Sparticle mass spectra from $SU(5)$ SUSY GUT models with $b - \tau$ Yukawa coupling unification

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Abstract

Supersymmetric grand unified models based on the gauge group $SU(5)$ often require in addition to gauge coupling unification, the unification of $b$-quark and $\tau$-lepton Yukawa couplings. We examine $SU(5)$ SUSY GUT parameter space under the condition of $b - \tau$ Yukawa coupling unification using 2-loop MSSM RGEs including full 1-loop threshold effects. The Yukawa-unified solutions break down into two classes. Solutions with low $\tan \beta \sim 3 - 11$ are characterized by $m_{\tilde{g}} \sim 1 - 4$ TeV and $m_{\tilde{q}} \sim 1 - 5$ TeV. Many of these solutions would be beyond LHC reach, although they contain a light Higgs scalar with $m_h < 123$ GeV and so may be excluded should the LHC Higgs hint persist. The second class of solutions occurs at large $\tan \beta \sim 35 - 60$, and are a subset of $t - b - \tau$ unified solutions. Constraining only $b - \tau$ unification to $\sim 5\%$ favors a rather light gluino with $m_{\tilde{g}} \sim 0.5 - 2$ TeV, which should ultimately be accessible to LHC searches. While our $b - \tau$ unified solutions can be consistent with a picture of neutralino-only cold dark matter, invoking additional moduli or Peccei-Quinn superfields can allow for all of our Yukawa-unified solutions to be consistent with the measured dark matter abundance.

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1 Introduction

Grand unified theories (GUTs) based upon the Lie group $SU(5)$ are very compelling in that they unify the disparate gauge groups of the Standard Model (SM) into a theory based upon just a single gauge group [1]. Furthermore, the $SU(5)$ theory provides a rationale for the seemingly ad-hoc weak-hypercharge assignments of SM matter fields. A third triumph occurs in that models based on $SU(5)$ unification unify the $b$-quark and $\tau$-lepton Yukawa couplings at the unification scale $M_{GUT} \sim 10^{16}$ GeV: then, renormalization group effects provide roughly the correct values of $m_b$ and $m_\tau$ at low energy scales [2].

Adding supersymmetry to $SU(5)$ grand unified theories seems essential in order to stabilize the vast hierarchy separating the weak scale from the GUT scale [3]. The additional SUSY degrees of freedom contained in the Minimal Supersymmetric Standard Model (MSSM) alter the RG running of gauge couplings below the scale $M_{GUT}$. Indeed, the celebrated unification of the three SM gauge couplings within the MSSM is often touted as indirect evidence for weak scale SUSY, and for the possible existence of a SUSY GUT theory [4].

Some drawbacks to the SUSY $SU(5)$ theory include the incorporation of a rather awkward set of Higgs multiplets which are necessary for appropriate GUT symmetry breaking. Foremost among these problems is embedding the MSSM Higgs doublets $\hat{H}_u$ and $\hat{H}_d$ into a $5$ and $\bar{5}'$ respectively of $SU(5)$: one must then explain why the color triplets obtain GUT scale masses while the MSSM multiplets receive weak scale masses: the so-called doublet-triplet splitting problem. In addition, in SUSY GUT theories based in four spacetime dimensions with spontaneous GUT symmetry breaking via the Higgs mechanism, protons are expected to decay even in the SUSY theories with rates which now seem excluded by experiment [5, 6].

However, if one formulates $SU(5)$ SUSY GUT models in five or more spacetime dimensions, then the GUT symmetry can alternatively be broken by compactification of the extra dimensions on an appropriate manifold such as an orbifold [7]. This method of symmetry breaking can solve the doublet-triplet splitting problem while suppressing or even eliminating proton decay.
Construction of SUSY GUT models in extra dimensions can solve many problems endemic to 4-d theories while preserving many of the compelling features of unified theories. Indeed, in string theory it is possible for SUSY GUT theories to emerge on four or more dimensions as the low energy (GUT scale) effective theory, where the 6-7 additional stringy dimensions must be dispensed with anyway [8].

In this paper, we seek to avoid the very model-dependent physics associated with the GUT sector and possible extra dimensions, and use instead data and some general $SU(5)$ SUSY GUT characteristics as a guide to what weak scale physics should look like at colliders such as the LHC. We will assume here that nature is described by an $SU(5)$ SUSY GUT theory at energy scales $Q \sim M_{GUT} \simeq 2 \times 10^{16}$ GeV. At $M_{GUT}$, the MSSM superfields $Q, \tilde{U}^c$ and $\tilde{E}^c$ live in the antisymmetric 10 of $SU(5)$: $\tilde{\psi}^ij$, while the $D^c$ and $\tilde{L}$ superfields live in the 5\* of $SU(5)$: $\hat{\phi}_i$. (Here, $i$ and $j$ are $SU(5)$ indices running from 1-5.) The MSSM Higgs doublet $H_d$ is an element of a 1\*; $H_u$, while $\tilde{H}_d$ is an element of a 5\*; $\tilde{H}_u$. The superpotential $\hat{f}$ then contains the terms [9, 10]

$$\hat{f} \equiv \frac{1}{4} f_t \epsilon_{ijklm} \tilde{\psi}^i j \tilde{\psi}^k l m \hat{H}_d^m + \sqrt{2} f_b \tilde{\psi}^i j \hat{\phi}_i \hat{H}_1 j + \mu \hat{H}_1 \hat{H}_2 + \cdots \tag{1}$$

so that the third generation Yukawa couplings $f_b$ and $f_\tau$ are unified at $M_{GUT}$, but are distinct from $f_t$.

The soft SUSY breaking terms in an $SU(5)$ SUSY GUT theory are expected to include:

$$L_{soft} \equiv -m_H^2 |H_1|^2 - m_{H_2}^2 |H_2|^2 - m_\phi^2 |\phi|^2 - m_\tilde{\psi}^2 tr \{\psi \dagger \psi\} - \frac{1}{2} m_{1/2} \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

$$+ \left[ \frac{1}{2} A_t f_t \epsilon_{ijklm} \tilde{\psi}^i j \tilde{\psi}^k l m \hat{H}_d^m + \sqrt{2} A_b f_b \tilde{\psi}^i j \hat{\phi}_i \hat{H}_1 j + h.c. \right]. \tag{2}$$

For $SU(5)$ SUSY GUT models with $b - \tau$ Yukawa coupling unification, we will adopt a GUT scale parameter space given by

$$m_5, \ m_{10}, \ m_{R_3}^2, \ m_{H_d}^2, \ m_{1/2}, \ A_t, \ A_b, \ \tan \beta, \ \text{sign}(\mu) \tag{3}$$

where we identify $m_{R_3}^2 = m_{H_d}^2$ and $m_{H_d}^2 = m_{H_u}^2$. We also take the top quark pole mass to be $m_t = 173.3$ GeV, in accord with recent measurements from CDF and D0 [11].

Recent previous work on Yukawa coupling unification has focused on $t - b - \tau$ unification which is expected to occur in the simplest $SO(10)$ SUSY GUT models [12]. In these models, unification of all matter (super)fields of a single generation into a 16-dimensional spinor $\hat{\psi}$ occurs. The two MSSM Higgs multiplets are also unified into a 10-dimensional Higgs representation $\hat{\phi}$. In these models, it was found that $t - b - \tau$ unification can occur if the soft SUSY breaking (SSB) parameters are related as $A_0^b \simeq 2 m_{t0}^8 \simeq 4 m_{t0}^2$ [13, 14, 15, 16]. With matter scalar SSB masses in the multi-TeV range and gaugino mass $m_{1/2}$ as small as possible, these relations lead to a weak scale sparticle mass spectrum of the inverted mass hierarchy type [19]: first/second generation squarks in the $5 - 20$ TeV range while third generation scalars are at $\lesssim 1$ TeV, as required by naturalness. Either a “just-so” splitting of Higgs SSB terms (with $m_{H_d}^2 > m_{R_3}^2$ at the GUT scale), or $D$-term splitting of scalars (in the DR3 model [20]) is required for radiative electroweak symmetry breaking (REWSB) [21].

In SUSY models with $t - b - \tau$ Yukawa unification and unified gaugino masses, there is a tendency in the sparticle mass spectrum for rather light gluinos with $m_{\tilde{g}} \lesssim 500$ GeV [13, 15, 16] (although solutions can also be found with significantly higher gluino masses [22]). Recent searches

$$1$$
for gluino pair production in Yukawa-unified models require \( m_{\tilde{g}} \gtrsim 500 \text{ GeV} \), placing some stress on this class of models [23]. One path to relieve such stress is to assume a two-stage breaking pattern

\[
SO(10) \to SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y.
\]

In this case, one might expect a high degree of \( b-\tau \) Yukawa unification, but perhaps a lesser degree of \( t-b-\tau \) unification. If the scales of the two stages are significantly separated, then one needs to take into account the evolution of the SSB terms above \( M_{\text{GUT}} \). Such super-GUT effects can lead to sufficiently different sparticle spectra with interesting phenomenology [9, 10, 17]: for example, the no-scale scenario can be made compatible with experimental constraints [18]. The breaking pattern (4) may also allow for heavier gluino masses to occur in the range of \( m_{\tilde{g}} \sim 0.5 - 1 \text{ TeV} \). Such gluino masses should be accessible to LHC SUSY searches with \( \sqrt{s} = 7 \text{ TeV} \) and 20–30 fb\(^{-1}\) of integrated luminosity [24].

Spurred by these developments, the authors of [25, 26] investigated \( t-b-\tau \) Yukawa unification in the framework of SUSY \( SU(4)_c \times SU(2)_L \times SU(2)_R \) [27] (4-2-2, for short). The 4-2-2 structure allows one to have non-universal gaugino masses while preserving Yukawa unification. An important conclusion reached in Ref. [25] is that with the same sign but non-universal soft gaugino masses, Yukawa unification in 4-2-2 for \( \mu > 0 \) is compatible with neutralino dark matter, with gluino co-annihilation [25, 28] playing an important role.

By considering opposite sign gauginos with \( \mu < 0, M_2 < 0, M_3 > 0 \), (where \( M_2 \) and \( M_3 \) are the SSB gaugino mass terms corresponding to \( SU(2)_L \) and \( SU(3)_c \) respectively, it is shown in Ref. [26] that Yukawa coupling unification consistent with the experimental constraints can be implemented in 4-2-2. With \( \mu < 0 \) and opposite sign gauginos \( (M_2 < 0, M_3 > 0) \), Yukawa coupling unification is achieved for \( m_{16} \gtrsim 300 \text{ GeV} \), as opposed to \( m_{16} \gtrsim 8 \text{ TeV} \) for the case of same sign gauginos. The finite corrections to the b-quark mass play an important role here [26]. Note that with \( M_2 < 0, M_3 > 0 \) and \( \mu < 0 \), we can obtain the desired contribution to \((g-2)_\mu\) [29]. This enables us to simultaneously satisfy the requirements of \( t-b-\tau \) Yukawa unification in 4-2-2, neutralino dark matter and \((g-2)_\mu\), as well as a variety of several other bounds.

Encouraged by the abundance of solutions and co-annihilation channels available in the case of Yukawa unified SUSY 4-2-2, Yukawa unification in SO(10) GUT was explored in [30] with non-universal MSSM gaugino masses at \( M_{\text{GUT}} \). This scenario can arise from non-singlet F-terms, compatible with the underlying GUT symmetry [30]. Furthermore, the soft masses for the two scalar Higgs doublets are set equal \( (m_{H_u}=m_{H_d}) \) at \( M_{\text{GUT}} \). It is intriguing to note that in these models, rather precise \( t-b-\tau \) Yukawa unification also happens to yield a mass for the lightest CP-even Higgs boson in the 122 – 124 GeV range [13, 31]. There is an approximately 2 GeV theoretical uncertainty in this calculation.

The remainder of this paper is organized as follows. In Sec. 2, we outline details of our sparticle mass spectra calculation, along with the requirement of \( b-\tau \) Yukawa unification, and constraints from earlier collider and \( B \) decay searches. In Sec. 3, we show preferred \( SU(5) \) model parameter choices which lead to \( b-\tau \) Yukawa unification. The solutions divide into two classes: 1. those with low \( \tan \beta \sim 3 - 11 \) for which the top Yukawa coupling \( f_t \gg f_b \approx f_\tau \) at the GUT scale, and 2. those at high \( \tan \beta \sim 35 - 60 \), which give \( t-b-\tau \) Yukawa quasi-unification, i.e. \( f_t \sim f_b \approx f_\tau \) at \( Q = M_{\text{GUT}} \). The low \( \tan \beta \) solutions may be eliminated if the LHC hint of Higgs at \( m_h \approx 125 \) holds true. Otherwise, LHC direct searches for sparticles can only cover a portion of the low \( \tan \beta \) solutions, while searches for gluino pair production at LHC can cover nearly all of the high \( \tan \beta \) solutions. In Sec. 4, we discuss aspects of the relic abundance of dark matter.
for $b - \tau$ Yukawa-unified models. While neutralino-only dark matter can be accommodated by a variety of co-annihilation, resonance annihilation or higgsino annihilation processes, generically we expect a standard overabundance of neutralinos. Either an overabundance or an underabundance of neutralino dark matter can be brought into accord with the measured CDM abundance by invoking either additional late-decaying scalar (moduli) fields, or by invoking a Peccei-Quinn axion superfield (containing axion, saxion and axino components) which is needed anyway as a solution to the strong $CP$ problem. A summary and conclusions are presented in Sec. 5.

## 2 Calculation of sparticle mass spectra with $b - \tau$ Yukawa unification

For our calculations, we adopt the Isajet 7.80 [32, 33] SUSY spectrum generator Isasugra. Isasugra begins the calculation of the sparticle mass spectrum with input $\overline{DR}$ gauge couplings and $f_b, f_\tau$ Yukawa couplings at the scale $Q = M_Z$ ($f_t$ running begins at $Q = m_t$) and evolves the 6 couplings up in energy to scale $Q = M_{GUT}$ (defined as the value $Q$ where $g_1 = g_2$) using two-loop RGEs. We do not strictly enforce the unification condition $g_3 = g_1 = g_2$ at $M_{GUT}$, since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [34]. At $Q = M_{GUT}$, the SSB boundary conditions are input, and the set of 26 coupled two-loop MSSM RGEs [35] are evolved back down in scale to $Q = M_Z$. Full two-loop MSSM RGEs are used for soft term evolution, while the gauge and Yukawa coupling evolution includes threshold effects in the one-loop beta-functions, so the gauge and Yukawa couplings transition smoothly from the MSSM to SM effective theories as different mass thresholds are passed. In Isajet 7.80, the values of SSB terms which mix are frozen out at the scale $Q \equiv M_{SUSY} = \sqrt{m_{\tilde{t}_L}m_{\tilde{t}_R}}$, while non-mixing SSB terms are frozen out at their own mass scale [33]. The scalar potential is minimized using the RG-improved one-loop MSSM effective potential evaluated at an optimized scale $Q = M_{SUSY}$ which accounts for leading two-loop effects [36]. Once the tree-level sparticle mass spectrum is computed, full one-loop radiative corrections are calculated for all sparticle and Higgs boson masses, including complete one-loop weak scale threshold corrections for the top, bottom and tau masses at scale $Q = M_{SUSY}$ [37]. These fermion self-energy terms are critical to evaluating whether or not Yukawa couplings do indeed unify [38]. Since the GUT scale Yukawa couplings are modified by the threshold corrections, the Isajet RGE solution must be imposed iteratively with successive up-down running until a convergent sparticle mass solution is found. For most of parameter space, there is excellent agreement between Isajet and the SoftSUSY, SuSpect and Spheno codes, although at the edges of parameter space agreement between the four codes typically diminishes [39].

We searched for Yukawa-unified solutions in the $SU(5)$ parameter space (3) in two stages. First, we performed the MCMC scan [16, 40] over the large parameter range

\[
\begin{align*}
    m_{10}, m_5, m_{H_u}, m_{H_d} : & \quad 0 - 20 \text{ TeV}, \\
    m_{1/2} : & \quad 0 - 2 \text{ TeV}, \\
    -60 \text{ TeV} < A_t, A_b < 60 \text{ TeV}, \\
    \tan \beta : & \quad 1.1 - 60.
\end{align*}
\]

\[6\] These three codes invoke an “all-at-once” transition from MSSM to SM effective theories in contrast to the Isasugra approach.
We identify several solutions with good $b - \tau$ Yukawa unification ($R \leq 10\%$) and the neutralino Relic Density $\Omega_{\tilde{\chi}^0} h^2$ within the WMAP bound [41]. Those solutions become centers of second-stage scans with narrower parameter ranges, where we look for more solutions with good $b - \tau$ Yukawa unification, good $\Omega_{\tilde{\chi}^0} h^2$ and try to make the spectra as light as possible. Each generated parameter set is entered into Isasugra using the non-universal SUGRA model inputs, and our initial selection criteria is that the points generate a neutralino $\tilde{\chi}^0_1$ as lightest MSSM particle, and appropriate REWSB. In plots to follow, these points are labeled with gray color.

We next require the following bounds (inspired by LEP2/Tevatron searches) on sparticle masses:

- $m_{h} > 114.4 \text{ GeV}$,
- $m_{\tilde{t}_1}, m_{\tilde{b}_1} > 100 \text{ GeV}$,
- $m_{\tilde{\tau}_1} > 105 \text{ GeV}$,
- $m_{\tilde{g}} > 250 \text{ GeV}$,
- $m_{\tilde{\chi}^\pm_1} > 103 \text{ GeV}$.

Using Isatools [42, 43] and [44], we also require the following bounds from heavy flavor ($B$-physics)

to be respected:

- $BF(B_s \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-8}$ [45],
- $2.85 \times 10^{-4} < BF(b \rightarrow s\gamma) < 4.24 \times 10^{-4}$ [46],
- $0.15 \leq BF^{SUSY}(B_u \rightarrow \tau \nu_{\tau})/BF^{SM}(B_u \rightarrow \tau \nu_{\tau}) \leq 2.41$ [46].

Points passing both mass and $B$-physics cuts are labeled as red or green.

For each solution, we calculate the degree of $b - \tau$ Yukawa unification at the GUT scale via the $R$-parameter:

$$R = \frac{\max(f_b, f_\tau)}{\min(f_b, f_\tau)}.$$  \hspace{1cm} (9)

Thus, $R = 1.0$ would tag a solution with perfect $b - \tau$ Yukawa coupling unification.

3 Results

3.1 $SU(5)$ parameters required by $b - \tau$ unification

Our first results are shown in Fig. 1. In Fig. 1a), we plot the value of $R$ vs. $\tan \beta$. Points with $R \lesssim 1.05$ have a high degree of $f_b - f_\tau$ Yukawa unification. We see immediately that the solutions break up into two classes: low $\tan \beta \sim 3 - 11$ and high $\tan \beta \sim 35 - 60$. We color code the resulting points according to this criteria: red points have $\tan \beta < 20$ and green points have $\tan \beta > 20$. Apparently no $b - \tau$ unified points can be generated for $11 < \tan \beta < 35$ which satisfy the mass and $B$-physics bounds.

We will first discuss the low $\tan \beta \sim 3 - 11$ solutions. From Fig. 1b) and c), we see that this class of solutions requires $m_{10} \sim 1 - 4 \text{ TeV}$ and $m_5 \sim 1 - 5 \text{ TeV}$. In addition, from frame d), we see that rather large values of $m_{1/2} \sim 0.6 - 1.5 \text{ TeV}$ are required. Such high $m_{1/2}$ values
Figure 1: $b-\tau$ Yukawa unification as function of model parameters for $\mu > 0$ and $m_t = 173.3$ GeV. Gray points satisfy REWSB and neutralino as LSP conditions. Red and green points satisfy additional sparticle mass and $B$-physics bounds and have $\tan \beta < 20$ and $\tan \beta > 20$, respectively. The horizontal dashed line indicates the 5% Yukawa unification.
lead to gluinos with $m_\tilde g \gtrsim 1.3$ TeV. Moreover, as noted above, if we insist that $R \leq 1.05$, there is a clear distinction between low and high tan $\beta$ solutions. However, if we relax this condition ($R \gtrsim 1.3$), this distinction between the low and high tan $\beta$ solutions disappears. Another point to note is that here we have $b - \tau$ unified solutions for low tan $\beta$. Such solutions are ruled out in the CMSSM because of the Higgs mass bound [47]. In our scans we find solutions with tan $\beta$ as low as 3.5. This limit can be slightly changed by varying $m_t$ and $m_b$. From frames e) and f), we see that $R < 1.05$ solutions require the GUT-scale trilinear SSB parameters to be in the range $-2.3m_{10} < A_t < 0$ and $A_b \sim (10 - 20)m_5$. The latter parameter $A_b(M_{\text{GUT}})$ again strongly differentiates between the low and high tan $\beta$ solutions. The low tan $\beta$ solutions are characterized by $f_b \simeq f_\tau \sim 0.04$ at the GUT scale, while $f_t(M_{\text{GUT}}) \sim 0.5$, i.e. there is a large disparity between $f_t$ and $f_b \simeq f_\tau$. This class of models might be indicative of an $SU(5)$ GUT theory, but with no connection to $SO(10)$ (unless we proceed to $SO(10)$ models where the MSSM Higgs doublets live in separate $10$s of $SO(10)$ [10]).

In contrast, from Fig. 1 we see the green points with tan $\beta \sim 35 - 60$ require $m_{10} \sim m_5 \sim 5 - 20$ TeV, i.e. these solutions require multi-TeV matter scalars just as do SUSY models with $t - b - \tau$ Yukawa unification [15, 16, 48]. Furthermore, we see from frame d) that the high tan $\beta$ points require much lower values of $m_{1/2} \lesssim 0.7$ TeV, which leads to an upper bound on the gluino mass of $m_\tilde g \lesssim 2$ TeV. From frame e), we find that $-2.8m_{10} < A_t < -1.8m_{10}$, with also a few solutions around $A_t \sim 2.2m_{10}$. In frame f), we see that $A_b$ is much less correlated, with $|A_b| \lesssim 3 m_3$. The high tan $\beta \sim 45 - 55$ solutions also tend to have a high degree of $f_t \simeq f_b \simeq f_\tau \sim 0.55$ unification, whereas the solutions with tan $\beta \sim 35 - 45$ tend to have $f_t \sim 0.55$, but $f_b \simeq f_\tau \sim 0.47$. These latter solutions might be indicative of an $SO(10)$ SUSY GUT which has broken to $SU(5)$ at a higher mass scale than where $SU(5)$ breaks to the SM gauge group.

In Table 1, we list low tan $\beta$ and high tan $\beta$ benchmark solutions for illustration. Points 1 and 2 belong to the set of low tan $\beta$ Yukawa unified points and also represent $A$-resonance and sbottom co-annihilation scenarios. Points 3 and 4 are representative of high tan $\beta$ Yukawa unified solutions, where point 3 depicts a stop co-annihilation solution, while point 4 shows a large $\Omega h^2$ value.

### 3.2 $SU(5)$ preferred masses

We next proceed to examine some derived parameters associated with the Higgs/higgsino sector from SUSY models with $b - \tau$ unification. In Fig. 2a), we show the correlation of the degree of the Yukawa unification with the parameter $\mu$. The magnitude of $\mu$ is determined by minimization conditions on the Higgs scalar potential. Here, we see that the low tan $\beta$ solutions also give rise to a range $\mu \sim 0 - 5$ TeV: i.e. $\mu$ is bounded from above, and furthermore $\mu$ can be well below the 1 TeV scale. This may allow for the lightest neutralino $\tilde \chi^0_1$ to be of mixed bino-higgsino type, which gives rise to WMAP-allowed values of thermal neutralino relic abundance. However, the high tan $\beta$ solutions require rather large values of $\mu$, typically in the multi-TeV range, so that for these solutions we would expect the $\tilde \chi^0_1$ state to be a nearly pure bino. Here too we can see the separation of low and high tan $\beta$ solutions for $R \lesssim 1.05$.

In frame b), we show correlations of the $R$-parameter with the mass of the $CP$-odd Higgs boson $A$. The low tan $\beta$ solutions require $m_A \sim 0 - 6$ TeV. The rather low range of $m_A$ may allow for neutralino annihilation through the $A$-resonance in the early universe. Note that for low tan $\beta$ values, we can have LHC accessible solutions for $m_A$ if we require $b - \tau$ unification better than 5%. Meanwhile, the high tan $\beta$ solutions tend to have $m_A$ inhabiting the multi-TeV range,
Figure 2: $R_{\text{br}}$ versus parameters in the Higgs sector for $\mu > 0$ and $m_t = 173.3$ GeV. The color coding is the same as in Fig. 1.
| Point  | Point 2 | Point 3 | Point 4 |
|--------|---------|---------|---------|
| $m_{10}$ | 2604 | 3849 | 18380 | 16800 |
| $m_\tau$ | 3443 | 900.1 | 16450 | 18960 |
| $m_{1/2}$ | 1049 | 1056 | 292.6 | 358.6 |
| $\tan \beta$ | 8.3 | 4.77 | 42.4 | 45 |
| $A_t$ | -5140 | -7455 | -4484 | -39510 |
| $A_b = A_\tau$ | 41070 | 40830 | -8170 | 23640 |
| $m_{H_u}$ | 3424 | 905 | 1850 | 17340 |
| $m_{H_d}$ | 1380 | 4700 | 14150 | 10410 |
| $\text{sign}(\mu)$ | + | + | + | + |
| $f_t(M_{\text{GUT}})$ | 0.496 | 0.518 | 0.555 | 0.567 |
| $f_b(M_{\text{GUT}})$ | 0.058 | 0.033 | 0.474 | 0.542 |
| $f_\tau(M_{\text{GUT}})$ | 0.059 | 0.034 | 0.485 | 0.542 |
| $m_h$ | 120.9 | 119.6 | 125.1 | 125.2 |
| $m_A$ | 2934 | 2345 | 17562 | 17394 |
| $\mu$ | 1049 | 905 | 1850 | 17340 |
| $m_{3/2}$ | 541, 882 | 2857, 2859 | 2291, 2295 | 16406, 16406 |
| $m_{\chi^0_{1,2}}$ | 881, 2857 | 887, 2311 | 368, 17075 | 16429 |
| $m_{\tilde{g}}$ | 2385 | 2431 | 17562 | 17394 |
| $m_{\tilde{b}_{1,2}}$ | 3314, 3211 | 4336, 4405 | 18374, 18265 | 16788, 16608 |
| $m_{\tilde{q}_{1,2}}$ | 1211, 1798 | 1007, 2825 | 215, 10165 | 3289, 7153 |
| $m_{\tilde{l}_{1,2}}$ | 3315, 3984 | 4337, 2033 | 18374, 16488 | 16788, 19095 |
| $m_{\tilde{e}}_{1,2}$ | 3479, 2719 | 1321, 3731 | 16319, 18556 | 18850, 17052 |
| $m_{\chi^\pm_{1,2}}$ | 876, 2939 | 803, 341 | 14263, 14864 | 11256, 16464 |
| $\Omega_{\tilde{h}} h^2$ | 0.113 | 0.074 | 0.11 | 2269 |
| $\langle \sigma v \rangle(v \rightarrow 0) \ [cm^3/s]$ | 3.886×10^{-27} | 9.512×10^{-29} | 1.684×10^{-26} | 4.385×10^{-31} |
| $\sigma_{S}^{\nu}(\chi^0_{p}) \times 10^{12} \ [pb]$ | 5.639 | 9.689 | 1.640 | 0.127 |
| $a_{\chi^0_{p}}^{\nu, SUSY} \times 10^{10}$ | 0.134 | 0.239 | 0.015 | 0.013 |
| $BF(b \rightarrow s\gamma) \times 10^{4}$ | 3.319 | 3.501 | 3.059 | 3.038 |
| $BF(B_S \rightarrow \mu \mu) \times 10^{9}$ | 3.826 | 3.838 | 3.867 | 3.903 |

Table 1: Input parameters and resulting mass spectra and rates for several sample points from the scan. All masses and dimensionful parameters are in GeV units.

so that $A$ resonance annihilation is unlikely to be a possibility.

In frames $c)$ and $d)$, we plot $R$ as function of the mass of the light $CP$-even Higgs boson $h$ for low $\tan \beta$ (red) and high $\tan \beta$ (green) solutions, respectively. In this case, we see that the low $\tan \beta$ solutions require $m_h \lesssim 123$ GeV, with $m_h$ usually much lower. Meanwhile, the large $\tan \beta$ solutions allow for $m_h \sim 123 – 133$ GeV. Recently, some evidence has been reported from the Atlas and CMS experiments [49, 50, 51] for a SM-like Higgs boson very near to $\sim 125$ GeV. If this result is maintained by the factor of 4-6 more data from LHC expected in 2012, then it would likely rule out the low $\tan \beta b – \tau$ unified solutions, while maintaining consistency with the
high tan $\beta$ solutions!

Because good $b - \tau$ Yukawa unification requires large values of SSB masses, $m_3 \geq 1$ TeV, first and second generation sleptons are rather heavy with masses greater than $\sim 1$ TeV ($\gtrsim 4$ TeV for high tan $\beta$ values). This leads to the large suppression of the SUSY contribution to the muon anomalous magnetic moment $(g-2)_\mu$ that arises at 1-loop level from diagrams involving smuon and muon sneutrino. As result $a_\mu^{\text{SUSY}}$ values, that we computed using the IsaAMU [52] subroutine, is always several orders of magnitude below the extracted discrepancy $\Delta a_\mu = (28.7\pm8.0) \times 10^{-10}$ [53]. This can be seen in several sample points we listed in Table 1.

3.3 Prospects for LHC SUSY searches

In this section, we discuss prospects for detection of $b - \tau$ Yukawa-unified SUSY at the CERN LHC $pp$ collider with either $\sqrt{s} = 7$ or 14 TeV. In Fig. 3, we show solutions which pass the mass and $B$-physics cuts - but also with $R < 1.05$ - in the $m_{\tilde{g}}$ vs. $m_{\tilde{q}}$ plane. The value of $m_{\tilde{g}}$ is meant to exhibit a typical first/second generation squark mass. The red low $\tan \beta$ points all have $m_{\tilde{g}} > 1$ TeV with $m_{\tilde{q}} \sim 1.5 - 5$ TeV. In this case, we find $m_{\tilde{q}} \sim m_{\tilde{g}}$ or slightly heavier. The reach of LHC with $\sqrt{s} = 7$ TeV and 20 fb$^{-1}$ (LHC7) extends to $m_{\tilde{g}} \sim m_{\tilde{q}} \sim 1.5$ TeV [24], while LHC with $\sqrt{s} = 14$ TeV and 100 fb$^{-1}$ extends to $m_{\tilde{g}} \sim m_{\tilde{q}} \sim 3$ TeV [54]. Thus, about half the red points will be within reach of LHC14, while those with $m_{\tilde{q}} > 3$ TeV and $m_{\tilde{g}} > 2$ TeV will likely be beyond LHC14 reach. LHC luminosity or energy upgrades will be necessary to probe more deeply into the low tan $\beta$ Yukawa-unified space of solutions.

In the case of high tan $\beta$ solutions (green points), we see that $m_{\tilde{q}}$ exceeds - and frequently far exceeds - 5 TeV. Meanwhile, the gluino mass is bounded from above, with $m_{\tilde{g}}$ almost always $< 2$ TeV. In this case, LHC searches will focus on gluino pair production [55]. For $m_{\tilde{q}} \gg m_{\tilde{g}}$, the LHC7 reach is to $m_{\tilde{g}} \sim 1$ TeV [24], while LHC14 reach is to $m_{\tilde{g}} \sim 1.7$ TeV [54]. Recent work on LHC signatures in the case where $m_{\tilde{q}} \gg m_{\tilde{g}}$ implies the maximal LHC14 reach in models with gaugino mass unification is to $m_{\tilde{g}} \sim 2$ TeV in the $\chi^0_{1,2} \rightarrow \tau E_T$ channel [56]. Thus, we expect LHC7 to probe the region $m_{\tilde{g}} \lesssim 1$ TeV, and LHC14 to nearly cover the remaining parameter space with 100-1000 fb$^{-1}$ of integrated luminosity.

4 Dark matter relic density in $b - \tau$ unified models

It has been noted long ago that $t - b - \tau$ Yukawa-unified models tended to give a huge overabundance of thermally produced neutralino-only dark matter [15]. To this end, we adopt the IsaReD relic density calculator [59] to compute the thermally produced neutralino abundance $\Omega_{\chi^0_1} h^2$ from $b - \tau$ unified models. The value of $\Omega_{\chi^0_1} h^2$ versus $m_{\chi^0_1}$ is plotted for solutions with $R < 1.05$ in Fig. 4. The red solutions with low tan $\beta$ span a range $10^{-3} < \Omega_{\chi^0_1} h^2 < 10^2$. The large tan $\beta$ solutions populate a much larger range of $10^{-3} < \Omega_{\chi^0_1} h^2 < 10^5$ owing to the suppression of $\chi^0_1$ pair annihilation by exchange of multi-TeV scalars in the relevant Feynman diagrams. This is to be compared with the CDM abundance $\Omega_{\text{CDM}} h^2 = 0.1109 \pm 0.0056$ reported by WMAP7 [41], which we indicate as a horizontal black line.

[57] In Ref. [57], it is suggested that $A$-resonance annihilation may be available for bring neutralino-only CDM into its measured range. However, a number of other authors have failed to reproduce $t - b - \tau$ unified solutions with very low $m_A$ values such that $2m_{\chi^0_1} \sim m_A$ [15, 16, 58].
Figure 3: Distribution of points from the scan in the mass plane of gluino and 1st/2nd generation squarks for $\mu > 0$ and $m_t = 173.3$ GeV. Gray points satisfy REWSB and neutralino as LSP conditions. Red and green points satisfy additional mass bounds, $B$-physics bounds, have $R < 1.05$ and represent $\tan \beta < 20$ and $\tan \beta > 20$, respectively. The dashed lines represent approximate reaches for LHC7.

Figure 4: Neutralino relic density $\Omega_{\tilde{\chi}_0} h^2$ versus the neutralino mass $m_{\tilde{\chi}_0}$ from the scan with $\mu > 0$. All points satisfy mass bounds, $B$-physics bounds and have $R < 1.05$. Red and green color represent solutions with $\tan \beta < 20$ and $\tan \beta > 20$, respectively. The solid horizontal line represents the WMAP measured value [41].
For the low tan $\beta$ case, it is possible to gain solutions with $A$-resonance annihilation, higgsino annihilation or stop, sbottom or stau co-annihilation. For these processes to be significant, certain mass conditions needs to be fulfilled: the mass gap between $\tilde{\chi}_1^0$ and the next lightest sparticle needs to be within $\sim 15\%$ for coannihilation or $m_{\tilde{\chi}_1^0} \sim 2m_A$ for $A$-resonance annihilation. For higgsino annihilation, $\tilde{\chi}_1^0$ needs a sizable higgsino content, which makes it close in mass with the chargino $\tilde{\chi}_1^\pm$, and the ratio $m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_1^\pm}$ needs to be within $\sim 15\%$ for coannihilation or $m_{\tilde{\chi}_1^0} \sim 2m_A$ for $A$-resonance annihilation. For higgsino annihilation, $\tilde{\chi}_1^0$ needs a sizable higgsino content, which makes it close in mass with the chargino $\tilde{\chi}_1^\pm$, which is a higgsino-wino mixture. This is illustrated in Fig. 5, where we show solutions with $R < 1.05$ in the a) $m_{\tilde{t}_1}$ vs. $m_{\tilde{\chi}_1^0}$ plane, the b) $m_{\tilde{b}_1}$ vs. $m_{\tilde{\chi}_1^0}$ plane, c) the $m_{\tilde{b}_1}$ vs. $m_{\tilde{\chi}_1^\pm}$ plane, d) the $m_{\tilde{\chi}_1^\pm}$ vs. $m_{\tilde{\chi}_1^0}$ plane. In each case, the approximate needed conditions for co-annihilation, resonance annihilation or mixed higgsino annihilation are illustrated by diagonal black lines. The neutralino-sbottom co-annihilation solutions shown in Fig. 5c) are consistent with the results presented in Ref. [60], where it is shown that it is not trivial to have such a scenario. One needs to go to the more flexible $SU(5)$ GUT scale boundary conditions to realize such solutions.

For the high tan $\beta$ case, the value of $\Omega_{\chi_1^0} h^2$ tends to be very high, well over $\Omega_{\chi_1^0} h^2 \sim 1$. We see that there are no solutions with sbottom and stau coannihilation, as shown in Figs. 5b) and c). This is because Yukawa unification requires $A_b = A_t \simeq 0$ at $M_{GUT}$, which combined with large SSB mass-squared parameters result in $\tilde{b}_1$ and $\tilde{\tau}_1$ heavier than $\sim 3$ TeV, much larger than the $\tilde{\chi}_1^0$ mass. However, dedicated scans can find some solutions where stop co-annihilation does occur [47], as shown in Fig. 5a). These solutions tend to be very fine-tuned, since a large value of weak scale $A_t$ must be generated which pushes a normally several-TeV $\tilde{t}_1$ state into the range where $m_{\tilde{t}_1} \sim m_{\tilde{\chi}_1^0}$.

We note here that solutions with a neutralino overabundance may be brought into accord with the WMAP measured value of CDM by at least two methods.

1. The $\tilde{\chi}_1^0$ may not in fact be the LSP, but instead decays into a (usually) much lighter state. This occurs in models with mixed axion/axino ($a\tilde{a}$) dark matter [61], where $\chi_1^0 \rightarrow \gamma\tilde{a}$. Then the neutralino abundance is converted into an axino abundance with [62] $\Omega_{\tilde{a}} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1^0}} \Omega_{\chi_1^0} h^2$. If $m_{\tilde{a}} \sim$ MeV scale, then the ratio $m_{\tilde{a}}/m_{\tilde{\chi}_1^0}$ can reduce the putative neutralino mass abundance by many orders of magnitude. In this case of mixed $a\tilde{a}$ CDM, axion-domination tends to be favored [63].

2. If additional late decaying scalar fields are present in the model, they may get produced at large rates via coherent oscillations. If they temporarily dominate the energy density of the universe, and then decay to mainly SM particles, they may inject considerable entropy into the cosmic soup, thus diluting all relics which are present at the time of decay. Entropy injection can occur at large rates for instance from saxion production in the Peccei-Quinn augmented MSSM [64, 65], or from moduli production and decay, as is expected in string theory [66].

In the cases where the neutralino relic abundance is too low – e.g., the low tan $\beta$ higgsino line of solutions at $\Omega_{\tilde{\chi}_1^0} h^2 \sim 10^{-3}$ in Fig. 4 – then the neutralino abundance can be augmented in the PQMSSM case where $m_{\tilde{a}} > m_{\tilde{\chi}_1^0}$, and additional neutralinos are produced via thermal axino production and decay $\tilde{a} \rightarrow \gamma\tilde{\chi}_1^0$, or via saxion cascade decays [65]. In these cases, the CDM tends to be neutralino dominated with a small component of axions.
Figure 5: Distribution of points from the scan in various planes of sparticles/Higgs masses for \( \mu > 0 \) and \( m_t = 173.3 \) GeV. All points satisfy mass bounds, B-physics bounds and have \( R < 1.05 \) and \( \Omega h^2 < 0.139 \). Red and green color represent solutions with \( \tan \beta < 20 \) and \( \tan \beta > 20 \), respectively. Diagonal black lines represent approximate mass conditions for sizable coannihilation or resonance pair annihilation of neutralinos.
5 Conclusions

In this paper, we have used the Isasugra sparticle mass calculator to explore the possibility of $b-\tau$ Yukawa-unified solutions as would be expected to occur in minimal $SU(5)$ SUSY GUT theories. Our main assumption is that $SU(5)$ breaks at $Q = M_{GUT}$ to the MSSM as the low energy effective theory, so that soft SUSY breaking terms are related by $SU(5)$ boundary conditions at the GUT scale. This could occur for instance in $4-d$ models with GUT symmetry breaking via the Higgs mechanism, or in extra dimensional GUTs where $SU(5)$ is broken via extra-dimensional compactification on perhaps an orbifold. We search for sparticle mass spectra which maintain $f_b \simeq f_\tau$ at $M_{GUT}$.

We have found two sets of solutions. At low $\tan\beta$, the solutions are characterized by $f_b \simeq f_\tau \sim 0.04$, while $f_t \sim 0.55$. These solutions have $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 1 - 3$ TeV, and only a portion of solution space will be accessible to LHC14 searches. A variety of mechanisms are available so that thermal production of neutralino CDM may occur in the early universe and generate a dark matter abundance at the measured value. However, these low $\tan\beta$ Yukawa-unified solutions tend to have $m_h < 123$ GeV, and so may be ruled out if the Atlas/CMS preliminary evidence for a Higgs with $m_h \simeq 125$ GeV persists.

The large $\tan\beta \sim 35 - 60$ solutions exhibit many of the characteristics of $t-b-\tau$ unified solutions which are expected to occur in $SO(10)$ SUSY GUTs. Our solutions tend to have $f_b \simeq f_\tau$, but with a small mis-match with $f_t$. These solutions tend to have multi-TeV matter scalars, but $m_{\tilde{g}} \lesssim 2$ TeV. Thus, they relax somewhat the tendency that $m_{\tilde{g}} \lesssim 500$ GeV as occurs in $t-b-\tau$ unified models with gaugino mass unification and $\mu > 0$. This class of models should lead ultimately to detection of gluino pair events at either LHC7 or LHC14. They tend to overproduce neutralino dark matter except in the (unlikely) case where top-squark co-annihilation may occur.

The cases of neutralino dark matter overproduction can be brought into accord with astrophysical measurements by invoking further neutralino decays (for instance decay to an axino LSP), or via entropy dilution of any relics by saxion or moduli decays.

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