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

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ABSTRACT: We explore t-b-τ Yukawa unification (YU) in a supersymmetric $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ model without imposing a discrete left-right (L-R) symmetry. A number of interesting solutions that are compatible with t-b-τ 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.

Contents

1 Introduction

Third family t-b-τ Yukawa Unification (YU) [1–3] arises naturally in the simplest versions of supersymmetric SO(10) and $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ (4-2-2) models and it has attracted a fair amount of attention in recent years [4–30]. 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-τ YU allows the gluino NLSP solutions in 4-2-2 [31–35] 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-τ YU to b-τ YU also allows stop NLSP solutions with $m_{\tilde{t}_1} \lesssim 1\,\mathrm{TeV}$ [36].

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 [37–39]. However, using the 210-plet yields 4-2-2 symmetry but the C-parity in this case is absent [40]. The spontaneous breaking of LR symmetry also avoids a potential domain wall problem [38]. Recent works [41, 42] 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-τ YU condition.

In the case of broken LR symmetry the universality between the $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$ 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

$$M_1 = \frac{3}{5}M_{2R} + \frac{2}{5}M_3 \ . \tag{1.1}$$

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 [43]. However, t-b-τ 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 [44].

In this paper we explore the low energy consequences of imposing t-b-τ 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-τ YU is imposed at $M_{\rm GUT}$ 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 [45] 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 $M_{\rm GUT}$ via the MSSM renormalization group equations (RGEs) in the $\overline{DR}$ regularization scheme. We apply the gauge coupling unification condition approximately as $g_3 \approx g_2 = g_1$, since g_3 can deviate from the unification by a few percent due to unknown GUT scale threshold corrections [46–48]. We only accept solutions in which g_3 deviates from unification up to 3%, at most. With the boundary conditions given at $M_{\rm GUT}$, all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale $M_{\rm Z}$.

In evaluating Yukawa couplings the SUSY threshold corrections [49] are taken into account at the common scale $M_{\rm SUSY} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. The entire parameter set is iteratively run between $M_{\rm Z}$ and $M_{\rm GUT}$ using the full 2-loop RGEs until a stable solution is obtained. To better account for 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 $M_{\rm SUSY}$, 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:

$$
\begin{aligned}
0.1 &\leq m_L &&\leq 10 \text{ TeV} \\
0.05 &\leq M_{2L} &&\leq 5 \text{ TeV} \\
-3 &\leq M_3 &&\leq 5 \text{ TeV} \\
-3 &\leq A_0/m_L &&\leq 3 \\
2 &\leq \tan\beta &&\leq 65 \\
-3 &\leq {\rm x_{LR}} &&\leq 3 \\
-3 &\leq {\rm y_{LR}} &&\leq 3 \\
0 &\leq {\rm x_d} &&\leq 3 \\
-1 &\leq {\rm x_u} &&\leq 2 \, .
\end{aligned}
\tag{2.1}
$$

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 $\tan\beta \equiv v_u/v_d$. $\mathrm{x_{LR}}$ measures the LR breaking in the scalar sector with $m_{2R} = \mathrm{x_{LR}}m_L$, 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 $M_{2R} = \mathrm{y_{LR}}M_{2L}$. 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 [50, 51]. The data points collected all satisfy the requirement of REWSB, with the neutralino in each case being the LSP. After collecting data, we impose the mass bounds on all particles [52] including the current bounds on the Higgs boson [53, 54] and the gluino [55]. In addition, we use the IsaTools package [56–61] to implement the phenomenological constraints from rare $B-$meson decays such as those from $\mathrm{BR}(B_s \to \mu^+\mu^-)$ [62], $\mathrm{BR}(B_s \to X_s\gamma)$ [63] and $\mathrm{BR}(B_u \to \tau\nu)$ [64]. We also apply the Planck bound on the relic density of LSP neutralino within 5σ [65]. The following experimental constraints along with their uncertainties are employed in our analyses:

$$m_h = 123 - 127 \text{ GeV}$$

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

$$0.8 \times 10^{-9} \leq \mathrm{BR}(B_s \to \mu^+\mu^-) \leq 6.2 \times 10^{-9} \ (2\sigma)$$

$$2.99 \times 10^{-4} \leq \mathrm{BR}(B \to X_s\gamma) \leq 3.87 \times 10^{-4} \ (2\sigma) \quad (2.2)$$

$$0.15 \leq \frac{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{MSSM}}}{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{SM}}} \leq 2.41 \ (3\sigma)$$

$$0.114 \leq \Omega_{\mathrm{CDM}}h^2 \leq 0.126 \ (5\sigma) \ .$$

In addition to these constraints, we quantify t-b-τ YU with the parameter $R_{tb\tau}$ as

$$R_{tb\tau} \equiv \frac{\mathrm{Max}(y_t, y_b, y_\tau)}{\mathrm{Min}(y_t, y_b, y_\tau)} \quad (2.3)$$

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

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. (2.2) as well as t-b-τ YU with the LHC bounds and future prospects. To this end, we employ the tools provided by the Smodels-v1.2.2. [66–69]. 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 [70, 71]. For each model, we use SUSY-HIT [72] to compute the decay ratios of the SUSY particles and PYTHIA [73] to produce the corresponding cross sections.
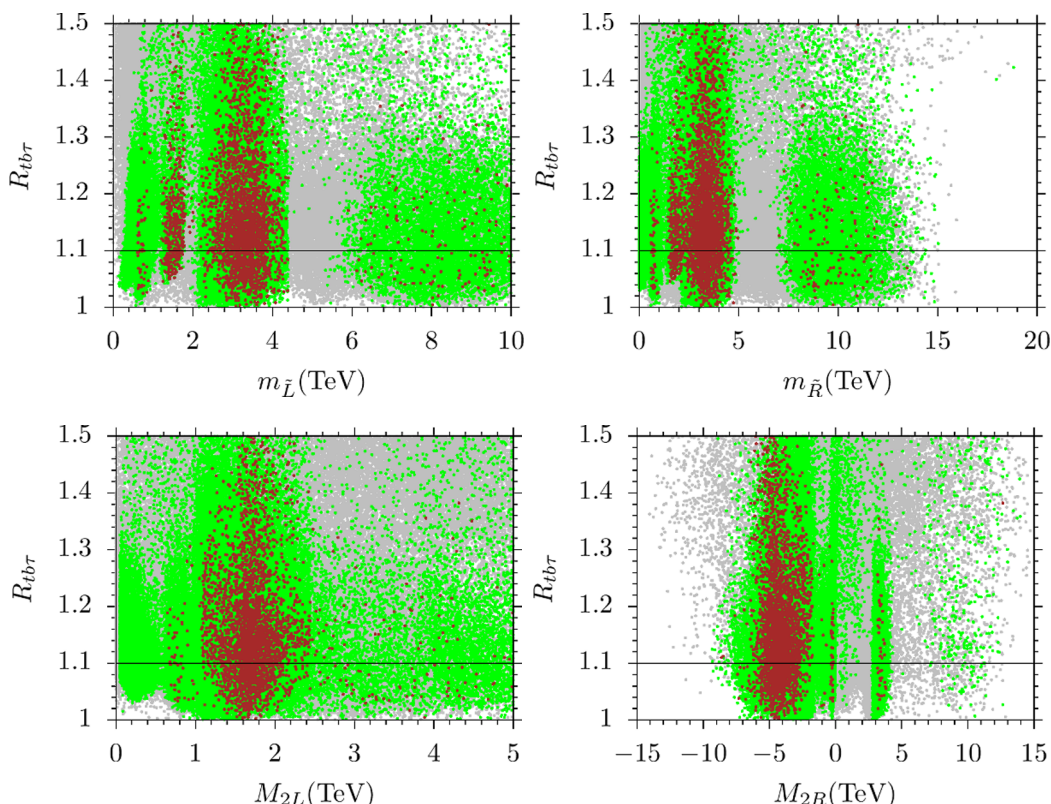
Figure 1. Plots in the $R_{tb\tau} - m_{\tilde{L}}$, $R_{tb\tau} - m_{\tilde{R}}$, $R_{tb\tau} - M_{2L}$ and $R_{tb\tau} - M_{2R}$ planes. All points are comparible with the REWSB and LSP neutralino conditions. Green points satisfy the mass bounds and constraints from rare $B-$meson decays. Brown points form a subset of green and they yield relic abundance of LSP neutralino consistent with the Planck measurements within 5σ. The regions below the horizontal lines correspond to $R_{tb\tau} = 1.1$ are considered as to be compatible with the t-b-τ Yukawa unification.

3 t-b-τ YU and DM Implications

In this section we present our results for t-b-τ YU within the 4-2-2 framework. Figure 1 displays the fundamental parameter space of t-b-τ YU in terms of the SSB scalar (top panels) and gaugino (bottom panels) mass terms with plots in the $R_{tb\tau} - m_{\tilde{L}}$, $R_{tb\tau} - m_{\tilde{R}}$, $R_{tb\tau} - M_{2L}$ and $R_{tb\tau} - M_{2R}$ 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 5σ. The horizontal line indicates the region with $R_{tb\tau} = 1.1$, and points below this line are considered as being in very good agreement with the t-b-τ Yukawa unification. The $R_{tb\tau} - m_{\tilde{L}}$ plane shows that t-b-τ YU can be realized within a wide range of $m_{\tilde{L}}$ from about $400\,\text{GeV}$ to $10\,\text{TeV}$. 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 $1\,\text{TeV}$, while t-b-τ YU condition restricts it at about $15\,\text{TeV}$ from above, as seen from the
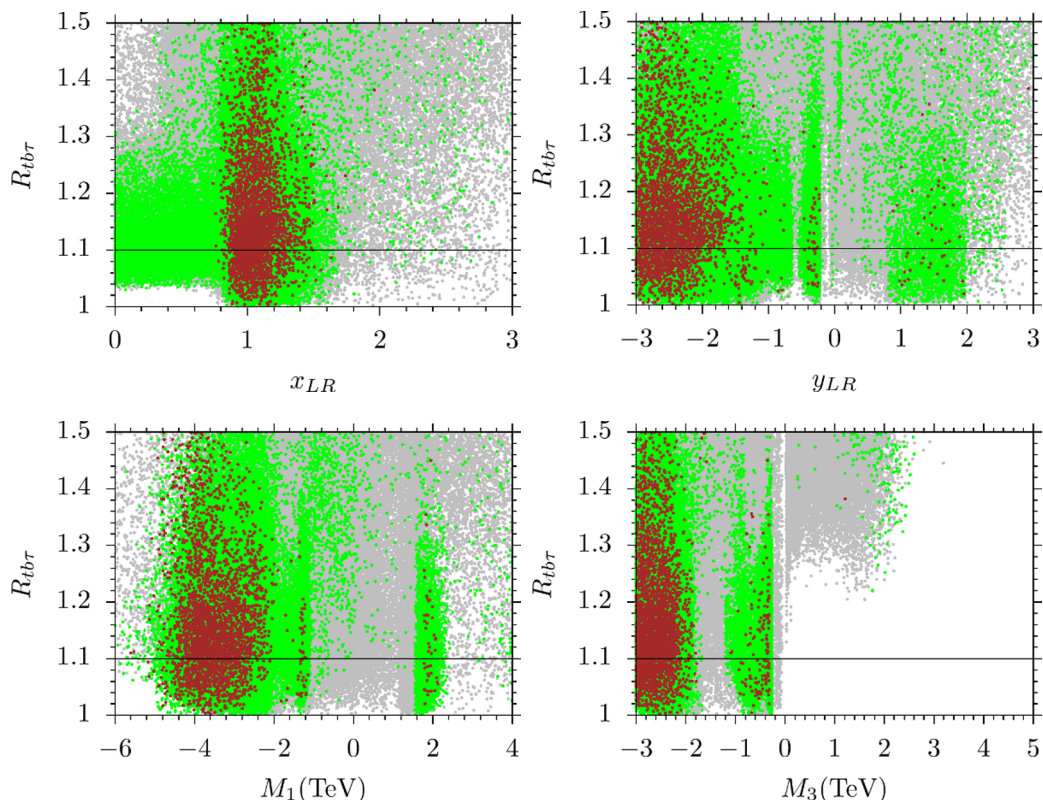
Figure 2. Plots in the $R_{tb\tau} - x_{LR}$, $R_{tb\tau} - y_{LR}$, $R_{tb\tau} - M_1$ and $R_{tb\tau} - M_3$ planes. The color coding is the same as in figure 1.

$R_{tb\tau} - m_{\tilde{R}}$ plane. The left-bottom plane displays the SSB mass term for M_{2L}, and as is seen, the t-b-τ YU solutions can be realized in a wide range of values for M_{2L} in our scan. It is bounded at about $800\,\mathrm{GeV}$ from below by the DM constraints. The mass term for the $SU(2)_R$ gaugino could lie in a wider range from about $-10\,\mathrm{TeV}$ to $4\,\mathrm{TeV}$ 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 $R_{tb\tau} - x_{LR}$, $R_{tb\tau} - y_{LR}$, $R_{tb\tau} - M_1$ and $R_{tb\tau} - M_3$ planes. The color coding is the same as in figure 1. Despite its wider range in our scan, the $R_{tb\tau} - x_{LR}$ 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-τ YU, as seen from the $R_{tb\tau} - y_{LR}$ plane with $|y_{LR}|$ as large as 3. Even though t-b-τ 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 $R_{tb\tau} - M_1$ plane where M_1 is mostly negative and its magnitude can be as high as about $5\,\mathrm{TeV}$, while it is restricted to $M_1 \sim 2\,\mathrm{TeV}$ 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-τ
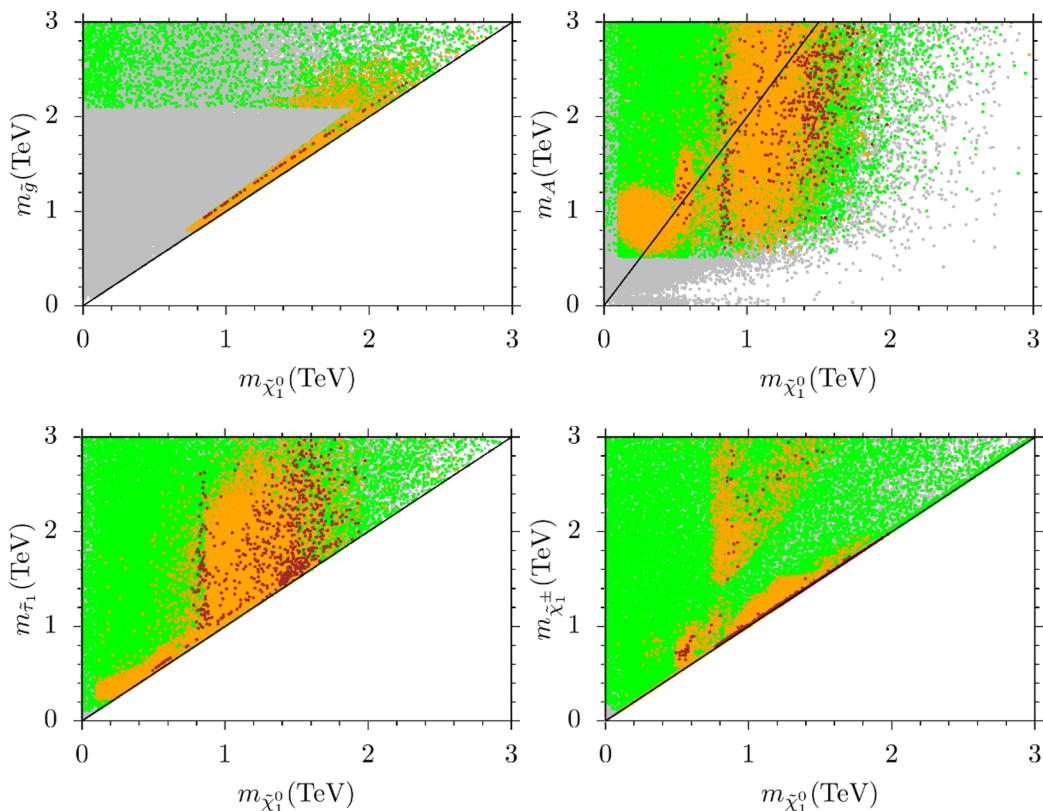
Figure 3. Plots in the $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$, $m_A - m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ planes. All points are compatible with the REWSB and LSP neutralino conditions. Green points satisfy the mass bounds and constraints from rare B−meson decays. Orange points form a subset of green and they are compatible with t-b-τ Yukawa unification. Brown points are a subset of orange, they are consistent with the Planck bound on the relic abundance of LSP neutralino within 5σ. 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 $m_A = 2m_{\tilde{\chi}_1^0}$.

YU condition allows only negative M_3 values. In this context, according to eq. (1.1), one can expect very 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-τ YU. Brown points are a subset of orange and they are consistent with the Planck bound on the relic abundance of LSP neutralino within 5σ. 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-τ 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-τ YU
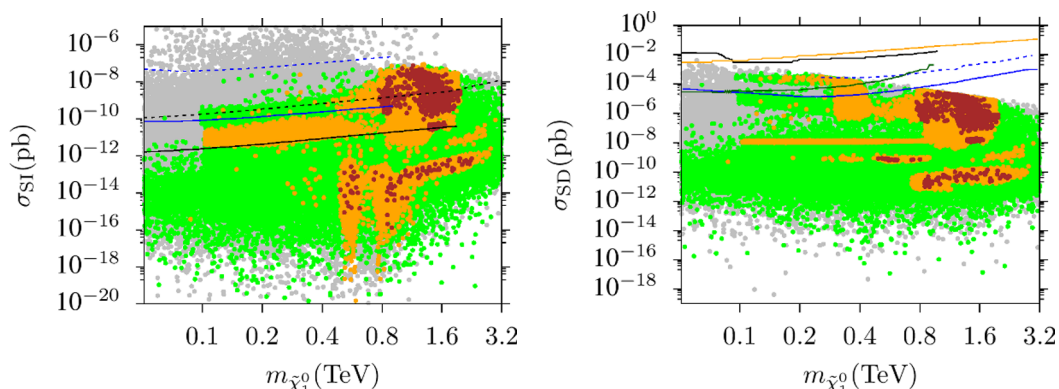
Figure 4. Spin-independent (left) and spin-dependent (right) scattering cross-sections versus the LSP neutralino mass. In the $\sigma_{SI} - m_{\tilde{\chi}_1^0}$ plane, the dashed (solid) blue line represents the current (future) results from the SuperCDMS experiment [74]. The dashed (solid) black line indicates the current (future) results from the LUX-Zeplin experiment [75]. In the $\sigma_{SD} - m_{\tilde{\chi}_1^0}$ plane, the solid black line represents the currrent bound from Super-K [76], and the solid orange line is set by the LUX results [77]. The green line is obtained from collider analyses [78], and the dashed (solid) blue line shows the current (future) results from IceCube DeepCore.

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 $1 \lesssim m_A \lesssim 3\,\text{TeV}$, and stau-neutralino and chargino-neutralino coannihilation solutions if $0.6 \lesssim m_{\tilde{\tau}_1} \lesssim 1.6\,\text{TeV}$. 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 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 [74]. The dashed (solid) black line indicates the current (future) results from the LUX-Zeplin experiment [75]. In the $\sigma_{SD} - m_{\tilde{\chi}_1^0}$ plane, the solid black line represents the currrent bound from Super-K [76], and the solid orange line is set by the LUX results [77]. The green line is obtained from collider analyses [78], 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.

Most of the models allowed by the constraints listed in eq. (2.2) and compatible with t-b-τ 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-b-τ 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 [79, 80]. Figure 3 also shows that the stau can be as light as 500 GeV or so, consistent with all the constraints and t-b-τ 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 [81–83]. 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 $t-b-\tau$ YU, we present five benchmark points that are compatible with the experimental constraints. All masses are given in GeV, and the masses shown in red indicate the mass degeneracy with the LSP neutralino within 10%, except Point 3, in which the red color emphasizes the mass relation between the neutral Higgs bosons and LSP neutralino, namely $m_{H,A} \simeq 2m_{\tilde{\chi}_1^0}$. Points 1 and 2 depict solutions for the gluino-neutralino coannihilation scenario with NLSP gluino masses of about 933 and 2357 GeV, respectively. 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 of these three species lead to the desired relic DM abundance. Point 5 is a typical solution for Higgsino-like DM with the chargino and neutralino masses given as $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^0}$. The spin-independent cross-section is calculated to be slightly below the current LUX result and so this scenario will be tested relatively soon.

In addition, Point 3 in table 1 depicts solutions with relatively light Higgs bosons whose masses are about 1 TeV. Such solutions are severely constrained if these Higgs bosons mostly decay into leptons [84, 85]. On the other hand, the solutions exemplified with Point 3 predict that these Higgs bosons mostly decays into top and bottom quarks with $\mathrm{BR}(H, A) \to b\bar{b} \approx \mathrm{BR}(H^\pm \to tb) \simeq 85\%$. The analyses for these decay channels lead to the mass bounds as $m_{H,A,H^\pm} \gtrsim 800$ GeV for moderate $\tan\beta$ values [86, 87]. In this context, the predictions of our model can also be tested through the decay channels of the extra Higgs bosons in Run-3 and HL$-$LHC.

	Point 1	Point 2	Point 3	Point 4	Point 5
$m_{\tilde{L}}$	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
$A_0/m_{\tilde{L}}$	-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
$m_{\tilde{R}}$	11460	7398	646.9	1740	3111
M_{2R}	3188	-7399	-210.1	-4221	-5811
μ	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, 1638	850.6, 853.3
$m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}$	7757, 7757	5962, 5962	3190, 3190	3165, 3165	2044, 2058
$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$	2535, 7710	3439, 5962	713.8, 3162	1389, 3137	871.5, 2018
$M_{\tilde{g}}$	933.9	2357	5954	5781	5360
$m_{\tilde{u}_L}, m_{\tilde{u}_R}$	8183, 11379	9906, 7462	5172, 5145	5163, 5294	6019, 5540
$m_{\tilde{t}_1}, m_{\tilde{t}_2}$	4075, 9113	4763, 7707	4371, 4506	4331, 4564	3523, 4338
$m_{\tilde{d}_L}, m_{\tilde{d}_R}$	8183, 11558	9906, 7623	5173, 5151	5164, 5258	6019, 5516
$m_{\tilde{b}_1}, m_{\tilde{b}_2}$	4131, 8784	3491, 7690	4340, 4490	4327, 4466	3556, 4327
$m_{\tilde{\nu}_{e,\mu}}, m_{\tilde{\nu}_\tau}$	8104, 6498	9720, 8794	909.3, 905.6	1668, 1449	4042, 3245
$m_{\tilde{e}_L}, m_{\tilde{e}_R}$	8110, 11641	9714, 7811	914.7, 843.7	1667, 2236	4043, 3600
$m_{\tilde{\tau}_1}, m_{\tilde{\tau}_2}$	6509, 9396	5167, 8783	605.6, 988.1	1436, 1896	1178, 3245
$\sigma_{\text{SI}}\ (pb)$	0.40×10^{-14}	0.71×10^{-12}	0.13×10^{-13}	0.47×10^{-10}	0.19×10^{-9}
$\sigma_{\text{SD}}\ (pb)$	0.16×10^{-10}	0.48×10^{-10}	0.68×10^{-9}	0.17×10^{-7}	0.29×10^{-6}
Ωh^2	0.116	0.124	0.122	0.120	0.125
$R_{tb\tau}$	1.04	1.08	1.09	1.08	1.09

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 $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^0}$.

4 Conclusion

We have explored the LHC and DM implications of t-b-τ 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 $m_{\tilde{g}} \lesssim 2.4\,\mathrm{TeV}$. Without the NLSP constraint the gluino can be as heavy as about $6\,\mathrm{TeV}$, 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 $1 \lesssim m_A \lesssim 3\,\mathrm{TeV}$. Similarly, the stau-neutralino and chargino-neutralino coannihilation processes can be realized with the stau and chargino masses in the range $0.6 \lesssim m_{\tilde{\tau}}, m_{\tilde{\chi}_1^{\pm}} \lesssim 2\,\mathrm{TeV}$.

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 $3\,\mathrm{TeV}$, while squarks of the first two families are relatively heavy ($\gtrsim 5\,\mathrm{TeV}$). In addition, we identify some solutions which predict the heavy Higgs bosons masses at about $1\,\mathrm{TeV}$. These Higgs bosons mostly decay into the top and bottom quarks, and they are expected to be tested in Run-3 and HL$-$LHC through their hadronic decays.

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