125 GeV Higgs Boson from $t$-$b$-$\tau$ Yukawa Unification

Ilia Gogoladze$^1$, Qaisar Shafi$^2$ and Cem Salih Ün $^3$

Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

Abstract

We identify a class of supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ models in which imposing essentially perfect $t$-$b$-$\tau$ Yukawa coupling unification at $M_{GUT}$ yields a mass close to 122-126 GeV for the lightest CP-even (SM-like) Higgs boson. The squark and gluino masses in these models exceed 3 TeV, but the stau and charginos in some cases can be considerably lighter. We display some benchmark points corresponding to neutralino-stau and bino-wino coannihilations as well as A-resonance. The well-known MSSM parameter $\tan \beta$ is around 46-52.

---

$^1$E-mail: ilia@bartol.udel.edu

On leave of absence from: Andronikashvili Institute of Physics, 0177 Tbilisi, Georgia.

$^2$E-mail: shafi@bartol.udel.edu

$^3$E-mail: cemsalihun@bartol.udel.edu
1 Introduction

In a recent paper, hereafter referred to as [1], we explored the LHC implications of a supersymmetric $SO(10)$ model with third family Yukawa coupling unification [2, 3, 4] and $SO(10)$ compatible gaugino mass ratio at $M_{\text{GUT}}$ given by $M_3 : M_2 : M_1 = 2 : -3 : -1$ [5]. Here $M_3$, $M_2$ and $M_1$ respectively stand for $SU(3)_c$, $SU(2)_L$ and $U(1)_Y$ soft supersymmetry breaking (SSB) gaugino masses. It was also assumed in [1] that the SSB mass terms for the up and down type Higgs doublets of the minimal supersymmetric standard model (MSSM) are universal at $M_{\text{GUT}}$. It was shown in [1] that $t$-$b$-$\tau$ Yukawa coupling unification and neutralino dark matter abundance are readily compatible with each other in this $SO(10)$ model, and a prediction of $122 - 124$ GeV for the lightest CP-even Higgs mass (with a theoretical uncertainty of $\pm 3$ GeV [6]) was highlighted.

Spurred by these results, we investigate here $t$-$b$-$\tau$ Yukawa coupling unification in the framework of supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ (4-2-2, for short). The 4-2-2 structure [7] allows us to consider non-universal gaugino masses, while preserving Yukawa coupling unification and universality of the up and down type SSB Higgs masses. Previously, $t$-$b$-$\tau$ Yukawa unification in the framework of 4-2-2 was investigated in [8, 9, 10], where non-universal up and down type SSB Higgs masses were assumed. An important conclusion reached in [8, 9] is that with same sign non-universal gaugino soft mass terms and $\mu > 0$, where $\mu$ denotes the coefficient of the bilinear Higgs mixing term, Yukawa unification in 4-2-2 is compatible with neutralino dark matter, with gluino co-annihilation [8, 9, 11, 12] being the unique dark matter scenario.

By considering opposite sign gauginos such that $\mu < 0$, $M_2 < 0$ and $M_3 > 0$, it is shown in [10] that Yukawa coupling unification consistent with the experimental constraints can be implemented in 4-2-2. Yukawa coupling unification in this case is achieved for $m_{16} \gtrsim 300$ GeV, as opposed to $m_{16} \gtrsim 8$ TeV for the case of same sign gauginos. The finite corrections to the b-quark mass play an important role here [10]. With $M_2 < 0$, $M_3 > 0$ and $\mu < 0$ in 4-2-2, we can also obtain additional contributions with the correct sign for the muon anomalous magnetic moment [13]. This enables us to simultaneously satisfy the requirements of $t$-$b$-$\tau$ Yukawa unification, neutralino dark matter abundance and constraints from $(g - 2)_\mu$, as well as a variety of other bounds.

A crucial difference between this paper and previous studies of 4-2-2 with $t$-$b$-$\tau$ Yukawa unification is the universality of the up and down type SSB Higgs masses assumed here. As we will see, the condition $m_{H_u}^2 = m_{H_d}^2$ at $M_{\text{GUT}}$ significantly reduces the range of allowed masses for the lightest CP-even Higgs boson. With $m_{H_u}^2 \neq m_{H_d}^2$ and imposing $t$-$b$-$\tau$ Yukawa unification in 4-2-2, one finds $80$ GeV $\lesssim m_h \lesssim 128$ GeV. However, in our present model, this range shrinks to $122$ GeV $\lesssim m_h \lesssim 126$ GeV [10], which is in good agreement with the recently reported evidence from the ATLAS and
CMS experiments [14, 15] for a Higgs boson of mass around 125 GeV.

The outline for the rest of the paper is as follows. In Section 2 we briefly describe the SSB terms in the 4-2-2 model. In Section 3 we summarize the scanning procedure and the experimental constraints that we have employed. In Section 4 we present our results, focusing in particular on the mass of the lightest (SM-like) CP-even Higgs boson. The squarks and gluino turn out to be relatively heavy, \( \gtrapprox 3 \text{ TeV} \). However, the stau and chargino in some cases can be considerably lighter. The table in this section highlights some benchmark points which can be tested at the LHC. Our conclusions are summarized in Section 5.

2 Supersymmetric 4-2-2 and SSB Terms

In 4-2-2 the 16-plet of SO(10) matter fields consists of \( \psi (4, 2, 1) \) and \( \psi_c (4, 1, 2) \). The third family Yukawa coupling \( \psi_c \psi H \), where \( H(1,2,2) \) denotes the bi-doublet \( (1,2,2) \), yields the following relation at \( M_{\text{GUT}} [2] \):

\[
Y_t = Y_b = Y_\tau = Y_{\nu_\tau}.
\]

Supplementing 4-2-2 with a discrete left-right (LR) symmetry [7, 16] (more precisely C-parity) [17] reduces the number of independent gauge couplings in 4-2-2 from three to two. This is because C-parity imposes the gauge coupling unification condition, \( g_L = g_R \) at \( M_{\text{GUT}} \). We will assume that due to C-parity the SSB mass terms, induced at \( M_{\text{GUT}} \) through gravity mediated supersymmetry breaking [18], are equal in magnitude for the squarks and sleptons of the three families. The tree level asymptotic SSB gaugino masses, on the other hand, can be non-universal from the following consideration. From C-parity, we can expect that the gaugino masses at \( M_{\text{GUT}} \) associated with \( SU(2)_L \) and \( SU(2)_R \) are the same \( (M_2 \equiv M^R_2 = M^L_2) \). However, the asymptotic \( SU(4)_c \) and consequently \( SU(3)_c \) SSB gaugino masses can be different. With the hypercharge generator in 4-2-2 given by \( Y = \sqrt{2/5} \ (B - L) + \sqrt{3/5} \ I_3R \), where \( B - L \) and \( I_3R \) are the diagonal generators of \( SU(4)_c \) and \( SU(2)_R \), we have the following asymptotic relation among the three SSB gaugino masses:

\[
M_1 = \frac{3}{5} M_2 + \frac{2}{5} M_3.
\]

The supersymmetric 4-2-2 model with C-parity that we consider thus has two independent parameters \( (M_2 \text{ and } M_3) \) in the gaugino sector.

As was pointed out in ref [1], with non-universal gaugino masses at \( M_{\text{GUT}} \), radiative electroweak symmetry breaking (REWSB) compatible with perfect or near-perfect \( t\bar{b}\tau \) Yukawa unification can occur even if we set \( m_{H_u} = m_{H_d} \). Note that this is quite difficult, if not impossible, to achieve if gaugino mass universality is imposed at \( M_{\text{GUT}} \) [19].
The fundamental parameters of the 4-2-2 model that we consider are as follows:

\[ m_{16}, m_{10}, M_2, M_3, A_0, \tan \beta, \text{sign}(\mu). \] (3)

Here \( m_{16} \) is the universal SSB mass for MSSM sfermions, \( m_{10} \) is the universal SSB mass for MSSM Higgs doublets, \( A_0 \) is the universal coupling of the SSB terms for the trilinear scalar interactions (with the corresponding Yukawa coupling factored out), \( \tan \beta \) is the ratio of the vacuum expectation values (VEVs) of the two MSSM Higgs doublets, and the magnitude of \( \mu \), but not its sign, is determined by the REWSB condition. Although not necessary, we will assume that the gauge coupling unification condition \( g_3 = g_1 = g_2 \) holds at \( M_{GUT} \) in 4-2-2. Such a scenario can arise, for example, from a higher dimensional \( SO(10) \) model [20], or from a \( SU(8) \) model after suitable compactification [21].

3 Experimental Constraints, Scanning Procedure and Parameter Space

We employ the ISAJET 7.80 package [22] to perform random scans over the fundamental parameter space. In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to \( M_{GUT} \) 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 \( M_{GUT} \), since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [23]. The deviation between \( g_1 = g_2 \) and \( g_3 \) at \( M_{GUT} \) is no worse than \( 3-4\% \). For simplicity, we do not include the Dirac neutrino Yukawa coupling in the RGEs, whose contribution is expected to be small.

The various boundary conditions are imposed at \( M_{GUT} \) and all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale \( M_Z \). In the evolution of Yukawa couplings the SUSY threshold corrections [24] are taken into account at the common scale \( M_{SUSY} = \sqrt{m_{\tilde{t}_L}m_{\tilde{t}_R}} \), where \( m_{\tilde{t}_L} \) and \( m_{\tilde{t}_R} \) denote the masses of the third generation left and right-handed stop quarks. The entire parameter set is iteratively run between \( M_Z \) and \( M_{GUT} \) using the full 2-loop RGEs until a stable solution is obtained. To better account for leading-log corrections, one-loop step-beta functions are adopted for the gauge and Yukawa couplings, and the SSB parameters \( m_i \) are extracted from RGEs at multiple scales \( m_i = m_i(m_i) \). The RGE-improved 1-loop effective potential is minimized at \( M_{SUSY} \), which effectively accounts for the leading 2-loop corrections. Full 1-loop radiative corrections are incorporated for all sparticle masses.
The approximate error of $\pm 3$ GeV in the ISAJET estimation of the lightest CP-even Higgs boson mass largely arises from theoretical uncertainties [6] in the calculation and to a lesser extent from experimental uncertainties.

An important constraint on the parameter space arises from limits on the cosmological abundance of stable charged particles [25]. This excludes regions in the parameter space where charged SUSY particles become the lightest supersymmetric particle (LSP). We accept only those solutions for which one of the neutralinos is the LSP and saturates the WMAP bound on relic dark matter abundance.

We have performed random scans for the following parameter range:

\[
\begin{align*}
0 &\leq m_{16} \leq 6 \text{ TeV} \\
0 &\leq m_{10} \leq 5 \text{ TeV} \\
0 &\leq M_3 \leq 5 \text{ TeV} \\
-5 \text{ TeV} &\leq M_2 \leq 0 \\
35 &\leq \tan \beta \leq 55 \\
-3 &\leq A_0/m_{16} \leq 3 \\
\mu &< 0
\end{align*}
\]  

We set $m_t = 173.3$ GeV [26], and we show that our results are not too sensitive to one or two sigma variation from the central value of $m_t$ [27]. Note that $m_h(m_Z) = 2.83$ GeV, which is hard-coded into ISAJET.

In order to obtain the correct sign for the desired contribution to $(g - 2)_\mu$, we will focus here on the case $\mu < 0$ and $M_2 < 0$.

In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in [28]. The data points collected all satisfy the requirement of REWSB, with the neutralino in each case being the LSP. After collecting the data, we impose the mass bounds on all the particles [25] and use the IsaTools package [29] to implement the various phenomenological constraints. We successively apply the following experimental constraints on the data that we acquire from ISAJET:

\[
\begin{align*}
m_h \text{ (lightest Higgs mass)} &\geq 114.4 \text{ GeV} \quad [30] \\
BR(B_s \to \mu^+ \mu^-) &< 4.5 \times 10^{-9} \quad [31] \\
2.85 \times 10^{-4} &\leq BR(b \to s \gamma) \leq 4.24 \times 10^{-4} \quad (2\sigma) \quad [32] \\
0.15 &\leq \frac{BR(B_s \to \mu^+ \mu^-)_{\text{MSM}}}{BR(B_s \to \tau^+ \tau^-)_{\text{MSM}}} \leq 2.41 \quad (3\sigma) \quad [32] \\
\Omega_{\text{CDM}} h^2 & = 0.1123 \pm 0.0035 \quad (5\sigma) \quad [33] \\
0 &\leq \Delta (g - 2)_\mu / 2 \leq 55.6 \times 10^{-10} \quad [13]
\end{align*}
\]
Figure 1: Plots in $R - m_{16}$, $R - \tan \beta$, $R - A_0/m_{16}$ and $R - m_{10}$ planes. Gray points are consistent with REWSB and neutralino LSP. Green points satisfy particle mass bounds and constraints from $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_d \to \tau\nu\tau)$. In addition, we require that green points do no worse than the SM in terms of $(g-2)_\mu$. Brown points belong to a subset of green points and satisfy the WMAP bounds on neutralino dark matter abundance.

4 Sparticle Spectroscopy

In order to quantify Yukawa coupling unification, we define the quantity $R$ as,

$$ R = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)} $$

In Figure 1 we show the results in the $R - m_{16}$, $R - A_0/m_{16}$ and $R - m_{10}$ planes. The gray points are consistent with REWSB and neutralino LSP. The green points
Figure 2: Plots in $M_2 - M_1$, $\mu - M_1$, $M_3 - m_{16}$ and $m_{10} - m_{16}$ planes. The color coding is the same as in Figure 1. In addition, we have used yellow color to denote a subset of the green points, that have Yukawa unification better than 5%. Brown points belong to a subset of yellow points and satisfy the WMAP bounds on neutralino dark matter abundance.

satisfy particle mass bounds and constraints from $BR(B_s \rightarrow \mu^+\mu^-)$, $BR(b \rightarrow s\gamma)$ and $BR(B_u \rightarrow \tau\nu_\tau)$. In addition, the green points do no worse than the SM in terms of $(g - 2)_\mu$. The brown points belong to a subset of the green points and satisfy the WMAP bound on neutralino dark matter abundance.

In the $R - m_{16}$ plane of Figure 1, we can see realization of perfect Yukawa unification consistent with all constraints mentioned in Section 3. This is possible because we can implement Yukawa unification for relatively small values of $m_{16}$ ($\sim 1$TeV). A similar conclusion was reached in ref. [10] but with relatively lighter values for $m_{16}$. This difference is related to the additional condition $m_{H_u} = m_{H_d}$ which we have imposed in the current paper.
Figure 3: Plots in the $R - m_h$ plane. The color coding is the same as in Fig 1. In the left panel, the top mass is set equal to its current central value ($m_t = 173.3$ GeV [26]), while $1\sigma$ deviation in the top mass ($m_t = 174.4$ GeV) is considered in the right panel to investigate the effect on the CP-even light higgs mass.

Note that there is more than an order of magnitude reduction in the $m_{16}$ values required for Yukawa unification, as compared with the case $\mu > 0$ and universal gaugino masses [4, 8]. There is upper bound for $m_{16}$ once Yukawa unification is imposed. Indeed, one predicts $\tan \beta \approx 47$ for perfect Yukawa unification. In $R - A_0/m_{16}$ plane, we see that perfect Yukawa unification can occur for $A_0 < 0$, in contrast to the SO(10) case with universal gaugino mass condition where perfect Yukawa unification takes place for $A_0/m_{16} \sim 2.6$. From the $R - m_{10}$ plane we see that perfect Yukawa unification also puts an upper bound on $m_{10}$.

In Figure 2 we show the results in the $M_2 - M_1$, $\mu - M_1$, $M_3 - m_{16}$ and $m_{10} - m_{16}$ planes. The color coding is the same as in Figure 1. In addition, we have used yellow color for the subset of green points satisfying Yukawa unification to better than 5%. The brown points belong to a subset of green points which satisfy the WMAP bounds on neutralino dark matter abundance.

From the $M_2 - M_1$ plane, we see that some of the brown points lie near the line corresponding to $M_1/M_2 \approx -2$, which yields at low sale $M_\tilde{\beta} \approx M_\tilde{\nu}$, the condition for bino-wino coannihilation [34] scenario. At the same time there is no colored point near the line corresponding to $M_1/M_2 \approx 2$, which means that in our model we do not have bino-wino mixed dark matter [35].

In the $\mu - M_1$ plane we have shown lines corresponding to $\mu/M_1 = 1$ and $\mu/M_1 = -1$. The yellow points describing 5% or better Yukawa unification are far from these lines, which means that we do not have bino-higgsino mixed dark matter in this
Figure 4: Plots in the \(m_{\tilde{\tau}} - m_h\), \(m_A - m_h\), \(m_{\tilde{\chi}^\pm} - m_h\), \(m_{\tilde{t}} - m_h\), \(m_{\tilde{b}} - m_h\) and \(m_{\tilde{g}} - m_h\) planes. The color coding is the same as in Figure 1. The brown points in the \(m_{\tilde{\tau}} - m_h\) plane represent stau-neutralino coannihilation, A-funnel region in the \(m_A - m_h\) panel, bino-wino dark mater and bino-wino coannihilation in the \(m_{\tilde{\chi}^\pm} - m_h\) plane. In the \(m_{\tilde{t}} - m_h\), \(m_{\tilde{b}} - m_h\) and \(m_{\tilde{g}} - m_h\) planes, the blue points form a subset of the green points and do not satisfy Yukawa unification. Blue points represent stop-neutralino coannihilation in the \(m_{\tilde{t}} - m_h\) plane, and gluino-neutralino coannihilation in the \(m_{\tilde{g}} - m_h\) plane.
model. Accordingly, as shown in ref [36], it will be difficult to find dark matter predicted in this model in direct and indirect searches.

The $M_3 - m_{16}$ panel indicates that the minimal value of $M_3$ which corresponds to 5% or better Yukawa unification (yellow points) is above 1.5 TeV, which means that the colored particle are much heavier than 1 TeV. In particular, the minimum gluino mass is close to 3 TeV.

From the $m_{10} - m_{16}$ plane we see that one can reduce number of independent parameters, assuming $m_{16} = m_{10}$, and still retain decent Yukawa unification with the correct relic abundances.

In Figure 3, we present results in the $R - m_h$ plane for $m_t = 173.3$ GeV and $m_t = 174.4$ GeV. The color coding is the same as the one used in Figure 1. In the left panel, the top quark mass is set equal to its central value ($m_t = 173.3$ GeV [26]), and it shows that we can find solutions with $m_h \sim 125$ GeV consistent with the constraints mentioned in Section 3 as well as $t$-$b$-$\tau$ Yukawa unification. It is interesting to note that the Higgs mass interval is significantly reduced compared with the 4-2-2 model with $m_{H_u} \neq m_{H_d}$ where it lies in the interval $80$ GeV $< m_h < 129$ GeV, compatible with perfect Yukawa unification condition. In the current model, as seen from Figure 3, the Higgs mass lies in the range $118$ GeV $< m_h < 127$ GeV (gray points). This is further reduced once collider bounds and precise Yukawa unification are imposed (green points) and the range becomes $122$ GeV $< m_h < 126$ GeV, which is in very good agreement with the recent ATLAS and CMS measurements [14, 15].

As far as neutralino dark matter abundance compatible with the WMAP bound is concerned, in Figure 4 we present results in the $m_{\tilde{\tau}} - m_h$, $m_A - m_h$, $m_{\tilde{\chi}^\pm} - m_h$, $m_{\tilde{t}} - m_h$, $m_{\tilde{b}} - m_h$ and $m_{\tilde{g}} - m_h$ planes. The color coding is the same as in Figure 1. The brown points in the $m_{\tilde{\tau}} - m_h$ plane represent only stau-neutralino coannihilation, they also represent A-funnel solution in the $m_A - m_h$ panel, as well as bino-wino dark matter and bino-wino coannihilation in the $m_{\tilde{\chi}^\pm} - m_h$ plane. In the $m_{\tilde{t}} - m_h$, $m_{\tilde{b}} - m_h$ and $m_{\tilde{g}} - m_h$ planes, the blue points are a subset of the green points and do not satisfy Yukawa unification.

If the preliminary evidence for a Higgs with $m_h = 125$ GeV from ATLAS/CMS is verified, we see from the $m_{\tilde{\tau}} - m_h$ panel solutions with $200$ GeV $\lesssim m_{\tilde{\tau}} \lesssim 600$ GeV, linked to stau-neutralino coannihilation. Similarly, the $m_A - m_h$ plane shows A-funnel solutions with $500$ GeV $\lesssim m_A \lesssim 1200$ GeV. The $m_{\tilde{\chi}^\pm} - m_h$ panel shows that we have bino-wino dark matter, and bino-wino coannihilation is realized in nature with $100$ GeV $\lesssim m_{\tilde{\chi}^\pm} \lesssim 600$ GeV. We did not find solutions with neutralino-stop coannihilation compatible with 5% or better Yukawa unification. However, such solutions appear if the Yukawa unification condition is relaxed (blue points). In the $m_{\tilde{b}} - m_h$ plane we do not see either brown or blue points which shows that in the 4-2-2 model it is not easy to find neutralino-sbottom coannihilation, a scenario which is easily realized in SU(5) [37]. We also did not find neutralino-gluino coannihilation.
compatible with Yukawa unification (no brown points in the $m_{\tilde{g}} - m_h$ plane), but there are blue points which show that we can have neutralino-gluino coannihilation for NLSP gluino up to 1.5 TeV mass, if we ignore Yukawa unification.

Finally, in Table 1 we present three benchmark points which satisfy the various constraints mentioned in Section 3. Point 1 displays a solution corresponding to stau-neutralino coannihilation, point 2 depicts an A-funnel solution, point 3 stands for a solution with bino-wino coannihilation, and point 4 corresponds to a solution with $m_{t6} = m_{t0}$. Each point in Table 1 has the CP-even lightest Higgs boson mass of about 125 GeV.

5 Conclusion

We have reconsidered $t$-$b$-$\tau$ Yukawa unification in supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ within a slightly revised framework in this paper. The main difference from most previous investigations stems from the assumptions we make related to the soft supersymmetry breaking parameters. We set the masses of the two MSSM Higgs doublets to be equal at $M_{\text{GUT}}$. The ramifications of these slightly different assumptions for TeV scale physics turn out to be quite startling, with the low energy predictions being quite different from previous studies. In particular, in the present framework with $\mu$ and $M_2$ both negative, demanding perfect or near-perfect Yukawa unification yields a Higgs boson mass of 122 - 125 GeV (with an uncertainty of $\pm 3$ GeV).

The solutions, obtained using the ISAJET software, are compatible with all experimental observations, as well as the WMAP dark matter constraint. The masses of the gluino and first two family squarks are found to lie in the 2.7 - 5 TeV range, while the lightest stop (top squark) weighs at least 2 TeV or so. The MSSM parameter $\tan \beta$ is around 46 - 52.
|            | Point 1   | Point 2   | Point 3   | Point 4   |
|------------|-----------|-----------|-----------|-----------|
| $m_{16}$   | 1729      | 2777      | 2406      | 2016      |
| $M_1$      | -809      | 1262      | 1177      | -1046     |
| $M_2$      | -4180     | -685      | -633      | -4867     |
| $M_3$      | 4247      | 4183      | 3892      | 4686      |
| $m_{10}$   | 965       | 640       | 227       | 2016      |
| $\tan \beta$ | 49.2  | 48.6      | 48.2      | 48.2      |
| $A_0/m_0$  | 1.04      | -2.74     | -2.82     | -2.81     |
| $m_t$      | 173.3     | 173.3     | 173.3     | 173.3     |
| $\mu$      | -3762     | -5765     | -5305     | -4539     |
| $\Delta (g-2)_\mu$ | $0.62 \times 10^{-10}$ | $0.50 \times 10^{-10}$ | $0.59 \times 10^{-10}$ | $0.43 \times 10^{-10}$ |
| $m_h$      | 125       | 125       | 125       | 125       |
| $m_H$      | 949       | 1160      | 1197      | 1048      |
| $m_A$      | 943       | 1152      | 1190      | 1042      |
| $m_{H^\pm}$ | 954    | 1164      | 1201      | 1053      |
| $m_{\tilde{\chi}_{1,2}^0}$ | 405, 3608 | 556, 663  | 515, 614  | 508, 4188 |
| $m_{\tilde{\chi}_{3,4}^0}$ | 3769, 3795 | 5739, 5740 | 5283, 5283 | 4540, 4552 |
| $m_{\tilde{\chi}_{1,2}^\pm}$ | 3605, 3812 | 666, 5738 | 616, 5282 | 4193, 4555 |
| $m_{\tilde{g}}$ | 8496    | 8455      | 7891      | 9340      |
| $m_{\tilde{\nu}_1}$ | 7828, 7386 | 7691, 7705 | 7128, 7140 | 8674, 8138 |
| $m_{\tilde{\nu}_2}$ | 6265, 6943 | 5978, 6209 | 5579, 5800 | 6541, 7387 |
| $m_{\tilde{\mu}_{1,2}}$ | 7828, 7388 | 7692, 7706 | 7128, 7141 | 8675, 8139 |
| $m_{\tilde{\mu}_1}$ | 6430, 6903 | 6128, 6225 | 5716, 5813 | 6743, 7346 |
| $m_{\tilde{\tau}_1}$ | 3147    | 2807      | 2435      | 3650      |
| $m_{\tilde{\tau}_2}$ | 2909    | 2344      | 2037      | 3376      |
| $m_{\tilde{\chi}_{1,2}}$ | 3155, 1743 | 2810, 2810 | 2439, 2439 | 3658, 2040 |
| $m_{\tilde{\chi}_{3,4}}$ | 426, 2925 | 1617, 2330 | 1388, 2028 | 710, 3402 |
| $\sigma_{SI}$ (pb) | $0.67 \times 10^{-11}$ | $0.11 \times 10^{-11}$ | $0.11 \times 10^{-11}$ | $0.36 \times 10^{-11}$ |
| $\sigma_{SD}$ (pb) | $0.46 \times 10^{-9}$ | $0.30 \times 10^{-10}$ | $0.45 \times 10^{-10}$ | $0.20 \times 10^{-9}$ |
| $\Omega_{CDM} h^2$ | 0.26    | 0.11      | 0.11      | 1.22      |
| $R$        | 1.03      | 1.02      | 1.04      | 1.03      |

Table 1: Benchmark points for the 4-2-2 model with $\mu < 0$. Point 1 shows stau-coannihilation, point 2 represents the A-resonance solution, point 3 depicts bino-wino coannihilation, and point 4 displays a solution with $m_{16} = m_{10}$. 

References

[1] I. Gogoladze, Q. Shafi and C. S. Un, arXiv:1112.2206 [hep-ph].

[2] B. Ananthanarayan, G. Lazarides and Q. Shafi, Phys. Rev. D 44, 1613 (1991) and Phys. Lett. B 300, 24 (1993); Q. Shafi and B. Ananthanarayan, Trieste HEP Cosmol.1991:233-244.

[3] L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev. D 50, 7048 (1994); M. Olechowski and S. Pokorski, Phys. Lett. B 214, 393 (1988); T. Banks, Nucl. Phys. B 303, 172 (1988); V. Barger, M. Berger and P. Ohmann, Phys. Rev. D 49, (1994) 4908; M. Carena, M. Olechowski, S. Pokorski and C. Wagner, Nucl. Phys. B 426, 269 (1994); B. Ananthanarayan, Q. Shafi and X. Wang, Phys. Rev. D 50, 5980 (1994); G. Anderson et al. Phys. Rev. D 47, (1993) 3702 and Phys. Rev. D 49, 3660 (1994); R. Rattazzi and U. Sarid, Phys. Rev. D 53, 1553 (1996); T. Blazek, M. Carena, S. Raby and C. Wagner, Phys. Rev. D 56, 6919 (1997); T. Blazek, S. Raby and K. Tobe, Phys. Rev. D 62, 055001 (2000); H. Baer, M. Diaz, J. Ferrandis and X. Tata, Phys. Rev. D 61, 111701 (2000); H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D 63, 015007(2001); C. Balazs and R. Dermisek, JHEP 0306, 024 (2003); C. Pallis, Nucl. Phys. B 678, 398 (2004); U. Chattopadhyay, A. Corsetti and P. Nath, Phys. Rev. D 66 035003, (2002); T. Blazek, R. Dermisek and S. Raby, Phys. Rev. Lett. 88, 111804 (2002) and Phys. Rev. D 65, 115004 (2002); M. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, Phys. Rev. D 72, 095008 (2005); K. Tobe and J. D. Wells, Nucl. Phys. B 663, 123 (2003); I. Gogoladze, Y. Mimura, S. Nandi, Phys. Lett. B562, 307 (2003); W. Altmannshofer, D. Guadagnoli, S. Raby and D. M. Straub, Phys. Lett. B 668, 385 (2008); S. Antusch and M. Spinrath, Phys. Rev. D 78, 075020 (2008); H. Baer, S. Kraml and S. Sekmen, JHEP 0909, 005 (2009); S. Antusch and M. Spinrath, Phys. Rev. D 79, 095004 (2009); D. Guadagnoli, S. Raby and D. M. Straub, JHEP 0910, 059 (2009); K. Choi, D. Guadagnoli, S. H. Im and C. B. Park, JHEP 1010, 025 (2010); S. Dar, I. Gogoladze, Q. Shafi and C. S. Un, Phys. Rev. D 84, 085015 (2011); N. Karagiannakis, G. Lazarides and C. Pallis, Phys. Lett. B 704, 43 (2011); I. Gogoladze, Q. Shafi and C. S. Un, Phys. Lett. B 704, 201 (2011); M. Badziak, M. Olechowski and S. Pokorski, JHEP 1108, 147 (2011); S. Antusch, L. Calibbi, V. Maurer, M. Monaco and M. Spinrath, arXiv:1111.6547 [hep-ph]; J. S. Gainer, R. Huo and C. E. M. Wagner, arXiv:1111.3639 [hep-ph]; M. Badziak and K. Sakurai, JHEP 1202, 125 (2012).

[4] H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP 0803, 056 (2008); H. Baer, M. Haider, S. Kraml, S. Sekmen and H. Summy, JCAP 0902, 002 (2009); H. Baer, S. Raza and Q. Shafi, arXiv:1201.5668 [hep-ph].
[5] See, for instance, S. P. Martin, Phys. Rev. D79, 095019 (2009); U. Chattoppadhyay, D. Das and D. P. Roy, Phys. Rev. D 79, 095013 (2009); B. Ananthanarayan, P. N. Pandita, Int. J. Mod. Phys. A22, 3229-3259 (2007); S. Bhattacharyya, A. Datta and B. Mukhopadhyaya, JHEP 0710, 080 (2007); A. Corsetti and P. Nath, Phys. Rev. D 64, 125010 (2001) and references therein.

[6] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, Eur. Phys. J. C 28, 133 (2003).

[7] J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974).

[8] I. Gogoladze, R. Khalid and Q. Shafi, Phys. Rev. D 79, 115004 (2009).

[9] I. Gogoladze, R. Khalid and Q. Shafi, Phys. Rev. D 80, 095016 (2009);

[10] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, JHEP 1012, 055 (2010).

[11] H. Baer, S. Kraml, A. Lessa and S. Sekmen, JHEP 1002, 055 (2010); D. Feldman, Z. Liu and P. Nath, Phys. Rev. D 80, 015007 (2009); M. A. Ajaib, T. Li, Q. Shafi and K. Wang, JHEP 1101, 028 (2011).

[12] S. Profumo and C. E. Yaguna, Phys. Rev. D 69, 115009 (2004); D. Feldman, Z. Liu and P. Nath, Phys. Rev. D 80, 015007 (2009).

[13] G. W. Bennett et al. [Muon G-2 Collaboration], Phys. Rev. D 73, 072003 (2006).

[14] F. Gianotti (ATLAS Collaboration), talk at CERN public seminar, Dec. 13, 2011; ATLAS collaboration, ATLAS-CONF-2011-163 (2011).

[15] G. Tonelli (CMS Collaboration), talk at CERN public seminar, Dec. 13, 2011.

[16] R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 2558 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975); M. Magg, Q. Shafi and C. Wetterich, Phys. Lett. B 87, 227 (1979); M. Cvetic, Nucl. Phys. B 233, 387 (1984).

[17] T. W. B. Kibble, G. Lazarides and Q. Shafi, Phys. Lett. B 113, 237 (1982); T. W. B. Kibble, G. Lazarides and Q. Shafi, Phys. Rev. D 26, 435 (1982); R. N. Mohapatra and B. Sakita, Phys. Rev. D 21, 1062 (1980).

[18] A. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. 49 (1982) 970; R. Barbieri, S. Ferrara and C. Savoy, Phys. Lett. B119 (1982) 343; N. Ohta, Prog. Theor. Phys. 70 (1983) 542; L. J. Hall, J. D. Lykken and S. Weinberg, Phys. Rev. D27 (1983) 2359; for a review see S. Weinberg, The Quantum Theory of Fields: Volume 3, Supersymmetry, Cambridge University Press (2000) 442p.
[19] M. Olechowski and S. Pokorski, Phys. Lett. B 344, 201 (1995); D. Matalliotakis and H. P. Nilles, Nucl. Phys. B 435, 115 (1995); H. Murayama, M. Olechowski and S. Pokorski, Phys. Lett. B 371, 57 (1996). H. Baer, S. Kraml and S. Sekmen, JHEP 0909, 005 (2009).

[20] See, for instance A. Hebecker and J. March-Russell, Nucl. Phys. B 625, 128 (2002).

[21] I. Gogoladze, Y. Mimura and S. Nandi, Phys. Lett. B 562, 307 (2003); Phys. Rev. D 69, 075006 (2004); I. Gogoladze, C. A. Lee, Y. Mimura and Q. Shafi, Phys. Lett. B 649, 212 (2007).

[22] F. E. Paige, S. D. Protopopescu, H. Baer and X. Tata, hep-ph/0312045.

[23] J. Hisano, H. Murayama, and T. Yanagida, Nucl. Phys. B 402 (1993) 46. Y. Yamada, Z. Phys. C 60 (1993) 83; J. L. Chkareuli and I. G. Gogoladze, Phys. Rev. D 58, 055011 (1998).

[24] D. M. Pierce, J. A. Bagger, K. T. Matchev, and R.-j. Zhang, Nucl. Phys. B 491 (1997) 3.

[25] K. Nakamura et al. [ Particle Data Group Collaboration ], J. Phys. G 37, 075021 (2010).

[26] [Tevatron Electroweak Working Group and CDF Collaboration and D0 Collab], arXiv:0903.2503 [hep-ex].

[27] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, JHEP 1106 (2011) 117.

[28] G. Belanger, F. Boudjema, A. Pukhov and R. K. Singh, JHEP 0911, 026 (2009); H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP 0803, 056 (2008).

[29] H. Baer, C. Balazs, and A. Belyaev, JHEP 03 (2002) 042; H. Baer, C. Balazs, J. Ferrandis, and X. Tata Phys. Rev. D 64 (2001) 035004.

[30] S. Schael et al. Eur. Phys. J. C 47, 547 (2006).

[31] Jose Angel Hernando, LHCb-TALK-2012-028.

[32] E. Barberio et al. [Heavy Flavor Averaging Group], arXiv:0808.1297 [hep-ex].

[33] E. Komatsu et al. [WMAP Collaboration], Astrophys. J. Suppl. 180, 330 (2009).

[34] H. Baer, T. Krupovnickas, A. Mustafayev, E. -K. Park, S. Profumo and X. Tata, JHEP 0512, 011 (2005).
[35] H. Baer, A. Mustafayev, E. -K. Park, S. Profumo and X. Tata, JHEP 0604, 041 (2006).

[36] I. Gogoladze, R. Khalid, Y. Mimura and Q. Shafi, Phys. Rev. D 83, 095007 (2011); S. Gori, P. Schwaller and C. E. M. Wagner, Phys. Rev. D 83, 115022 (2011).

[37] I. Gogoladze, S. Raza and Q. Shafi, JHEP 1203, 054 (2012); H. Baer, I. Gogoladze, A. Mustafayev, S. Raza and Q. Shafi, JHEP 1203, 047 (2012).