Testing Yukawa Unification at LHC Run-3 and HL-LHC

Mario E. Gómez\textsuperscript{a1} Qaisar Shafi\textsuperscript{b2} and Cem Salih Ün\textsuperscript{c3}

\textsuperscript{a}Departamento de Ciencias Integradas y Centro de Estudios Avanzados en Física Matemáticas y Computación, Campus del Carmen, Universidad de Huelva, Huelva 21071, Spain.
\textsuperscript{b}Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
\textsuperscript{c}Department of Physics, Bursa Uludağ University, TR16059 Bursa, Turkey

Abstract

We explore $t$-$b$-$\tau$ Yukawa unification (YU) in a supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ model without imposing a discrete left-right (L-R) symmetry. A number of interesting solutions that are compatible with $t$-$b$-$\tau$ YU, LSP neutralino dark matter (DM), and LHC and other experimental constraints are identified. In particular, they include gluino-neutralino and stau-neutralino co-annihilation scenarios, where the NLSP gluino mass can range from 1-3 TeV. Higgsino-like dark matter solutions are also identified for which gluino masses can approach 5 TeV or so. This scenario will be tested at LHC Run-3 and its future upgrades.

\textsuperscript{1}Email: mario.gomez@dfa.uhu.es
\textsuperscript{2}Email: shafi@bartol.udel.edu
\textsuperscript{3}E-mail: cemsalihun@uludag.edu.tr
1 Introduction

Third family $t$-$b$-$\tau$ Yukawa Unification (YU) [1] arises naturally in the simplest versions of supersymmetric SO(10) and $SU(4)_c \times SU(2)_L \times SU(2)_R$ (4-2-2) models and it has attracted a fair amount of attention in recent years [2]. Most work on the implications of YU have assumed the presence of a discrete Left-Right (LR) symmetry (more precisely C-parity, also known as D-parity), which restricts the number of Soft Supersymmetry Breaking (SSB) parameters. It was also shown that $t$-$b$-$\tau$ YU allows the gluino NLSP solutions in 4-2-2 [3] models with LR symmetry. In this case the LSP neutralino can provide the desired dark matter (DM) abundance, but the gluino turns out to be not much heavier than a TeV or so. Switching from $t$-$b$-$\tau$ YU to $b$-$\tau$ YU also allows stop NLSP solutions with $m_{\tilde{t}_1} \lesssim 1$ TeV [4].

The spontaneous breaking of SO(10) to its maximal subgroup 4-2-2 can be accomplished either with a Higgs 54-plet or 210-plet. The breaking with 54-plet leaves the LR symmetry unbroken [5–7]. However, using the 210-plet yields 4-2-2 symmetry but the C-parity in this case is absent [8]. The spontaneous breaking of LR symmetry also avoids a potential domain wall problem [6]. Recent works [9] have discussed the sparticle spectroscopy, DM implications and muon $g-2$ in 4-2-2 with broken LR symmetry in the softly broken scalar sector without imposing the $t$-$b$-$\tau$ YU condition.

In the case of broken LR symmetry the universality between the $SU(2)_L$ and $SU(2)_R$ gauginos does not hold, i.e. $M_{2L} \neq M_{2R}$. Besides, the symmetrical structure of 4-2-2 also allows non-universality among the other gauginos as

$$M_1 = \frac{3}{5}M_{2R} + \frac{2}{5}M_3.$$  (1)

Despite non-universal gaugino masses, the gauge coupling unification can be maintained if 4-2-2 breaks to the MSSM gauge group at the grand unification scale ($M_{GUT}$). We should also note the fact that the presence of Higgs 210-plet, in general, breaks YU [10]. However, $t$-$b$-$\tau$ YU can be largely preserved if the third family matter fields acquire masses from the $(1, 2, 2)$ components of the effective MSSM Higgs doublets [11].

In this paper we explore the low energy consequences of imposing $t$-$b$-$\tau$ YU in a supersymmetric 4-2-2 model without assuming LR symmetry in the softly broken scalar and gaugino sectors. We employ a variety of constraints from collider physics, rare $B-$meson decays and DM searches, and we require that the LSP neutralino saturates the dark matter limits set by the Planck satellite experiment. The rest of the paper is organized as follows. We briefly describe in Section 2 the scanning procedure and the experimental constraints. Section 3 discusses the low energy implications if $t$-$b$-$\tau$ YU is imposed at $M_{GUT}$ and present some benchmark points to exemplify our findings. In Section 4 we summarize our conclusions.

2 Scanning Procedure and Experimental Constraints

We employ the ISAJET 7.84 package [12] to perform random scans over the parameter space given below. 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 [13]. With the boundary conditions given at \( M_{\text{GUT}} \), all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale \( M_Z \).

In evaluating Yukawa couplings the SUSY threshold corrections [14] are taken into account at the common scale \( M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_L}m_{\tilde{t}_R}} \). The entire parameter set is iteratively run between \( M_Z \) and \( M_{\text{GUT}} \) 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 gauge and Yukawa couplings, and the SSB 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 \( M_{\text{SUSY}} \), which effectively accounts for the leading 2-loop corrections. Full 1-loop radiative corrections are incorporated for all sparticle masses.

We have scanned the parameter space of 4-2-2 with broken LR symmetry in both the scalar and gaugino sectors. The fundamental parameters in this framework and their ranges are as follows:

\[
\begin{align*}
0.1 & \leq m_L & \leq 10 \text{ TeV} \\
0.05 & \leq M_{2L} & \leq 5 \text{ TeV} \\
-3 & \leq M_3 & \leq 5 \text{ TeV} \\
-3 & \leq A_0/m_L & \leq 3 \\
2 & \leq \tan \beta & \leq 65 \\
-3 & \leq x_{LR} & \leq 3 \\
-3 & \leq y_{LR} & \leq 3 \\
0 & \leq x_d & \leq 3 \\
-1 & \leq x_u & \leq 2.
\end{align*}
\]

Here \( m_L \) is the universal SSB mass term for the left-handed SUSY scalars, while \( M_2 \) and \( M_3 \) are the SSB gaugino mass terms. \( A_0 \) denotes the SSB trilinear scalar interaction term, and \( \tan \beta \) is the ratio of the vacuum expectation values of the MSSM Higgs doublets such that \( \tan \beta = v_u/v_d \). \( x_{LR} \) measures the LR breaking in the scalar sector with \( m_{2R} = x_{LR} m_L \), where \( m_{2R} \) is the SSB mass term for the right-handed SUSY scalars. Similarly \( y_{LR} \) parametrizes the LR breaking in the gaugino sector as \( M_{2R} = y_{LR} M_{2L} \). We also employ non-universal SSB masses for the MSSM Higgs fields by setting \( m_{H_d} = x_d m_L \) and \( m_{H_u} = x_u m_L \).

In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in [15]. 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 [16–18] and use the IsaTools package [19,20] and Ref. [21] to implement the phenomenological constraints from the rare \( B \)-meson decays [22,23] and DM observations [24]. The following experimental constraints along with their uncertainties are employed in our analyses:
\[ m_h = 123 - 127 \text{ GeV} \]

\[ m_{\tilde{g}} \geq 2.1 \text{ TeV} \ (\geq 0.8 \text{ TeV if gluino is NLSP}) \]

\[ 0.8 \times 10^{-9} \leq \text{BR}(B_s \rightarrow \mu^+ \mu^-) \leq 6.2 \times 10^{-9} \ (2\sigma) \]

\[ 2.99 \times 10^{-4} \leq \text{BR}(B \rightarrow X_s \gamma) \leq 3.87 \times 10^{-4} \ (2\sigma) \]

\[ 0.15 \frac{\text{BR}(B_u \rightarrow \tau \nu)}{\text{BR}(B_u \rightarrow \tau \nu)_{\text{MSSM}}} \leq 2.41 \ (3\sigma) \]

\[ 0.114 \leq \Omega_{\text{CDM}} h^2 \leq 0.126 \ (5\sigma) . \]

In addition to these constraints, we quantify \( t-b-\tau \) YU with the parameter \( R_{tbr} \) as

\[ R_{tbr} = \frac{\text{Max}(y_t, y_b, y_\tau)}{\text{Min}(y_t, y_b, y_\tau)} \]

where \( R_{tbr} = 1 \) means perfect \( t-b-\tau \) YU. However, considering various uncertainties we consider solutions to be compatible with \( t-b-\tau \) YU for \( R_{tbr} \leq 1.1 \).

After the mass spectrum and DM implications are calculated, it is interesting to confront the predictions from the models consistent with the constraints given in Eq.(3) as well as \( t-b-\tau \) YU with the LHC bounds and future prospects. To this end, we employ the tools provided by the Smodels-v1.2.2. [25, 26]. This package decomposes the theoretical models into the Simplified Model Spectra (SMS) which are compared with the data provided by the ATLAS and CMS collaborations [27, 28]. For each model, we use SUSYHIT [29] to compute the decay ratios of the SUSY particles and PYTHIA [30] to produce the corresponding cross sections.

### 3 \( t-b-\tau \) YU and DM Implications

In this section we present our results for \( t-b-\tau \) YU within the 4-2-2 framework. Figure 1 displays the fundamental parameter space of \( t-b-\tau \) YU in terms of the SSB scalar (top panels) and gaugino (bottom panels) mass terms with plots in the \( R_{tbr} - m_{\tilde{L}} \), \( R_{tbr} - m_{\tilde{R}} \), \( R_{tbr} - M_{2L} \) and \( R_{tbr} - M_{2R} \) planes. All points are compatible with REWSB and LSP neutralino conditions. Green points satisfy the mass bounds and constraints from rare \( B-\)meson decays. Brown points form a subset of green and they yield relic abundance of LSP neutralino consistent with the Planck measurements within 5\( \sigma \). The horizontal line indicates the region with \( R_{tbr} = 1.1 \), and points below this line are considered as being in very good agreement with the \( t-b-\tau \) Yukawa unification. The \( R_{tbr} - m_{\tilde{L}} \) plane shows that \( t-b-\tau \) YU can be realized within a wide range of \( m_{\tilde{L}} \) from about 400 GeV to 10 TeV. Two regions can be identified, which are separated by a gray area. The gray region between them is excluded mostly by the gluino mass bound, which will be shown in more detail later. The SSB mass term for the right-handed scalar particles can be as light as about 1 TeV, while \( t-b-\tau \) YU condition restricts it at about 15 TeV from above, as seen from the \( R_{tbr} - m_{\tilde{R}} \) plane. The left-bottom plane displays the SSB mass term for \( M_{2L} \), and as is seen, the \( t-b-\tau \) YU solutions can be realized in a wide range of values for \( M_{2L} \) in our scan. It is bounded at about 800 GeV from below by the DM constraints. The mass term for
the $SU(2)_R$ gaugino could lie in a wider range from about $-10$ TeV to 4 TeV consistent with all the LHC and DM constraints.

The parameters quantifying non-universality in the scalar and gaugino sectors are shown in Figure 2 along with the SSB gaugino mass terms with plots in the $R_{tbr} - x_{LR}$, $R_{tbr} - y_{LR}$, $R_{tbr} - M_1$ and $R_{tbr} - M_3$ planes. The color coding is the same as in Figure 1. Despite its wider range in our scan, the $R_{tbr} - x_{LR}$ plane shows that LR breaking in the scalar sector can be realized consistent with the DM constraints if $0.8 \lesssim x_{LR} \lesssim 1.6$. Note that $x_{LR} = 1$ restores the symmetry in the scalar sector. On the other hand, the LR breaking in the gaugino sector can be crucial for $t$-$b$-$\tau$ YU, as seen from the $R_{tbr} - y_{LR}$ plane with $|y_{LR}|$ as large as 3. Even though $t$-$b$-$\tau$ YU mostly prefers $y_{LR}$ to be negative, it is possible to realize positive $y_{LR}$ values in a relatively small portion of the parameter space, which also leads to negative $M_{2R}$ in most of the parameter space. Its impact can be seen from the $R_{tbr} - M_1$ plane where $M_1$ is mostly negative and its magnitude can be as high as about 5 TeV, while it is restricted to $M_1 \sim 2$ TeV in the positive region. Since $M_1$ controls the bino mass at the low scale, such large values of $M_1$ prevent bino from being the LSP. The parameter $M_3$ is shown in the right-bottom panel, and it is seen that $t$-$b$-$\tau$ YU condition allows only negative $M_3$ values. In this context, according to Eq.(1), one can expect very
Figure 2: Plots in the $R_{\rm br} - x_{LR}$, $R_{\rm br} - y_{LR}$, $R_{\rm br} - M_1$ and $R_{\rm br} - M_3$ planes. The color coding is the same as in Figure 1.

large $M_{2L}$ for $M_1 > 0$; thus this region is most likely to realize a bino or Higgsino DM.

We present the low scale mass spectrum in Figure 3 with plots in the $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$, $m_A - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ planes. All points are compatible with REWSB and LSP neutralino conditions. Green points satisfy the mass bounds and constraints from rare $B-$meson decays. Orange points form a subset of green and they are compatible with $t$-$b$-$\tau$ YU. Brown points are a subset of orange and they are consistent with the Planck bound on the relic abundance of LSP neutralino within $5\sigma$. The diagonal lines indicate regions in which the displayed particles are degenerate in mass, and the line in the $m_A - m_{\tilde{\chi}_1^0}$ plane depicts solutions with $m_A = 2m_{\tilde{\chi}_1^0}$. Some of the most interesting results correspond to NLSP gluino solutions. In previous studies NLSP gluino masses of order 1 TeV are found, compatible with $t$-$b$-$\tau$ YU in the presence of LR symmetry. However, the $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ plane shows that in our case one can realize NLSP gluino solutions compatible with $t$-$b$-$\tau$ YU for gluino mass scales up to about 2.5 TeV. Moreover, as seen from the other panels of Figure 3, the mass spectra also favor the $A-$resonance solution if $1 \lesssim m_A \lesssim 3$ TeV, and stau-neutralino and chargino-neutralino coannihilation solutions if $0.6 \lesssim m_{\tilde{\tau}_1} \lesssim 1.6$ TeV. The $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane also shows that the lightest chargino is almost as light as the LSP neutralino in most of the parameter space. Approximate mass degeneracy between the lightest chargino and LSP neutralino is one of the characteristics features of DM composed of wino or Higgsino.

With a wino and/or Higgsino DM, one can expect large cross-section in the DM scattering processes. For wino DM, the scattering off nuclei occurs through $SU(2)$ interactions, while Yukawa interactions take part if the Higgsino happens to be the LSP. Figure 4 shows
Figure 3: Plots in the $m_\tilde{g} - m_{\tilde{\chi}_1^0}$, $m_A - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ planes. All points are compatible with the REWSB and LSP neutralino conditions. Green points satisfy the mass bounds and constraints from rare $B$–meson decays. Orange points form a subset of green and they are compatible with $t$-$b$-$\tau$ Yukawa unification. Brown points are a subset of orange, they are consistent with the Planck bound on the relic abundance of LSP neutralino within $5\sigma$. The diagonal lines indicate regions in which the displayed particles are degenerate in mass, except for the line in the $m_A - m_{\tilde{\chi}_1^0}$ plane which shows the solutions with $m_A = 2m_{\tilde{\chi}_1^0}$.

results for the spin-independent (left) and spin-dependent (right) scattering cross-sections versus the LSP neutralino mass. In the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ plane, the dashed (solid) blue line represents the current (future) results from the SuperCDMS experiment [31]. The dashed (solid) black line indicates the current (future) results from the LUX-Zeplin experiment [32]. In the $\sigma_{SD} - m_{\tilde{\chi}_1^0}$ plane, the solid black line represents the current bound from Super-K [33], and the solid orange line is set by the LUX results [34]. The green line is obtained from collider analyses [35], and the dashed (solid) blue line shows the current (future) results from IceCube/DeepCore. The region in the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ plane, which is cut by the dashed black exclusion curve of the current results from the LUX measurements, implies a Higgsino DM. Even though many solutions are already excluded due to large scattering cross-sections, it is still possible to realize a Higgsino DM slightly below this curve. These solutions are expected to be probed in the direct detection DM experiments in the near future. The solutions between the current and future exclusion curves also yield a wino DM, and they are within reach of future experiments. The remaining solutions lying below all the curves represent the DM in which bino is involved.
Figure 4: Spin-independent (left) and spin-dependent (right) scattering cross-sections versus the LSP neutralino mass. In the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ plane, the dashed (solid) blue line represents the current (future) results from the SuperCDMS experiment [31]. The dashed (solid) black line indicates the current (future) results from the LUX-Zeplin experiment [32]. In the $\sigma_{SD} - m_{\chi_1^0}$ plane, the solid black line represents the current bound from Super-K [33], and the solid orange line is set by the LUX results [34]. The green line is obtained from collider analyses [35], and the dashed (solid) blue line shows the current (future) results from IceCube DeepCore.

Most of the models allowed by the constraints listed in Eq.(3) and compatible with $t\bar{b}\tau$ YU present topologies that cannot be detected at the LHC according to the Smodels analysis. Note that this is the case for the subset of models satisfying the DM constraint. Although many models predict relatively low SUSY masses, their signals escape the LHC bounds as can be understood from our previous discussions. For instance, although the constraints on gluino masses are quite severe, we can find cases with gluino masses of order 800 GeV compatible with $t\bar{b}\tau$ YU. However, the DM constraint bound it at about 900 GeV from below, as seen in Figure 3. In this region, the gluino happens to be the NLSP, and it can decay into a LSP neutralino along with a quark-antiquark pair from the first two families. The bound from these processes is set as $m_{\tilde{g}} \gtrsim 800$ GeV [36]. Figure 3 also shows that the stau can be as light as 500 GeV or so, consistent with all the constraints and $t\bar{b}\tau$ YU, where the LSP neutralino is formed mostly from bino and/or wino. If the charginos and second lightest neutralino are allowed to decay into staus, YU with $m_{\tilde{\tau}} \lesssim 350$ GeV and/or $m_{\tilde{\chi}_1^\pm} \lesssim 1.1$ TeV is excluded [37]. On the other hand, the lightest stau in MSSM is mostly composed of the right-handed stau, which forbids the lightest chargino to decay into a stau. Besides, as seen from the chargino and LSP neutralino masses shown in the right bottom panel of Figure 3, the chargino decay into a LSP neutralino along with a $W$–boson is not kinematically allowed, which also loosens the constraints on the chargino and stau masses.

Before concluding the discussion about $t\bar{b}\tau$ YU, we present five benchmark points that are compatible with experimental constraints. All masses are given in GeV. Point 1 depicts a solution for the gluino-neutralino coannihilation scenario with NLSP gluino mass of about 2.4 TeV. In contrast, point 2 displays a relatively light NLSP gluino. Point 3 represents an $A$–resonance solution. The DM relic abundance is saturated with bino-like LSP neutralino in the first three points. Point 4 displays a wino-like DM solution where the lightest chargino mass is close to the wino and also to the lightest stau mass. Coannihilations
Table 1: Benchmark points are compatible with all experimental constraints used in this paper. All points are chosen to be allowed by the constraints. All masses are given in GeV. Points 1 and 2 depict NLSP gluino solutions and point 3 represents an $A$-resonance solution. The first three points predict bino-like DM. Point 4 displays a stau-neutralino coannihilation solution with a wino-like DM. Point 5 is a solution with a Higgsino-like DM and with $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^0}$.

| Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
|---------|---------|---------|---------|---------|
| $m_{L}$ | 8031    | 9461    | 781     | 1202    | 3714    |
| $M_1$   | 1786    | -4810   | -1288   | -3653   | -4502   |
| $M_{2L}$| 2859    | 3915    | 758.5   | 1559    | 2348    |
| $M_3$   | -316.7  | -926    | -2904   | -2802   | -2537   |
| $A_0/m_{L}$ | -1.06  | -0.13   | 1.57    | 1.16    | 1.30    |
| $\tan \beta$ | 48.0    | 47.8    | 43.8    | 42.6    | 52.4    |
| $x_{LR}$ | 1.43    | 0.78    | 0.83    | 1.45    | 0.84    |
| $y_{LR}$ | 1.11    | -1.89   | -0.28   | -2.71   | -2.47   |
| $m_{R}$  | 11460   | 7398    | 646.9   | 1740    | 3111    |
| $M_{2R}$ | 3188    | -7399   | -210.1  | -4221   | -5811   |
| $\mu$   | 8416    | 6401    | 3431    | 3398    | 894.4   |
| $m_h$   | 124.3   | 123.2   | 123.2   | 123.1   | 124.1   |
| $m_H$   | 6205    | 5568    | 1088    | 1549    | 2432    |
| $m_A$   | 6164    | 5531    | 1081    | 1539    | 2417    |
| $m_{H^\pm}$ | 6206   | 5568    | 1093    | 1552    | 2434    |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 849.6, 2530 | 2259, 3438 | 558.1, 711.6 | 1387, 1389 | 850.6, 853.3 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 7757, 7757 | 5962, 5962 | 3190, 3190 | 3165, 3165 | 2044, 2058 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 2535, 7710 | 3439, 5962 | 713.8, 3162 | 1389, 3137 | 871.5, 2018 |
| $M_{\tilde{g}}$ | 933.9 | 2357    | 5954    | 5781    | 5360    |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 8183, 11379 | 9906, 7462 | 5172, 5145 | 5163, 5294 | 6019, 5540 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 4075, 9113 | 4763, 7707 | 4371, 4506 | 4331, 4564 | 3523, 4338 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 6205, 5568 | 1093    | 1552    | 2434    |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 8183, 11558 | 9906, 7623 | 5173, 5151 | 5164, 5258 | 6019, 5516 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 4131, 8784 | 3491, 7690 | 4340, 4490 | 4327, 4466 | 3556, 4327 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 8110, 6498 | 9720, 8794 | 909.3, 905.6 | 1668, 1449 | 4042, 3245 |
| $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$ | 5615, 9396 | 5167, 8783 | 605.6, 988.1 | 1436, 1896 | 1178, 3245 |
| $\sigma_{SI} (pb)$ | $0.40 \times 10^{-14}$ | $0.71 \times 10^{-12}$ | $0.13 \times 10^{-13}$ | $0.47 \times 10^{-10}$ | $0.19 \times 10^{-9}$ |
| $\sigma_{SD} (pb)$ | $0.16 \times 10^{-10}$ | $0.48 \times 10^{-10}$ | $0.68 \times 10^{-9}$ | $0.17 \times 10^{-7}$ | $0.29 \times 10^{-6}$ |
| $\Omega h^2$ | 0.116 | 0.124 | 0.122 | 0.120 | 0.125 |
| $R_{tb\tau}$ | 1.04 | 1.08 | 1.09 | 1.08 | 1.09 |

of three species lead to a correct relic DM abundance. Point 5 is a typical solution for Higgsino-like DM with the chargino and neutralino masses given as $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^0}$.
4 Conclusion

We have explored the LHC and DM implications of $t$-$b$-$\tau$ YU in the supersymmetric 4-2-2 framework without imposing a discrete LR symmetry. We only accept solutions which yield one of the neutralinos as the LSP that saturates the DM abundance. We identify the gluino-neutralino coannihilation scenarios, and present consistent solutions for $m_{\tilde{g}} \lesssim 2.4$ TeV. Without the NLSP constraint the gluino can be as heavy as about 6 TeV, which can be probed at the LHC and future colliders. In addition to the gluino-neutralino coannihilation scenario, some $A-$resonance solutions are also identified with $1 \lesssim m_A \lesssim 3$ TeV. Similarly, the stau-neutralino and chargino-neutralino coannihilation processes can be realized with the stau and chargino masses in the range $0.6 \lesssim m_{\tilde{\tau}}, m_{\tilde{\chi}^\pm} \lesssim 2$ TeV.

The 4-2-2 model also yields wino and Higgsino-like DM as well as solutions with bino DM. We observe that while many of the Higgsino DM solutions are excluded by the direct detection experiments, it is still possible to realize some solutions lying slightly below the current exclusion curves. In other words, Higgsino DM in the 4-2-2 framework will be seriously tested in the near future. Wino-like DM solutions are allowed by the current measurements, and they lie within the reach of the near future experiments.

We exemplify our findings with five benchmark points including the full spectrum for the SUSY particles. In addition to the DM implications, the stop cannot be lighter than about 3 TeV, while squarks of the first two families are relatively heavy ($\gtrsim 5$ TeV).

Acknowledgments

We would like to thank Zafer Altin for discussions. CSU also thank Universidad de Huelva and Bartol Research Institute of University of Delaware for their kind hospitality, where part of this work has been done. The research of M.E.G. was supported by the Spanish MINECO, under grant FPA2017-86380-P. R. Q.S. acknowledges support by the DOE grant No. DE-SC0013880. The work of CSU is supported in part by the Scientific and Technological Research Council of Turkey (TUBITAK) Grant no. MFAG-118F090. Part of the calculations reported in this paper were performed at the National Academic Network and Information Center (ULAKBIM) of TUBITAK, High Performance and Grid Computing Center (TRUBA Resources). CSU also acknowledges support from the CEAFMC of the University of Huelva.

References

[1] 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;

[2] 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); S. Profumo, Phys. Rev. D 68 (2003) 015006; C. Balazs and R. Dermisek, JHEP 0306, 024 (2003); C. Pallis, Nucl. Phys. B 678, 398 (2004); M. Gomez, G. Lazarides and C. Pallis, Phys. Rev. D 61 (2000) 123512, Nucl. Phys. B 638, 165 (2002) and Phys. Rev. D 67, 097701(2003); I. Gogoladze, Y. Mimura, S. Nandi and K. Tobe, Phys. Lett. B 575, 66 (2003); 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); W. Altmannshofer, D. Guadagnoli, S. Raby and D. M. Straub, Phys. Lett. B 668, 385 (2008); D. Guadagnoli, S. Raby and D. M. Straub, JHEP 0910, 059 (2009); H. Baer, S. Kraml and S. Sekmen, JHEP 0909, 005 (2009); K. Choi, D. Guadagnoli, S. H. Im and C. B. Park, arXiv:1005.0618 [hep-ph]; B. Dutta and Y. Mimura, arXiv:1810.08413 [hep-ph].

[3] I. Gogoladze, R. Khalid and Q. Shafi, Phys. Rev. D 79, 115004 (2009) doi:10.1103/PhysRevD.79.115004 [arXiv:0903.5204 [hep-ph]]; I. Gogoladze, R. Khalid and Q. Shafi, Phys. Rev. D 80, 095016 (2009) [arXiv:0908.0731 [hep-ph]]; S. Profumo and C. E. Yaguna, Phys. Rev. D 69, 115009 (2004) [hep-ph/0402208]; D. Feldman, Z. Liu and P. Nath, Phys. Rev. D 80, 015007 (2009) [arXiv:0905.1148 [hep-ph]]; N. Chen, D. Feldman, Z. Liu, P. Nath and G. Peim, Phys. Rev. D 83, 035005 (2011) [arXiv:1011.1246 [hep-ph]].

[4] S. Raza, Q. Shafi and C. S. n, Phys. Rev. D 92, no. 5, 055010 (2015) [arXiv:1412.7672 [hep-ph]].

[5] T. W. B. Kibble, G. Lazarides and Q. Shafi, Phys. Rev. D 26, 435 (1982). doi:10.1103/PhysRevD.26.435

[6] G. Lazarides and Q. Shafi, Phys. Lett. 159B, 261 (1985). doi:10.1016/0370-2693(85)90246-1

[7] G. Lazarides and Q. Shafi, JHEP 1910, 193 (2019) [arXiv:1904.06880 [hep-ph]].

[8] D. Chang, R. N. Mohapatra and M. K. Parida, Phys. Rev. Lett. 52, 1072 (1984).

[9] M. E. Gomez, S. Lola, R. Ruiz De Austri and Q. Shafi, JHEP 1810, 062 (2018) [arXiv:1806.06220 [hep-ph]]; M. E. Gomez, S. Lola, R. Ruiz de Austri and Q. Shafi, Front. in Phys. 6, 127 (2018) [arXiv:1806.11152 [hep-ph]].

[10] K. S. Babu and R. N. Mohapatra, Phys. Rev. Lett. 70, 2845 (1993) [hep-ph/9209215].

[11] M. Adeel Ajaib, I. Gogoladze, Q. Shafi and C. S. Un, JHEP 1307, 139 (2013) [arXiv:1303.6964 [hep-ph]], and references therein.

[12] H. Baer, F. E. Paige, S. D. Protopopescu and X. Tata, arXiv:hep-ph/0001086.

[13] J. Hisano, H. Murayama, and T. Yanagida, Nucl. Phys. B402 (1993) 46. Y. Yamada, Z. Phys. C60 (1993) 83; J. L. Chkareuli and I. G. Gogoladze, Phys. Rev. D 58, 055011 (1998).
[14] D. M. Pierce, J. A. Bagger, K. T. Matchev, and R.-j. Zhang, Nucl. Phys. B491 (1997) 3.
[15] 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).
[16] K. A. Olive et al. [Particle Data Group Collaboration], Chin. Phys. C 38, 090001 (2014).
[17] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012); S. Chatrchyan et al. [CMS Collaboration], JHEP 1306, 081 (2013).
[18] T. A. Vami [ATLAS and CMS Collaborations], PoS LHCP 2019, 168 (2019).
[19] H. Baer and M. Brhlik, Phys. Rev. D 55 (1997) 4463; H. Baer, M. Brhlik, D. Castano and X. Tata, Phys. Rev. D 58 (1998) 015007;
[20] K. Babu and C. Kolda, Phys. Rev. Lett. 84 (2000) 228; A. Dedes, H. Dreiner and U. Nierste, Phys. Rev. Lett. 87 (2001) 251804; J. K. Mizukoshi, X. Tata and Y. Wang, Phys. Rev. D 66 (2002) 115003.
[21] D. Eriksson, F. Mahmoudi and O. Stal, J. High Energy Phys. 0811 (2008) 035.
[22] Y. Amhis et al. [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].
[23] D. Asner et al. [Heavy Flavor Averaging Group Collaboration], arXiv:1010.1589 [hep-ex].
[24] Y. Akrami et al. [Planck Collaboration], arXiv:1807.06205 [astro-ph.CO].
[25] F. Ambrogi et al., Comput. Phys. Commun. 227 (2018) 72 [arXiv:1701.06586 [hep-ph]].
[26] S. Kraml, S. Kulkarni, U. Laa, A. Lessa, W. Magerl, D. Proshoefsky-Spindler and W. Waltenberger, Eur. Phys. J. C 74, 2868 (2014) [arXiv:1312.4175 [hep-ph]]; J. Dutta, S. Kraml, A. Lessa and W. Waltenberger, LHEP 1, no. 1, 5 (2018) [arXiv:1803.02204 [hep-ph]]; J. Heisig, S. Kraml and A. Lessa, Phys. Lett. B 788, 87 (2019) [arXiv:1808.05229 [hep-ph]].
[27] H. Okawa [ATLAS Collaboration], arXiv:1110.0282 [hep-ex].
[28] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. D 88 (2013) no.5, 052017 [arXiv:1301.2175 [hep-ex]].
[29] A. Djouadi, M. M. Muhlleitner and M. Spira, Acta Phys. Polon. B 38 (2007) 635 [hep-ph/0609292].
[30] T. Sjstrand et al., Comput. Phys. Commun. 191 (2015) 159 doi:10.1016/j.cpc.2015.01.024 [arXiv:1410.3012 [hep-ph]].
[31] P. L. Brink et al. [CDMS-II Collaboration], eConf C 041213, 2529 (2004) [astro-ph/0503583].
[32] D. S. Akerib et al. [LUX-ZEPLIN Collaboration], arXiv:1802.06039 [astro-ph.IM].

[33] T. Tanaka et al. [Super-Kamiokande Collaboration], Astrophys. J. 742, 78 (2011) doi:10.1088/0004-637X/742/2/78 [arXiv:1108.3384 [astro-ph.HE]].

[34] D. S. Akerib et al. [LUX Collaboration], Phys. Rev. Lett. 116, no. 16, 161302 (2016) doi:10.1103/PhysRevLett.116.161302 [arXiv:1602.03489 [hep-ex]].

[35] V. Khachatryan et al. [CMS Collaboration], Eur. Phys. J. C 75, no. 5, 235 (2015) doi:10.1140/epjc/s10052-015-3451-4 [arXiv:1408.3583 [hep-ex]].

[36] M. Aaboud et al. [ATLAS Collaboration], Phys. Rev. D 97, no. 11, 112001 (2018) doi:10.1103/PhysRevD.97.112001 [arXiv:1712.02332 [hep-ex]]; M. Aaboud et al. [ATLAS Collaboration], Phys. Rev. D 96, no. 11, 112010 (2017) doi:10.1103/PhysRevD.96.112010 [arXiv:1708.08232 [hep-ex]].

[37] CMS Collaboration [CMS Collaboration], CMS-PAS-SUS-16-039; A. M. Sirunyan et al. [CMS Collaboration], JHEP 1711, 029 (2017) [arXiv:1706.09933 [hep-ex]]; CMS Collaboration [CMS Collaboration], CMS-PAS-SUS-16-034.

[38] Z. Altn, . zdal and C. S. Un, Phys. Rev. D 97, no. 5, 055007 (2018) [arXiv:1703.00229 [hep-ph]].