1.76
m_{10}	2512	988.7	370.5	189.4	1315
m_t	173.3	173.3	173.3	173.3	173.3
μ	-4845	-3707	-5648	-3926	-6276
Δa_μ	$\mathbf{31.5 \times 10^{-10}}$	$\mathbf{31.9 \times 10^{-10}}$	$\mathbf{25.7 \times 10^{-10}}$	$\mathbf{34.8 \times 10^{-10}}$	$\mathbf{28.6 \times 10^{-10}}$
m_h	124.6	123.3	124.7	123.1	125
m_H	1280	1244	1293	778.5	1651
m_A	1272	1236	1285	**773.5**	1641
$m_{H^\pm}$	1284	1248	1297	784.7	1654
$m_{\tilde{\chi}^0_{1,2}}$	**466.3**, 680.9	**392.9**, 625.9	**259.9, 304.8**	**361.4**, 426.6	**340.1, 402.7**
$m_{\tilde{\chi}^0_{3,4}}$	4843, 4843	3709, 3710	5635, 5635	3930, 3930	6262, 6262
$m_{\tilde{\chi}^\pm_{1,2}}$	683.5, 4841	627.8, 3710	**306.1**, 5633	428.3, 3929	**404.4**, 6259
$m_{\tilde{g}}$	8599	7247	8650	7436	9517
$m_{\tilde{u}_{L,R}}$	7332, 7346	6204, 6214	7373, 7401	6351, 6372	8094, 8120
$m_{\tilde{t}_{1,2}}$	6232, 6419	5363, 5496	6545, 6730	5734, 5830	7157, 7375
$m_{\tilde{d}_{L,R}}$	7332, 7348	6204, 6216	7374, 7406	6351, 6374	8094, 8125
$m_{\tilde{b}_{1,2}}$	6352, 6425	5427, 5489	6659, 6743	5775, 5837	7316, 7412
$m_{\tilde{\nu}_{1,2}}$	521.2	503.4	568	456.2	555.1
$m_{\tilde{\nu}_3}$	1991	778.7	2846	1437	321.6
$m_{\tilde{e}_{L,R}}$	546.5, 493.7	519.1, 448.8	592.3, 642.6	470.9, 510.2	588.4, 640.2
$m_{\tilde{\tau}_{1,2}}$	1469, 1994	437.1, 909.9	2454, 2846	1012, 1446	2695, 3209
$\sigma_{SI}(\text{pb})$	0.29×10^{-11}	0.49×10^{-11}	0.22×10^{-11}	0.16×10^{-10}	0.13×10^{-11}
$\sigma_{SD}(\text{pb})$	0.10×10^{-9}	0.33×10^{-9}	0.46×10^{-10}	0.28×10^{-9}	0.29×10^{-10}
$\Omega_{CDM}h^2$	0.12	0.12	0.11	0.11	0.13
R	1.06	1.05	1.05	1.01	1.09

Table 1. Benchmark points with Δa_μ within 1σ deviation from its theoretical value. All the masses are in units of GeV. Points are chosen to be consistent with all the constraints described on section 2. Point 1 depicts a solution for smuon (selectron) coannihilation, while point 2 represents stau-coannihilation. Points 3 and 4 display chargino-neutralino coannihilation and A-resonance solutions, respectively. Point 5 shows a solution with a 125 GeV Higgs boson and the central value of muon $g-2$.

solid line in this plane stands for the relation $m_h = 2 \cdot m_{\tilde{\chi}_1^0}$. Finally, the $m_{\tilde{q}} - m_{\tilde{g}}$ panel in figure 4 shows that t-b-τ Yukawa unification predicts $m_{\tilde{q}} \gtrsim 4\,\mathrm{TeV}$ and $m_{\tilde{g}} \gtrsim 5\,\mathrm{TeV}$ (*blue* points), which may be difficult to observe at LHC 14.

Table 1 lists four benchmark points for this scenario that have good Yukawa unification, satisfy the Higgs mass bound, yield the desired Δa_μ, and satisfy all other constraints described in section 2. In addition, the relic density is within the WMAP limit on the dark matter abundance. Point 1 depicts a solution for smuon/selectron-coannihilation while point 2 represents stau-coannihilation. Points 3 and 4 display chargino-neutralino coannihilation and A-resonance ($m_A \sim 2m_{\chi_1^0}$) solutions, respectively. Despite a large splitting between the gaugino masses at M_{GUT}, we find that the gauge couplings unify to within a few percent. This can be assigned to unknown GUT-scale threshold correction.

4   SO(10) with universal gauginos masses

In this section we present the SO(10) sparticle spectroscopy corresponding to t-b-τ Yukawa unification and universal gaugino mass terms at M_{GUT}. As shown in ref. [30, 31], in this case we must have non-universal SSB mass^2 terms for the MSSM Higgs bosons, namely $m_{H_u}^2 \neq m_{H_d}^2$ at M_{GUT}. Otherwise, it is very difficult to simultaneously implement REWSB and t-b-τ Yukawa unification (for discussion see ref. [19]). As in the previous case, the sfermions from the first and second families have common universal SSB mass terms $m_{16_{1,2}}$, and the third generation sfermions have the universal SSB mass term m_{16_3}.

The random scans are performed for the following range of parameters:

$$0 \leq m_{16_{1,2}} \leq 1\,\mathrm{TeV}$$
$$0 \leq m_{16_3} \leq 5\,\mathrm{TeV}$$
$$0 \leq M_{1/2} \leq 2\,\mathrm{TeV}$$
$$-3 \leq A_0/m_3 \leq 3$$
$$35 \leq \tan\beta \leq 55$$
$$0 \leq m_{H_u} \leq 30\,\mathrm{TeV}$$
$$0 \leq m_{H_d} \leq 30\,\mathrm{TeV}$$
$$\mu > 0. \tag{4.1}$$

Figure 5 shows the results in the $R_{tb\tau} - M_{1/2}$, $R_{tb\tau} - m_{16_{1,2}}$, $R_{tb\tau} - m_{16_3}$ and $m_{16_3} - \mu$ planes. *Gray* points are consistent with REWSB and neutralino LSP. *Green* points form a subset of the *gray* points and satisfy the sparticle and Higgs mass bounds along with all other constraints described in section 2.

The $R_{tb\tau} - M_{1/2}$ plane shows the same interval for the parameter $M_{1/2}$ which is compatible with t-b-τ Yukawa unification as previously found with universal SSB sfermion masses [9–11]. This result was expected since the different SSB mass terms for the first/second and the third families do not significantly affect the RGE running and threshold corrections to the third generation fermions which is very crucial for t-b-τ Yukawa unification. In this scenario, we do not find acceptable solutions with LSP neutralino as the correct dark mater candidate.
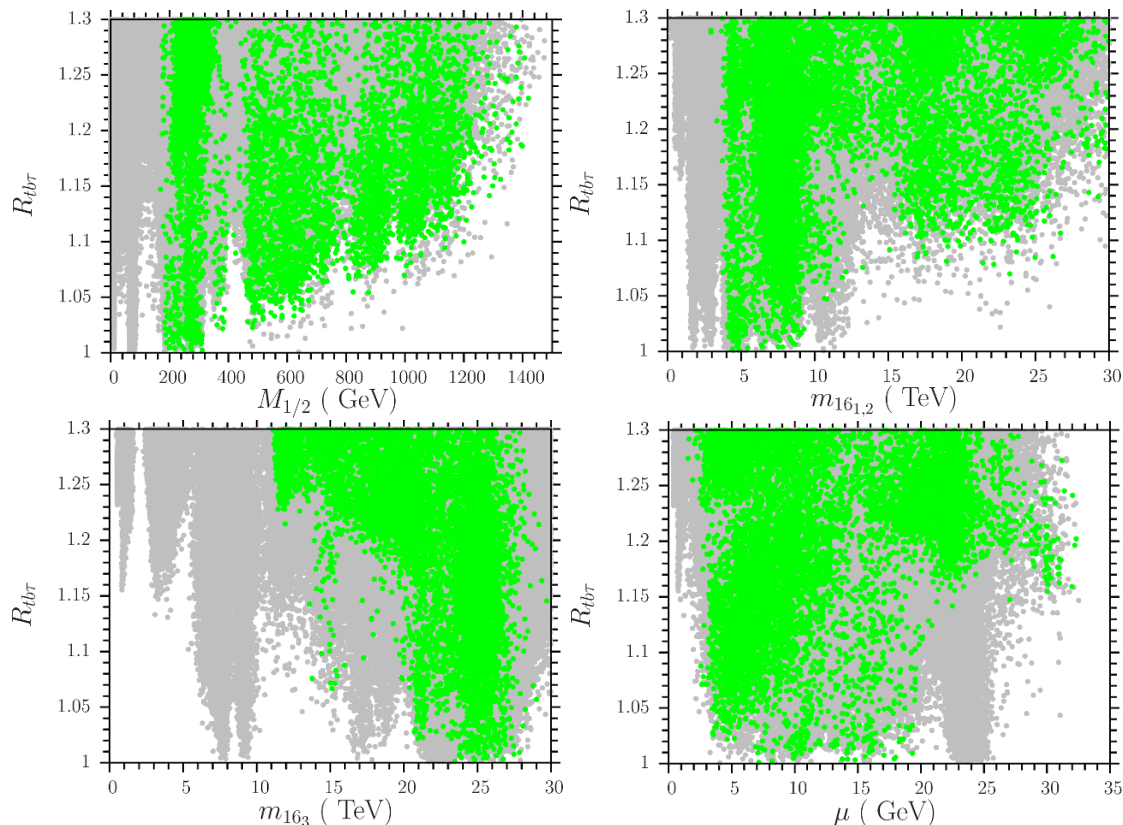
Figure 5. Plots in the $R_{tb\tau} - M_{1/2}$, $R_{tb\tau} - m_{16_{1,2}}$, $R_{tb\tau} - m_{16_3}$ and $m_{16_3} - \mu$ planes. *Gray* points are consistent with REWSB and neutralino LSP. *Green* points form a subset of the *gray* points and satisfy the sparticle and Higgs mass bounds, as well as all other constraints described in section 2.
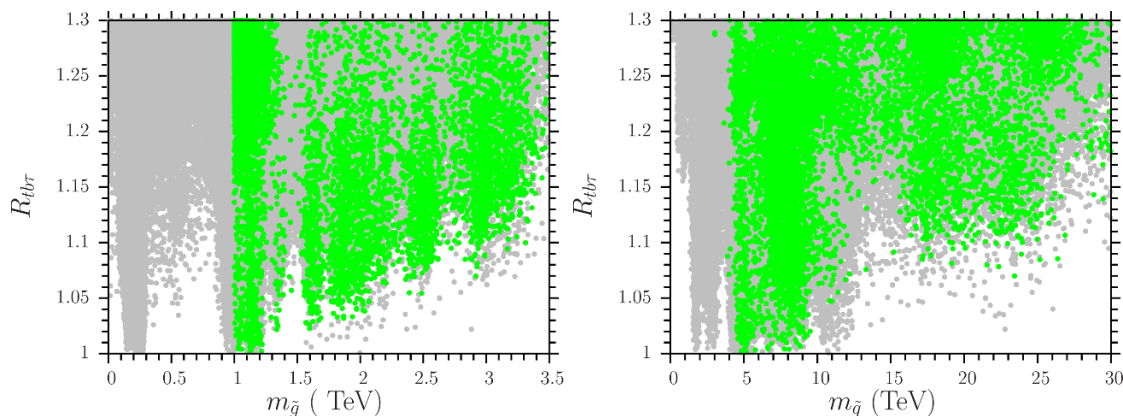

Figure 6. Plots in the $R_{tb\tau} - m_{\tilde{g}}$ and $R_{tb\tau} - m_{\tilde{q}}$ planes. Color coding same as in figure 5.

The $R_{tb\tau} - m_{16_{1,2}}$ plane shows how low the SSB mass term for the first and second generation sfermions ($m_{16_{1,2}}$) can become if they are independent from m_{16_3}. We can compare these observations with the $R_{tb\tau} - m_{16_3}$ plane and note that the parameter $m_{16_{1,2}}$ can be 4-5 times lighter than m_{16_3}. However, $m_{16_{1,2}}$ lighter than 4 TeV is difficult if the various experimental constraints are implemented.

	Point 1	Point 2	Point 3
$m_{16_{1,2}}$	7037.9	8195.9	22593.1
m_{16_3}	22196.8	25916.7	24856.1
$M_{1/2}$	465.6	644.4	1046.3
A_0/m_{16_3}	-2.2	-2.1	-2.1
$\tan\beta$	51.0	51.1	51.8
m_{H_d}	29104.8	34726.1	33575.9
m_{H_u}	25514.3	30738.2	29095.7
μ	7656	4788	5522
m_h	**125.8**	**125.9**	**124.6**
m_H	3386	3700	8802
m_A	3364	3676	8745
$m_{H^\pm}$	3388	3701	8803
$m_{\tilde{\chi}^0_{1,2}}$	$281, 583$	$372, 760$	$562, 1119$
$m_{\tilde{\chi}^0_{3,4}}$	$7522, 7522$	$4724, 4724$	$5461, 5462$
$m_{\tilde{\chi}^\pm_{1,2}}$	$585, 7492$	$762, 4683$	$1123, 5421$
$m_{\tilde{g}}$	**1567**	**2021**	**3005**
$m_{\tilde{u}_{L,R}}$	$7025, 6507$	$8199, 7617$	$22665, 22481$
$m_{\tilde{t}_{1,2}}$	$3805, 6468$	$4512, 7579$	$4393, 7780$
$m_{\tilde{d}_{L,R}}$	$7025, 7216$	$8200, 8421$	$22665, 22788$
$m_{\tilde{b}_{1,2}}$	$6546, 7370$	$7699, 8752$	$8037, 9480$
$m_{\tilde{\nu}_1}$	6637	7736	22451
$m_{\tilde{\nu}_3}$	16532	19314	18357
$m_{\tilde{e}_{L,R}}$	$6634, 7629$	$7733, 8868$	$22441, 22866$
$m_{\tilde{\tau}_{1,2}}$	$16487, 8172$	$19261, 9555$	$18335, 9020$
Δa_μ	1.45×10^{-11}	1.82×10^{-11}	2.88×10^{-12}
$\sigma_{SI}(\text{pb})$	2.31×10^{-14}	6.16×10^{-15}	1.84×10^{-15}
$\sigma_{SD}(\text{pb})$	2.53×10^{-12}	1.10×10^{-10}	1.39×10^{-10}
$R_{tb\tau}$	1.03	1.04	1.11

Table 2. Benchmark points with good Yukawa unification and $m_h \sim 125\,\text{GeV}$. The points are shown with increasing gluino mass from point 1 to 3.

The large difference between $M_{1/2}$ and $m_{16_{1,2}}$ (or m_{16_3}) values, if we require 10% or better unification, shows that the neutralino coannihilation scenario is not possible in order to yield the correct neutralino dark matter relic abundance. Since $m_{16_{1,2}} \gtrsim 4\,\text{TeV}$, there

can be no significant contribution to the muon $g - 2$ anomalous magnetic moment like we had in the previous section. We also learn from the $m_{16_3} - \mu$ panel that the μ-term is greater than $3\,\text{TeV}$ if we demand 10% or better Yukawa unification, (*green* points). Comparing this result with the gaugino mass interval obtained from demanding 10% or better unification, we conclude that the bino-higgsino mixed dark matter scenario is not viable here.

In figure 6 we display the results in the $R_{tb\tau} - m_{\tilde{g}}$ and $R_{tb\tau} - m_{\tilde{q}}$ planes, with color coding the same as in figure 5. The $R_{tb\tau} - m_{\tilde{g}}$ panel shows that t-b-τ Yukawa unification predicts an upper bound on the gluino mass which can easily be tested at LHC14. The result in green color from the $R_{tb\tau} - m_{\tilde{q}}$ plane shows that in this model squarks will be difficult to find at LHC14, but there is some hope that they might be accessible at LHC33 [36].

In table 2 we show three benchmark points for this scenario which display good Yukawa unification with the required Higgs mass. In addition all other constraints described in section 2 are satisfied. As previously mentioned, this SO(10) model does not exhibit coannihilation and the contribution to the $g - 2$ anomaly is also not significant. The gluino is the lightest colored sparticle for the three points and may be found at the LHC.

We have shown in this paper that good YU can arise in models with universal gaugino masses and non-universal Higgs masses at the M_{GUT} (NUHM2). But in this case, in order to realize good YU with gluino mass more than $1\,\text{TeV}$, one needs to have $m_{16_{1,2}} > 4\,\text{TeV}$, and consequently smuons are at least around $4\,\text{TeV}$. Imposing non-universal gaugino mass condition at M_{GUT} in the framework of YU can reduce the values of $m_{16_{1,2}}$ but not enough to provide significant contribution to muon $g - 2$. Because the aim of our study was to present scenarios with good YU and sizable contribution to muon $g - 2$ we did not consider same sign but non-universal gaugino case in this paper.

5   Conclusion

We discussed supersymmetric SO(10) grand unification with non-universal and universal gaugino masses at M_{GUT} with the sfermion masses of the first and second generations different from that of the third generation. We explored the consistency of good t-b-τ Yukawa unification in these models with various experimental observations, namely, the Higgs and sparticle mass limits, B-physics constraints, WMAP relic density bound and the muon anomalous magnetic moment. We further studied the sparticle spectroscopy of these models and listed some benchmark scenarios that can be explored at $14\,\text{TeV}$ LHC.

In the scenario with non-universal gaugino masses, the soft supersymmetry breaking parameters M_i (i=1, 2, 3) are treated as independent. In this case all of the above mentioned constraints can be satisfied. The colored sparticles are all found to be very heavy ($\gtrsim 5\,\text{TeV}$) for 10% or better Yukawa unification. The sleptons (smuon and stau) in this case can be as light as $200\,\text{GeV}$. The correct relic abundance for neutralino dark matter is realized through various channels including neutralino-stau(smuon) coannihilation and A resonance.

The second model has universal gaugino masses and non-universal Higgs masses at M_{GUT}. The gluino turns out to be the lightest colored sparticle with mass $\gtrsim 1.5\,\text{TeV}$. The sfermions including the sleptons, however, are all very heavy ($\gtrsim 4\,\text{TeV}$), so that the muon $g - 2$ anomaly is unresolved. The LSP neutralino in this case is not a viable dark

matter candidate. The remaining experimental constraints are satisfied in this scenario, and we present some benchmark points. They exhibit acceptable Yukawa unification and the gluino is the only sparticle accessible at the LHC.

Acknowledgments

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