

LHC and dark matter implications of t - b - τ Yukawa unification in split SUSY GUTs

Mureed Hussain^{*}*Higher Education Department Punjab, New Anarkali Road, Shahrah-e-Quaid-e-Azam, Lahore 54000, Pakistan*Rizwan Khalid[†]*School of Science and Engineering, Lahore University of Management Sciences (LUMS), Opposite Sector U, D.H.A, Lahore 54792, Pakistan*Cem Salih Un[‡]*Department of Physics, Bursa Uludağ University, TR16059 Bursa, Turkey*

(Received 4 July 2025; accepted 23 December 2025; published 30 January 2026)

We investigate a grand unification inspired version of the minimal supersymmetric standard model (MSSM) based on a left-right symmetric 4-2-2 gauge group, incorporating Yukawa coupling unification and current phenomenological constraints. Utilizing a split soft supersymmetry-breaking parameter space motivated by flavor symmetries, we analyze the implications of recent results from ATLAS, CMS, LHCb, and dark matter direct detection experiments. Our numerical scans, conducted with SARAH and SPheno, identify viable low-energy regions consistent with third-generation Yukawa unification, the observed Higgs boson mass, dark matter relic density, and flavor observables such as $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$ and $B_u \rightarrow \tau \nu_\tau$. Our findings suggest that while current bounds severely constrain much of the MSSM-like parameter space, substantial regions remain experimentally viable and testable in the ongoing LHC run and next-generation dark matter experiments.

DOI: [10.1103/physrevd.113.015044](https://doi.org/10.1103/physrevd.113.015044)

I. INTRODUCTION

The Large Hadron Collider (LHC) has established the Standard Model of particle physics (SM) [1,2] as an excellent effective field theory at the $O(10 \text{ TeV})$ scale with the experimental program of the ATLAS [3], CMS [4], and LHCb [5] collaborations. These experiments are also at the forefront of probing physics beyond the SM (BSM) and have managed to rule out low-scale manifestations of popular BSM scenarios. Within the context of this manuscript, the ATLAS and the CMS experiments have provided stringent lower mass bounds on “new” particles [6–13] suggested by the minimal supersymmetric standard model (MSSM). Likewise, the LHCb provides an indirect check on BSM physics by probing rare decays of B hadrons and providing increasingly precise bounds on, for example, the

branching ratios $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, and $B_u \rightarrow \tau \nu_\tau$. The standard model of cosmology predicts dark matter (DM) as an important constituent in the energy budget (27%) of the Universe [14]. Experiments have, over the past couple of decades, explored the possibility of dark matter particles via their direct couplings with nuclei [15–23] or in indirect searches [24–30]. In particular, the null result of DM searches has also helped constrain the parameter space of various models beyond the SM.

In this manuscript we consider the effect of the latest bounds from the ATLAS, CMS, and LHCb experiments as well as the dark matter searches to explore the low scale implications and confront a grand unification (GUT) version of the MSSM with the current experimental results. In particular, we address the question of t - b - τ third generation Yukawa coupling unification consistent with dark matter and LHC constraints and focus on the parameter space that can potentially be tested in the current run at the LHC and dark matter search experiments. To be precise, we have used a left-right symmetric model based on the $SU(4)_c \times SU(2)_L \times SU(2)_R$ [31,32] gauge group to feed our GUT scale boundary conditions on the soft supersymmetry breaking (SSB) parameters within the framework of gravity mediated supersymmetry (SUSY) breaking [33,34].

^{*}Contact author: mhussain617@gmail.com

[†]Contact author: rizwan_khalid@lums.edu.pk

[‡]Contact author: cemsalihun@uludag.edu.tr

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

Within the context of $SU(4)_c \times SU(2)_L \times SU(2)_R$ inspired MSSM models, several recent studies [35,36] have focused on spectroscopy as we do in this manuscript. However, while these papers are recent, there are updated results from the LHC both in terms of direct mass bounds on SUSY particles and on branching ratios of rare B decays that these studies do not incorporate. More importantly, we have addressed the question of Yukawa coupling unification consistent with dark matter and various LHC constraints. Further, we have been able to find interesting solutions with a more restrictive parameter set.

We underscore the fact that whereas a significant portion of the low-energy parameter space in MSSM-like models has been explored (and excluded) by the LHC [37–39], there still is quite interesting low-scale phenomenology that is consistent with current bounds. Therefore, it is interesting to ask what kind of minimalist GUT inspired scenarios can provide a low scale supersymmetric phenomenology, all the while remaining consistent with the latest bounds from direct SUSY and dark matter searches, along with the theoretically well motivated constraints arising from requiring Yukawa coupling unification.

In Sec. II, we provide the details of the model that we have employed in the current analysis as well as the experimental constraints that we have used. Following this, we present our results in Sec. III, and discuss the phenomenology relevant to the parameter space consistent with experimental constraints and theoretical requirements. We finally present our conclusions in Sec. IV.

II. MODEL PARAMETERS AND PHENOMENOLOGICAL CONSTRAINTS

One of the markers of many GUT models is Yukawa unification, which can be realized in models based on E_6 and $SO(10)$ symmetries. Such symmetries have a variety of representations in which the MSSM superfields can reside together with many other fields that play significant roles in the symmetry breaking and alter the low scale implications (see, for instance, [40–46]). In our work we follow a simple breaking mechanism in which $SO(10)$ breaks to its maximal subgroup $SU(4)_c \times SU(2)_L \times SU(2)_R$ (hereafter, for short, 4-2-2) [31,32,47] which in addition to predicting Yukawa coupling unification [48,49] also allows for nonuniversal soft SUSY breaking gaugino mass terms [50–54]. In particular, the SM gauge structure can be produced, for example, from a left-right symmetric model via the breaking mechanism,

$$SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow SU(2)_L \times U(1)_Y.$$

If the $U(1)_X$ is the robust $B - L$ symmetry, these models also provide a natural explanation for the conservation of the difference $B - L$, which has consequences for understanding the origin of the observed matter/antimatter asymmetry in the Universe [55,56]. Charge quantization

can be explained if $U(1)_{B-L}$ is formed by a $SU(4)_c$ group using the fact that $SU(3) \times U(1) \subset SU(4)_c$. In our work we follow the following breaking pattern,

$$\begin{aligned} SU(4)_c \times SU(2)_L \times SU(2)_R &\rightarrow \\ SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} &\rightarrow \\ SU(3)_c \times SU(2)_L \times U(1)_Y. \end{aligned}$$

This breaking mechanism can be realized if $SO(10)$ breaks into 4-2-2 via the 54 dimensional Higgs 54_H acquiring a vacuum expectation value (VEV) in the 4-2-2 singlet direction (1, 1, 1), and 4-2-2 subsequently breaks into $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ by the 210 dimensional Higgs acquiring a VEV. The conservation of R parity depends on the breaking mechanism of $U(1)_{B-L}$ and can be arranged if the 126 dimensional representations 126_H and $\overline{126}_H$ are used. The fields in these representations do not have direct Yukawa coupling with the MSSM matter superfields, except those in 126_H ; thus they do not complicate the Yukawa interactions. However, one can also include more Higgs representations to accommodate the consistent masses for the SM fermions [57]. Such a setup usually breaks the Yukawa unification (YU). On the other hand, if one assumes that the MSSM Higgs fields solely reside in 10_H and the other Higgs fields residing in higher dimensional representations negligibly interact with the third family fermions, YU can be maintained for the third family [58]. We assume that the various steps in symmetry breaking occur at around the scale M_{GUT} . It is important to note, however, that the fields residing in the (1, 2, 2) in decomposition of the ten-dimensional representation of $SO(10)$ do not decouple. Indeed, the fields in this representation further decompose into the H_u and H_d in order to accommodate a consistent electroweak symmetry breaking pattern [59]. We also note that as a consequence of our assumption about symmetry breaking at M_{GUT} , the $U(1)_{B-L}$ gauge boson and associated gaugino are also very heavy and decouple from the spectrum. In summary, the effective spectrum below M_{GUT} is populated by the MSSM particles.

The left-right symmetry and anomaly cancellation for $U(1)_{B-L}$ does require right-handed neutrinos in the spectrum. They can, in principle, interact via Yukawa interactions with H_u , but tiny masses of left-handed neutrinos require the relevant Yukawa coupling to be of the order of about 10^{-3} if the right-handed neutrinos are quite heavy [60] unless one imposes the inverse seesaw mechanism [61–63]. In this case, the MSSM phenomenology remains almost intact, since the right-handed neutrinos decouple at sufficiently high scales. Therefore, we ignore the effects from the right-handed neutrinos and the spectrum is effectively the MSSM under the GUT scale in our analyses.

In 4-2-2 models, the minimalist choice is to take a universal mass parameter m_0 for all sfermion (sleptons and

squarks) SSB mass terms at the GUT scale. However, the SUSY corrections to the Higgs mass require heavy [$O(\text{TeV})$] third family sfermions that would inevitably lead to a heavy SUSY spectrum for even the first two family sfermions. Motivated with focusing on LHC accessible SUSY solutions, we consider split soft SSB mass term assignment parameters, with m_{12} the common mass term for the first two families' sfermions and m_3 for the third family's sfermions. Such an assignment can be motivated theoretically using flavor symmetries like $SU(2)_f$ [64–66].

The choice of working with a left-right symmetric 4-2-2 model, relates the gaugino masses at the GUT scale, via

$$M_1 = \frac{3}{5}M_2 + \frac{2}{5}M_3, \quad (1)$$

and so leads to a more constrained model. This, again is done to allow for some freedom in the gaugino sector, but doing so in a minimalist way. The sign of the bilinear Higgs parameter plays a crucial role from the point of view of Yukawa coupling unification with $\text{sgn}(\mu) = -1$ being preferred [67,68]. On the other hand, the SUSY contributions to Δa_μ are proportional to μM_2 . These considerations motivate our choice of $\mu, M_2 < 0$. The so-called 4-2-2 inspired MSSM parameter space that we scan is given in Table II.

Parameter(s)	Min value	Max value
m_{12}	0	1.5 TeV
m_3, m_{Hu}, m_{Hd}	0	5 TeV
M_2	-2 TeV	0
M_3	0	5 TeV
A_0/m_3	-3	3
$\tan \beta$	0	60

We have used the *Mathematica* package SARAH [69,70], which generates the source code for the particle spectrum generator SPheno [71,72], and MicrOMEGAs [73], which calculates the DM observables. We have employed a modified Metropolis-Hastings algorithm to scan the relevant parameter space. In our scanning process, we have only retained solutions for which the neutralino is the lightest supersymmetric particle (LSP) to accommodate the DM implications.

Branching ratios of rare B processes ($b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$ and $B_u \rightarrow \tau\nu_\tau$) have been used to constrain the parameter space of new physics models [64–66,74–79]. We have applied constraints from branching fractions of the rare decays $B \rightarrow X_s\gamma$ [80], $B_s \rightarrow \mu^+\mu^-$ [81,82], $B_u \rightarrow \tau\nu_\tau$ [83,84] given as,

$$\begin{aligned} \text{BR}(B \rightarrow X_s\gamma) &= (3.49 \pm 0.19) \times 10^{-4}, \\ \text{BR}(B_s \rightarrow \mu^+\mu^-) &= (3.34 \pm 0.27) \times 10^{-9}, \\ \text{BR}(B_u \rightarrow \tau\nu_\tau) &= (1.09 \pm 0.24) \times 10^{-4}. \end{aligned} \quad (2)$$

The latest bounds on the masses of the smuon, stau, chargino, and neutralino are reported by the ATLAS and

CMS collaborations as exclusion limits in 2D neutralino-smuon, neutralino-stau, and neutralino-chargino planes [6–8]. We have applied the mass bounds on the supersymmetric particles as arising from direct searches at the ATLAS and CMS experiments at the 95% exclusion limit. The details are given in Appendix A. Further, we impose the following mass bounds [85–88]

$$\begin{aligned} m_{\tilde{\chi}_1^0} &\gtrsim 100 \text{ GeV}, \\ 122 \text{ GeV} &\lesssim m_h \lesssim 128 \text{ GeV}. \end{aligned} \quad (3)$$

Additionally, we report regions of the parameter space that satisfy the upper bound on the cosmological abundance of a dark matter relic, which in our case is the neutralino, i.e., $\Omega h^2 \lesssim 0.12$ [14]. We do not consider the lower bound due to two reasons: (1) the possibility of multiple sources for dark matter, and (2) a low dark matter relic density ($\Omega h^2 \lesssim 0.12$) in the MSSM is very finely tuned in the case of binolike solutions, which rely on some sort of resonant annihilation/coannihilation mechanism to cure the relic density. In these cases, one can almost be certain of finding a point in the neighborhood with a “correct” relic density if we consider only the upper bound. We will later discuss that we have binolike and winolike solutions in our scan.

It is important to comment on the recent results announced regarding the computation of the muon anomalous magnetic moment Δa_μ [89,90]. It seems that the community is converging to an understanding that the seemingly alarming anomaly [91,92] in this sector has disappeared and now the SM result agrees with the experimental one within 3σ . Insofar as this study is concerned, we are using the current 2σ upper bound ($0 \lesssim \Delta a_\mu \lesssim 6.75 \times 10^{-10}$) to constrain our available parameter space. In so doing, we ensure that we are doing no worse than the SM on the side of the lower bound on Δa_μ .

III. RESULTS

We begin the discussion of our results by looking at the behavior of the model parameters given experimental constraints. In Fig. 1 we discuss results in the $(m_{12}/m_3, M_2)$ plane and show the effect of applying various constraints successively.

In grey we show all the data that was collected (consistent with neutralino LSP), while the yellow points are a subset of the grey points and satisfy the constraints from B physics given in Eq. (2). The blue points form a subset of yellow points that additionally satisfy the various bounds on masses of particles provided by the ATLAS and the CMS experiments as explained in Sec. II. In orchid we show the subset of blue points that, in addition, satisfy the bounds on cosmological abundance of dark matter. Finally, the dark red points comprise the subset of orchid points that is consistent with the muon Δa_μ result as discussed in Sec. II, in addition to all the other constraints.

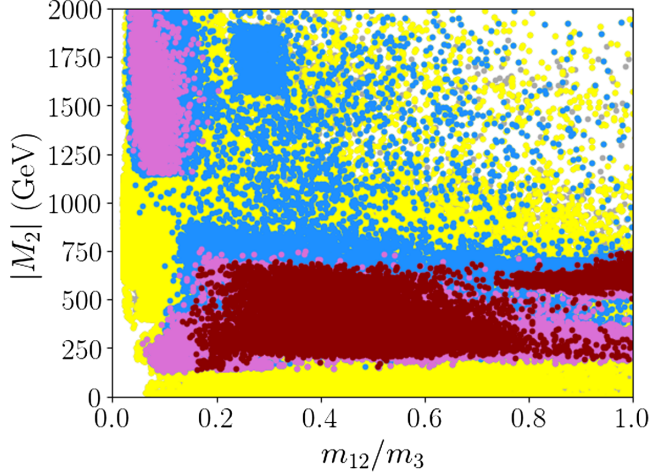


FIG. 1. $(m_{12}/m_3, M_2)$ plane. The constraints are shown in different colors and applied successively in the order: data consistent with neutralino LSP (grey), B Physics constraints (yellow), mass bounds from ATLAS and CMS (blue), cosmological abundance of dark matter (orchid), and points satisfying Δa_μ bounds within the 2σ range (red). We emphasize that the constraints are applied successively, so that red points satisfy all constraints considered while orchid points satisfy all constraints other than the bounds coming from Δa_μ .

The first thing to note about Fig. 1 is the impact of the particle mass bounds shown in blue preferring solutions with $m_{12}/m_3 \lesssim 0.5$. This is indicative of the stringent constraint on the gluino mass, which benefits from a large correction from m_3 . The yellow points in the region of small m_{12}/m_3 can clearly be seen to be excluded by the mass bounds for $|M_2| \lesssim 900$ GeV. The reason for this is the ATLAS bounds in the chargino-neutralino plane. Furthermore, the points consistent with dark matter relic density (orchid points) prefer the lower range of $|M_2| \lesssim 750$ GeV. Here the main channel for efficient dark matter annihilation in our parameter space is bino-wino coannihilation. In the case of the dark matter consistent region for larger $|M_2|$ in this figure, the dominant mechanism is selectron (and smuon, which is nearly degenerate with selectron) coannihilation, which is facilitated by a small m_{12}/m_3 . It is to be noted that the $800 \text{ GeV} \lesssim |M_2| \lesssim 1100 \text{ GeV}$ range is being excluded by the mass bounds in the neutralino-chargino plane, which exclude intermediate mass charginos [93].

We also observe from Fig. 1 that the region of parameter space allowed by the Δa_μ constraint (points in red) favors either a small $|M_2|$ (corresponding to light wino) or a small m_{12}/m_3 that allows for the possibility of a light muon-neutrino ($\tilde{\nu}_\mu$).

In Fig. 2 we show results in the $(A_0/m_3, \tan\beta)$ plane. We follow the same color coding as we did for Fig. 1. In Fig. 2 we have also drawn a contour corresponding to $R_{tb\tau} \simeq 1.1$, where

$$R_{tb\tau} \equiv \frac{\max(y_t, y_b, y_\tau)(M_{GUT})}{\min(y_t, y_b, y_\tau)(M_{GUT})}$$

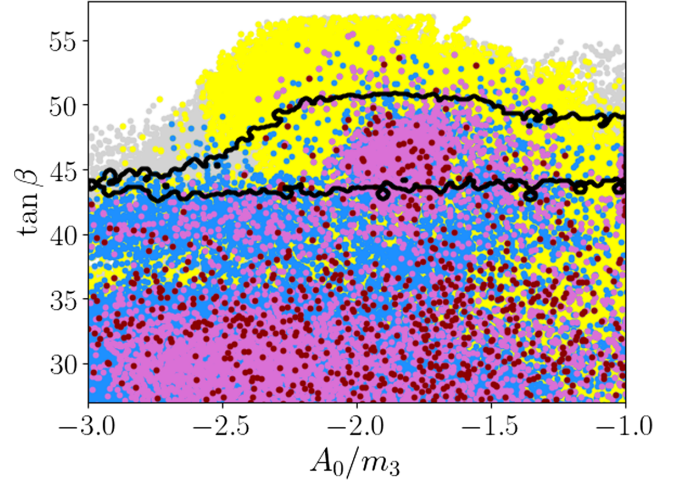


FIG. 2. $(A_0/m_3, \tan\beta)$ plane. Color coding is the same as in Fig. 1. Further we show the contour (in black) corresponding to $R_{tb\tau} \simeq 1.1$.

is the ratio of the maximum of the t, b, τ Yukawa couplings to the minimum of them and provides an appropriate parameter to quantify Yukawa coupling unification. We can see from Fig. 2 that Yukawa coupling unification favors large $\tan\beta$ solutions with $43 \lesssim \tan\beta \lesssim 52$, as expected. We can see from the density of points in blue, orchid, and dark red falling into the $R_{tb\tau} \simeq 1.1$ contour that we should expect Yukawa unified solutions consistent with all the experimental constraints that we consider. While Fig. 2 is suggestive, we can confirm that no particular value of $A_0/m_3 < 0$ is needed for Yukawa unification. In particular, while it is not apparent from this figure, one can accommodate solutions with even $R_{tb\tau} \rightarrow 1$ realized in our model [68,94]. In addition, it is also obvious from the contour that a broad range of A_0/m_3 values provide Yukawa unified solutions consistent with all experimental constraints.

In Fig. 3 we focus on the type of the dark matter solutions that we have found in our scan. We show the results in the $(\Omega h^2, R_{tb\tau})$ plane with points in blue satisfying the B Physics and mass bounds as in the case of the previous figures. The pink (green) points form that subset of blue points for which $\Omega h^2 \lesssim 0.12$ and which are predominantly wino (bino) in their constitution with the wino (bino) component larger than 90%. We refer here to Baer *et al* who show that in cases with opposite sign gauginos there is no continuous change between a binolike and winolike neutralino and this happens rather abruptly [95]. We have plotted the green points after the pink so some of them are hidden underneath. We have also drawn two horizontal lines in this plane corresponding to $R_{tb\tau} = 1.05, 1.10$ signifying the region of 5% and 10% or better Yukawa coupling unification. As explained earlier, we can see solutions with $R_{tb\tau} \rightarrow 1$ in the case of both winolike and binolike dark matter consistent with all other constraints.

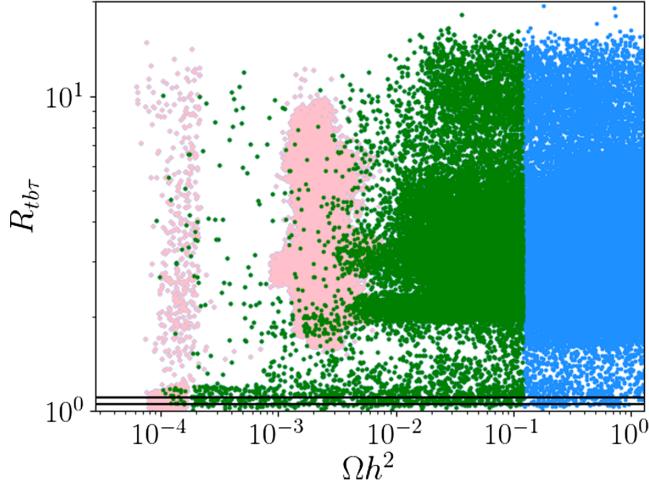


FIG. 3. $(\Omega h^2, R_{tb\tau})$ plane. The blue points satisfy B Physics constraints and mass bounds as in the previous figures. The pink (green) points form that subset of blue points that are predominantly wino (bino) in their constitution and have $\Omega h^2 \lesssim 0.12$. The horizontal lines correspond to $R_{tb\tau} = 1.05, 1.10$.

In Fig. 4 we present our results in the $(m_{H_d}/m_{H_u}, M_1)$ plane. We can infer from this figure that the dark matter relic density favors $|M_1| \gtrsim 200$ GeV but we want to emphasize on the fact that points with $M_1 \lesssim 200$ GeV do have the correct relic density (due to, for instance, Z pole and SM-like Higgs pole region) but are excluded by mass bounds on various particles.

We can see a predictable behavior in Fig. 4 from the point of view of Δa_μ wherein $M_1 \lesssim 1.5$ TeV is preferred. This is to be expected as M_1 is correlated with the LSP mass and so sets a scale for any SUSY contribution to SM processes.

We now turn our attention to the various dark matter allowed scenarios that can be found in our model and are consistent with the various experimental constraints we have discussed. In Fig. 5 we show the smuon coannihilation

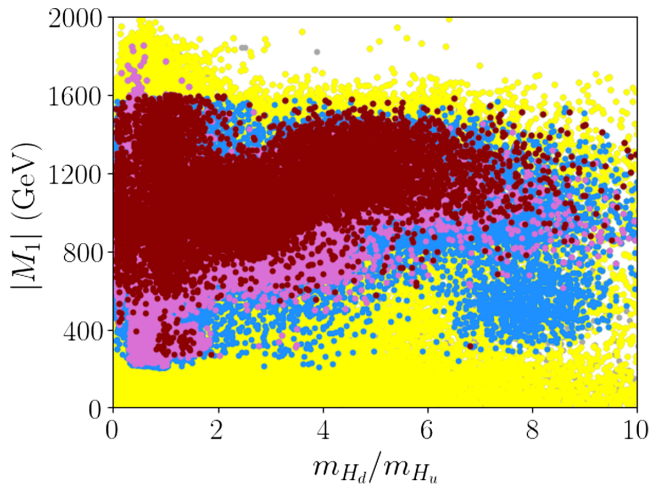


FIG. 4. $(m_{H_d}/m_{H_u}, M_1)$ plane. Color coding is the same as in Fig. 1.

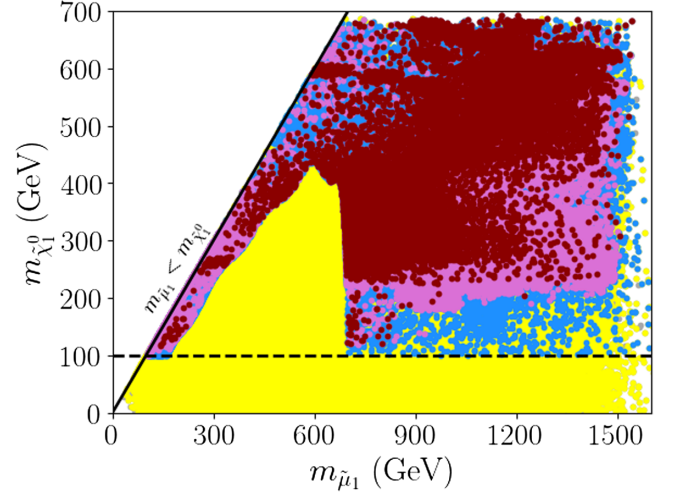


FIG. 5. $(m_{\tilde{\mu}_1}, m_{\tilde{\chi}_1^0})$ plane. Color coding is the same as in Fig. 1.

region (orchid and red) next to the line $m_{\tilde{\chi}_1^0} = m_{\tilde{\mu}_1}$. The selectron and the smuon in our model are effectively degenerate, since their masses are determined by m_{12} and do not split much via the renormalization group equations. Thus the solutions in this plane also indicate selectron coannihilation. The peculiar triangular shape of the yellow region is due to the ATLAS constraints in the $(m_{\tilde{\mu}_1}, m_{\tilde{\chi}_1^0})$ plane with the blue, orchid, and red points satisfying these constraints. The blue band sans orchid in the roughly rectangular region $m_{\tilde{\mu}_1}/\text{GeV} \gtrsim 700$ and $160 \lesssim m_{\tilde{\chi}_1^0}/\text{GeV} \lesssim 180$ arises as chargino coannihilation is the main mechanism of curing the dark matter relic density in this neighborhood. This region is naturally sensitive to the ATLAS bounds in the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$ plane, and we did not find consistent solutions in our scan. This is likely a numerical artifact of our simulation.

We see the general features seen in Fig. 5 repeat in Fig. 6 where we now shift focus to the $(m_{\tilde{\nu}_1}, m_{\tilde{\chi}_1^0})$ plane. We can

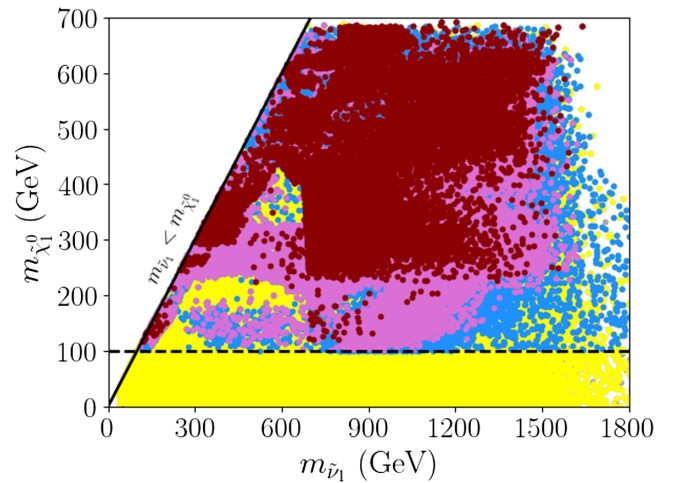
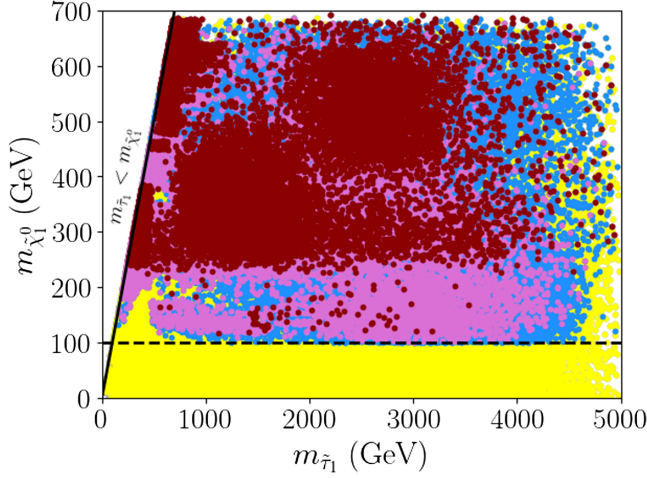


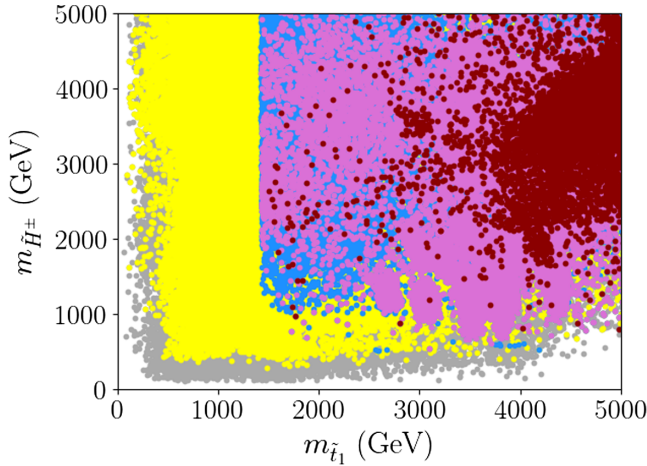
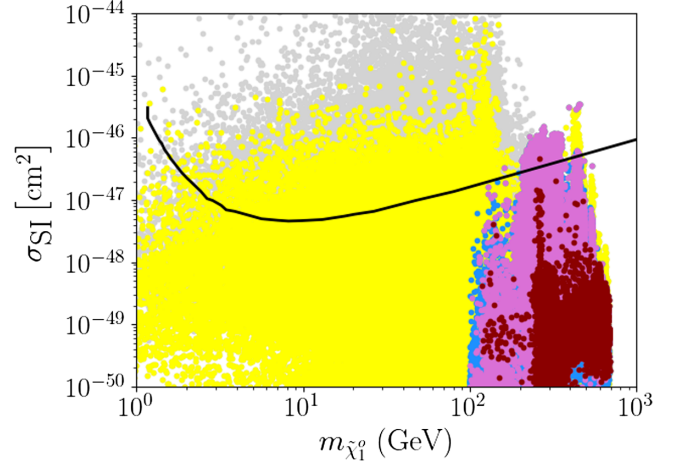
FIG. 6. $(m_{\tilde{\nu}_1}, m_{\tilde{\chi}_1^0})$ plane. Color coding is the same as in Fig. 1.


 FIG. 7. $(m_{\tilde{\tau}_1}, m_{\tilde{\chi}_1^0})$ plane. Color coding is the same as in Fig. 1.

see the sneutrino-coannihilation region along the line $m_{\tilde{\chi}_1^0} = m_{\tilde{\nu}_1}$. In this plane, the typical channel for efficient neutralino annihilation mostly involves the chargino, the sneutrino, and the selectron/smuon for $m_{\tilde{\nu}_1} \lesssim 1500$ GeV, with the sneutrino contribution significant only when it is the next to lightest supersymmetric particle (NLSP). Similarly, in Fig. 7 we can clearly see the stau-coannihilation region with a neutralino as light as ~ 200 GeV.

In Fig. 8, we present our results in the $(m_{\tilde{t}_1}, m_{H^\pm})$ plane. As the decay rates of rare B meson receive SUSY contributions from Higgs sector and stop, we can see that the constraints from the branching ratios of the B decays given in Sec. II put lower mass bounds on both $m_{H^\pm}$ and $m_{\tilde{t}_1}$ that can be seen as the visible grey regions where these masses are “small.”

We now focus our attention on ground based dark matter detection experiments that put limits on the spin-independent (σ_{SI}) and spin-dependent (σ_{SD}) nucleon-weakly interacting massive particle (WIMP) cross sections. Currently the most stringent bounds on σ_{SI} and σ_{SD}


 FIG. 8. $(m_{\tilde{t}_1}, m_{H^\pm})$ plane. Color coding is the same as in Fig. 1.

 FIG. 9. $(m_{\tilde{\chi}_1^0}, \sigma_{SI})$ plane. Color coding is the same as in Fig. 1. The black line shows the latest bounds on the WIMP-nucleon spin independent cross section by the LUX-ZEPLIN Collaboration [96].

(neutron) are reported by the LUX-ZEPLIN collaboration while PICO is competitive in the case of the σ_{SD} (proton) case. In Fig. 9 we plot the σ_{SI} -nucleon cross sections as a function of the neutralino mass. We show, conservatively, the 90% exclusion limit incorporating the 2σ uncertainty in the experimental result as a solid line in Fig. 9. It can be seen that some pink points (satisfying all bounds except the one from Δa_μ) are excluded by this result. More interestingly, this experiment should be applying increasingly stringent bounds on the parameter space in its current run. We have also looked at σ_{SD} , which shows a similar trend with the current experimental limit just at the edge of the otherwise allowed region.

IV. CONCLUSION

In this work, we have explored the phenomenological viability of a GUT-inspired MSSM framework based on a left-right symmetric $SU(4)_C \times SU(2)_L \times SU(2)_R$ model with nonuniversal soft SUSY-breaking terms. During the symmetry breaking all the additional fields acquire heavy masses comparable with M_{GUT} such that only the MSSM fields and their interactions remain available below M_{GUT} . By employing a detailed numerical scan of the parameter space using the SARAH and SPheno toolchains, we assessed the model against a comprehensive set of experimental constraints, including those from B-physics observables, dark matter relic density, direct detection limits, and collider searches from ATLAS and CMS.

Our analysis identifies viable regions of parameter space that satisfy the requirement of third-generation Yukawa coupling unification and remain consistent with the 2σ bounds on the anomalous magnetic moment of the muon (Δa_μ). These regions are characterized by either slepton or bino-wino coannihilation mechanisms that efficiently

deplete the neutralino dark matter relic density to the observed value.

While current LHC bounds significantly restrict the low-energy spectrum, our results demonstrate that well-motivated and testable MSSM scenarios persist. These models offer promising avenues for further exploration at ongoing and upcoming collider runs and dark matter experiments such as LUX-ZEPLIN. Future experimental advances will continue to play a decisive role in probing or constraining this class of supersymmetric theories.

ACKNOWLEDGMENTS

The work of C. S. U. is supported by the Scientific and Technological Research Council of Türkiye (TUBITAK) Grant. No. MFAG-125F122. The numerical calculations reported in this paper were partially performed at TUBITAK ULAKBIM, High Performance and Grid Computing Center (TRUBA resources). We also acknowledge the LUMS High Performance Computing Centre (HPCC) [97] (managed by Nouman Zubair) for providing the computing resources and technical support for this study under Allocation ID: LUMS-HPC-2025-01 for part of this study.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: MASS BOUNDS ON THE SPECTRUM

We now show the plots in the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$, $(m_{\tilde{\chi}_1^\pm}, \Delta m)$, where $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm})$, $(m_{\tilde{e}}, m_{\tilde{\chi}_1^0})$, $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$, $(m_{\tilde{b}}, m_{\tilde{\chi}_1^0})$, and $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ planes, in Figs. 10–17, where we have applied the mass bounds as

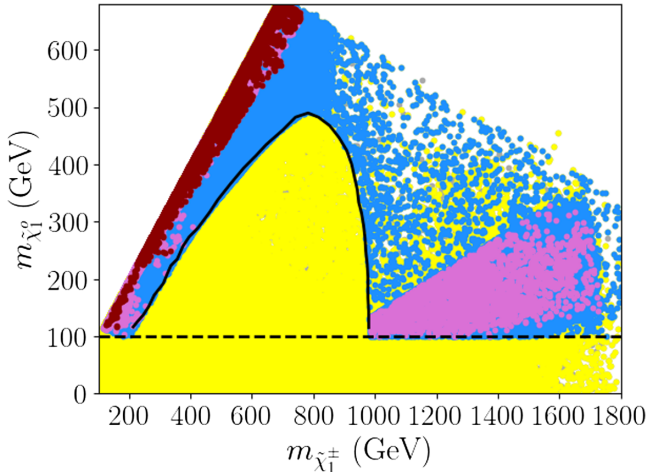


FIG. 10. $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [6,7]. The horizontal dashed line represents the Large Electron-Positron Collider (LEP) bound on $m_{\tilde{\chi}_1^0}$ [85]. The rest of the color coding is the same as in Fig. 1.

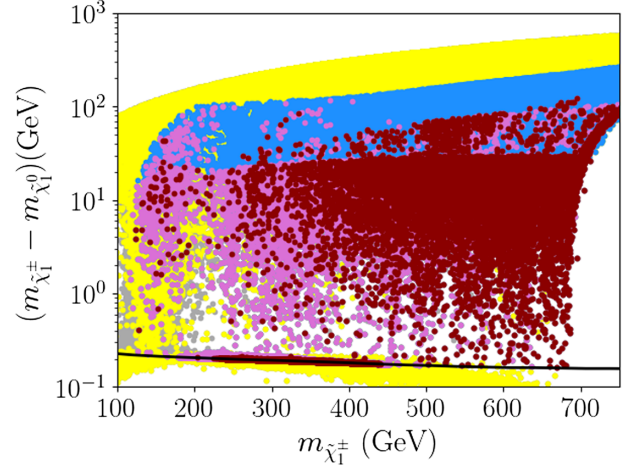


FIG. 11. $(m_{\tilde{\chi}_1^\pm}, (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}))$ plane. The black curve represents the 95% exclusion limit in this plane as given in [11]. The rest of the color coding is the same as in Fig. 10.

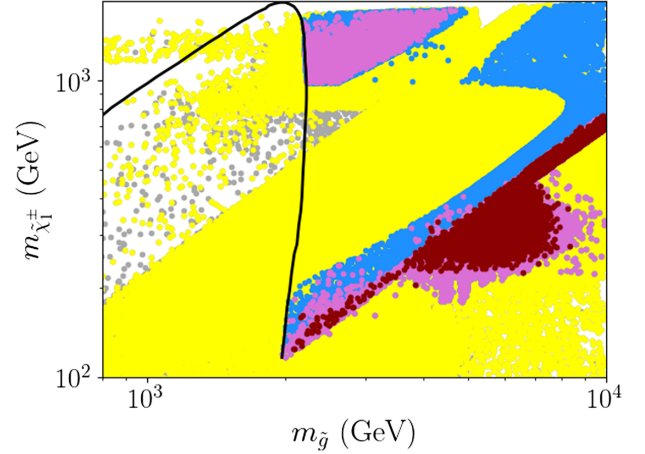


FIG. 12. $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [9]. The rest of the color coding is the same as in Fig. 10.

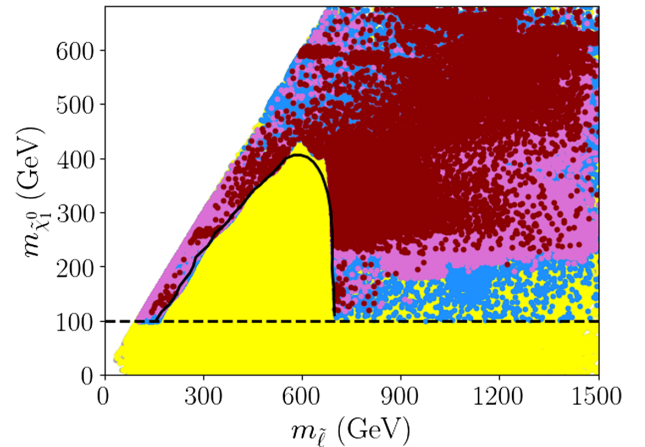


FIG. 13. $(m_{\tilde{e}}, m_{\tilde{\chi}_1^0})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [6]. The rest of the color coding is the same as in Fig. 10.

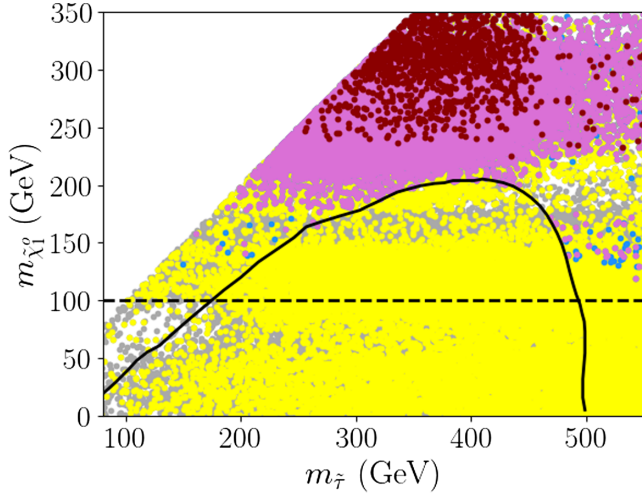


FIG. 14. $(m_{\tilde{\tau}}, m_{\tilde{\chi}_1^0})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [7]. The rest of the color coding is the same as in Fig. 10.

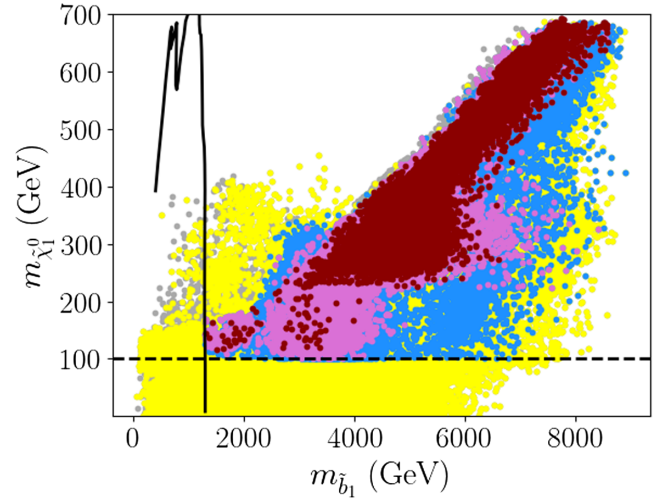


FIG. 16. $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [12]. The rest of the color coding is the same as in Fig. 10.

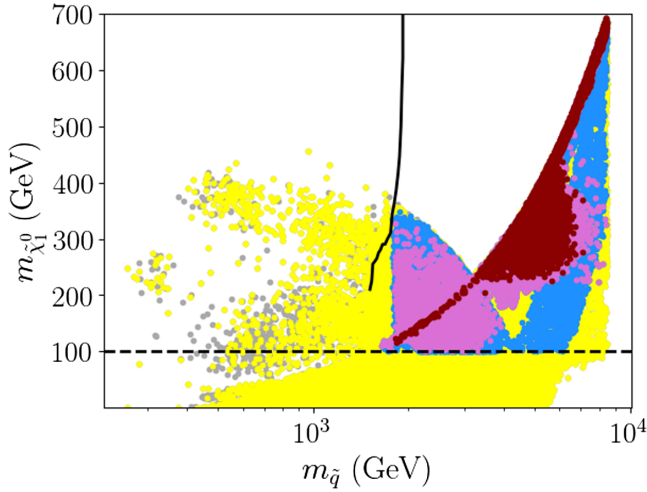


FIG. 15. $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [10]. The rest of the color coding is the same as in Fig. 10.

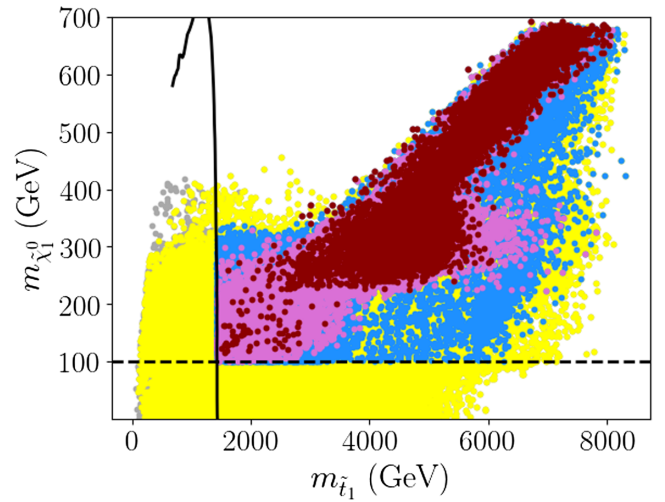


FIG. 17. $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane. The black curve represents the 95% exclusion limit in this plane as given in [13]. The rest of the color coding is the same as in Fig. 10.

given by the latest ATLAS, and CMS results. The color coding is the same as in Fig. 1. In all of these plots, we can see the allowed regions from the point of view of the mass bounds in blue, orchid, and red (with orchid and red being

subsets of blue). The exclusion limits are taken directly from the published literature and correspond to the 95% exclusion regions in the corresponding planes.

-
- [1] S. Weinberg, A model of leptons, *Phys. Rev. Lett.* **19**, 1264 (1967).
 [2] A. Salam and J.C. Ward, Electromagnetic and weak interactions, *Phys. Lett.* **13**, 168 (1964).

- [3] G. Aad *et al.*, The ATLAS experiment at the CERN large hadron collider, *J. Instrum.* **3**, S08003 (2008).
 [4] S. Chatrchyan *et al.*, The CMS experiment at the CERN LHC, *J. Instrum.* **3**, S08004 (2008).

- [5] A. A. Alves, Jr. *et al.*, The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [6] G. Aad *et al.*, Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector, *Eur. Phys. J. C* **80**, 123 (2020).
- [7] G. Aad *et al.*, Search for electroweak production of supersymmetric particles in final states with two τ -leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, *J. High Energy Phys.* **05** (2024) 150.
- [8] A. Tumasyan *et al.*, Search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **04** (2022) 147.
- [9] G. Aad *et al.*, Search for long-lived charginos based on a disappearing-track signature using 136 fb⁻¹ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Eur. Phys. J. C* **82**, 606 (2022).
- [10] A. Hayrapetyan *et al.*, Search for stealth supersymmetry in final states with two photons, jets, and low missing transverse momentum in proton-proton collisions at $s = 13$ TeV, *Phys. Rev. D* **109**, 112009 (2024).
- [11] A. Hayrapetyan *et al.*, Search for supersymmetry in final states with disappearing tracks in proton-proton collisions at $s = 13$ TeV, *Phys. Rev. D* **109**, 072007 (2024).
- [12] G. Aad *et al.*, Search for new phenomena in final states with b -jets and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, *J. High Energy Phys.* **05** (2021) 093.
- [13] A. M. Sirunyan *et al.*, Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **104**, 052001 (2021).
- [14] N. Aghanim *et al.*, Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); **652**, C4(E) (2021).
- [15] T. Marrodán Undagoitia and L. Rauch, Dark matter direct-detection experiments, *J. Phys. G* **43**, 013001 (2016).
- [16] J. Barreto *et al.*, Direct search for low mass dark matter particles with CCDs, *Phys. Lett. B* **711**, 264 (2012).
- [17] G. Gerbier *et al.*, NEWS: A new spherical gas detector for very low mass WIMP detection, [arXiv:1401.7902](#).
- [18] R. Bertoni *et al.*, A new technique for direct investigation of dark matter, *Nucl. Instrum. Methods Phys. Res., Sect. A* **744**, 61 (2014).
- [19] A. Drukier, K. Freese, A. Lopez, D. Spergel, C. Cantor, G. Church, and T. Sano, New dark matter detectors using DNA or RNA for nanometer tracking, [arXiv:1206.6809](#).
- [20] E. Aprile *et al.*, Physics reach of the XENON1T dark matter experiment, *J. Cosmol. Astropart. Phys.* **04** (2016) 027.
- [21] P. Cushman *et al.*, Working Group Report: WIMP Dark Matter Direct Detection, in *Snowmass 2013: Snowmass on the Mississippi*, 2013, [arXiv:1310.8327](#).
- [22] N. Fatemighomi, DEAP-3600 dark matter experiment, in *Proceedings of the 35th International Symposium on Physics in Collision* (2016), [arXiv:1609.07990](#).
- [23] J. Aalbers *et al.*, DARWIN: Towards the ultimate dark matter detector, *J. Cosmol. Astropart. Phys.* **11** (2016) 017.
- [24] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait, and H.-B. Yu, Constraints on dark matter from colliders, *Phys. Rev. D* **82**, 116010 (2010).
- [25] M. Beltran, D. Hooper, E. W. Kolb, Z. A. C. Krusberg, and T. M. P. Tait, Maverick dark matter at colliders, *J. High Energy Phys.* **09** (2010) 037.
- [26] P. J. Fox, R. Harnik, J. Kopp, and Y. Tsai, Missing energy signatures of dark matter at the LHC, *Phys. Rev. D* **85**, 056011 (2012).
- [27] O. Buchmueller, M. J. Dolan, S. A. Malik, and C. McCabe, Characterising dark matter searches at colliders and direct detection experiments: Vector mediators, *J. High Energy Phys.* **01** (2015) 037.
- [28] D. Abercrombie *et al.*, Dark matter benchmark models for early LHC run-2 searches: Report of the ATLAS/CMS dark matter forum, *Phys. Dark Universe* **27**, 100371 (2020).
- [29] M. G. Aartsen *et al.*, Search for dark matter annihilations in the Sun with the 79-string IceCube detector, *Phys. Rev. Lett.* **110**, 131302 (2013).
- [30] M. Klasen, M. Pohl, and G. Sigl, Indirect and direct search for dark matter, *Prog. Part. Nucl. Phys.* **85**, 1 (2015).
- [31] J. C. Pati and A. Salam, Lepton number as the fourth color, *Phys. Rev. D* **10**, 275 (1974); **11**, 703(E) (1975).
- [32] A. Melfo and G. Senjanovic, Minimal supersymmetric Pati-Salam theory: Determination of physical scales, *Phys. Rev. D* **68**, 035013 (2003).
- [33] P. Nath, R. L. Arnowitt, and A. H. Chamseddine, Gravity induced symmetry breaking and ground state of local supersymmetric GUTs, *Phys. Lett.* **121B**, 33 (1983).
- [34] E. Poppitz and S. P. Trivedi, New models of gauge and gravity mediated supersymmetry breaking, *Phys. Rev. D* **55**, 5508 (1997).
- [35] J. Ellis, M. E. Gomez, S. Lola, R. Ruiz de Austri, and Q. Shafi, Confronting grand unification with lepton flavour violation, dark matter and LHC data, *J. High Energy Phys.* **09** (2020) 197.
- [36] Q. Shafi, A. Tiwari, and C. S. Un, Muon $g - 2$ and dark matter in supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$, [arXiv:2308.14682](#).
- [37] J. Ellis, K. A. Olive, V. C. Spanos, and I. D. Stamou, The CMSSM survives Planck, the LHC, LUX-ZEPLIN, Fermi-LAT, H.E.S.S. and IceCube, *Eur. Phys. J. C* **83**, 246 (2023).
- [38] C. Han, K.-i. Hikasa, L. Wu, J. M. Yang, and Y. Zhang, Status of CMSSM in light of current LHC Run-2 and LUX data, *Phys. Lett. B* **769**, 470 (2017).
- [39] S. Chatrchyan *et al.*, Search for supersymmetry at the LHC in events with jets and missing transverse energy, *Phys. Rev. Lett.* **107**, 221804 (2011).
- [40] K. S. Babu, X.-G. He, and E. Ma, New supersymmetric left-right gauge model: Higgs boson structure and neutral current analysis, *Phys. Rev. D* **36**, 878 (1987).
- [41] K. Huitu, P. N. Pandita, and K. Puolamaki, Mass of the lightest Higgs boson in supersymmetric left-right models, *Phys. Lett. B* **423**, 97 (1998).
- [42] Y. Zhang, H. An, X.-d. Ji, and R. N. Mohapatra, Light Higgs mass bound in SUSY left-right models, *Phys. Rev. D* **78**, 011302 (2008).
- [43] R. N. Mohapatra and A. Rasin, Simple supersymmetric solution to the strong CP problem, *Phys. Rev. Lett.* **76**, 3490 (1996).
- [44] C. S. Aulakh, K. Benakli, and G. Senjanovic, Reconciling supersymmetry and left-right symmetry, *Phys. Rev. Lett.* **79**, 2188 (1997).

- [45] K. S. Babu and R. N. Mohapatra, Minimal supersymmetric left-right model, *Phys. Lett. B* **668**, 404 (2008).
- [46] A. Chatterjee, M. Frank, B. Fuks, K. Huitu, S. Mondal, S. K. Rai, and H. Waltari, Multileptonic signals of co-annihilating left-right supersymmetric dark matter, *Phys. Rev. D* **99**, 035017 (2019).
- [47] G. Lazarides, M. Magg, and Q. Shafi, Phase transitions and magnetic monopoles in $SO(10)$, *Phys. Lett.* **97B**, 87 (1980).
- [48] I. Gogoladze, R. Khalid, S. Raza, and Q. Shafi, Higgs and sparticle spectroscopy with Gauge-Yukawa unification, *J. High Energy Phys.* **06** (2011) 117.
- [49] I. Gogoladze, R. Khalid, and Q. Shafi, Coannihilation scenarios and particle spectroscopy in $SU(4)_c \times SU(2)_L \times SU(2)_R$, *Phys. Rev. D* **80**, 095016 (2009).
- [50] I. Gogoladze, R. Khalid, and Q. Shafi, Yukawa unification and neutralino dark matter in $SU(4)_c \times SU(2)_L \times SU(2)_R$, *Phys. Rev. D* **79**, 115004 (2009).
- [51] M. Hussain and R. Khalid, Yukawa unification with light supersymmetric particles consistent with LHC constraints, *Nucl. Phys.* **B942**, 30 (2019).
- [52] I. Gogoladze, Q. Shafi, and C. S. Un, 125 GeV Higgs boson from t - b - τ Yukawa unification, *J. High Energy Phys.* **07** (2012) 055.
- [53] I. Gogoladze, Q. Shafi, and C. S. Un, Higgs boson mass from t - b - τ Yukawa unification, *J. High Energy Phys.* **08** (2012) 028.
- [54] N. Okada, S. Raza, and Q. Shafi, Particle spectroscopy of supersymmetric $SO(10)$ with non-universal gaugino masses, *Phys. Rev. D* **84**, 095018 (2011).
- [55] P. Van Dong and D. Van Loi, Asymmetric matter from $B-L$ symmetry breaking, *Eur. Phys. J. C* **80**, 1137 (2020).
- [56] W. Ahmed, S. Raza, Q. Shafi, C. S. Un, and B. Zhu, Sparticle spectroscopy and dark matter in a $U(1)_{B-L}$ extension of MSSM, *J. High Energy Phys.* **01** (2021) 161.
- [57] K. S. Babu, B. Bajc, and S. Saad, Yukawa sector of minimal $SO(10)$ unification, *J. High Energy Phys.* **02** (2017) 136.
- [58] A. S. Joshipura and K. M. Patel, Yukawa coupling unification in $SO(10)$ with positive μ and a heavier gluino, *Phys. Rev. D* **86**, 035019 (2012).
- [59] K. S. Babu and S. Khan, Minimal nonsupersymmetric $SO(10)$ model: Gauge coupling unification, proton decay, and fermion masses, *Phys. Rev. D* **92**, 075018 (2015).
- [60] M. Abbas and S. Khalil, Neutrino masses, mixing and leptogenesis in TeV scale B - L extension of the standard model, *J. High Energy Phys.* **04** (2008) 056.
- [61] R. N. Mohapatra and J. W. F. Valle, Neutrino mass and baryon number nonconservation in superstring models, *Phys. Rev. D* **34**, 1642 (1986).
- [62] M. C. Gonzalez-Garcia and J. W. F. Valle, Fast decaying neutrinos and observable flavor violation in a new class of Majoron models, *Phys. Lett. B* **216**, 360 (1989).
- [63] S. Khalil, TeV-scale gauged B - L symmetry with inverse seesaw mechanism, *Phys. Rev. D* **82**, 077702 (2010).
- [64] K. S. Babu, I. Gogoladze, Q. Shafi, and C. S. Ün, Muon $g-2$, 125 GeV Higgs boson, and neutralino dark matter in a flavor symmetry-based MSSM, *Phys. Rev. D* **90**, 116002 (2014).
- [65] K. S. Babu, I. Gogoladze, S. Raza, and Q. Shafi, Flavor symmetry based MSSM (sMSSM): Theoretical models and phenomenological analysis, *Phys. Rev. D* **90**, 056001 (2014).
- [66] M. Hussain and R. Khalid, Understanding the muon anomalous magnetic moment in light of a flavor symmetry-based minimal supersymmetric standard model, *Prog. Theor. Exp. Phys.* **2018**, 083B06 (2018).
- [67] M. E. Gomez, G. Lazarides, and C. Pallis, On Yukawa quasiunification with μ less than 0, *Phys. Rev. D* **67**, 097701 (2003).
- [68] I. Gogoladze, Q. Shafi, and C. S. Ün, $SO(10)$ Yukawa unification with $\mu < 0$, *Phys. Lett. B* **704**, 201 (2011).
- [69] F. Staub, SARAH, *arXiv:0806.0538*.
- [70] F. Staub, Introduction to SARAH and related tools, *Proc. Sci. CORFU2015* (2016) 027.
- [71] W. Porod, SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e^+e^- colliders, *Comput. Phys. Commun.* **153**, 275 (2003).
- [72] M. D. Goodsell, K. Nickel, and F. Staub, Two-loop Higgs mass calculations in supersymmetric models beyond the MSSM with SARAH and SPheno, *Eur. Phys. J. C* **75**, 32 (2015).
- [73] G. Bélanger, F. Boudjema, A. Goudelis, A. Pukhov, and B. Zaldivar, MicrOMEGAs5.0: Freeze-in, *Comput. Phys. Commun.* **231**, 173 (2018).
- [74] J. R. Ellis, S. Heinemeyer, K. A. Olive, A. M. Weber, and G. Weiglein, The supersymmetric parameter space in light of B^- physics observables and electroweak precision data, *J. High Energy Phys.* **08** (2007) 083.
- [75] W. Altmannshofer, A. J. Buras, S. Gori, P. Paradisi, and D. M. Straub, Anatomy and phenomenology of FCNC and CP effects in SUSY theories, *Nucl. Phys.* **B830**, 17 (2010).
- [76] A. Bartl, T. Gajdosik, E. Lunghi, A. Masiero, W. Porod, H. Stremnitzer, and O. Vives, General flavor blind MSSM and CP violation, *Proc. Sci. HEP2001* (2001) 169 [arXiv:hep-ph/0112179].
- [77] A. Arbey, M. Battaglia, F. Mahmoudi, and D. Martínez Santos, Supersymmetry confronts $B_s \rightarrow \mu^+ \mu^-$: Present and future status, *Phys. Rev. D* **87**, 035026 (2013).
- [78] F. Mahmoudi, Direct and indirect searches for New Physics, in *Proceedings, 47th Rencontres de Moriond on QCD and High Energy Interactions: La Thuile, France, 2012* (2012), pp. 177–184, *arXiv:1205.3099*.
- [79] F. Mahmoudi, S. Neshatpour, and J. Orloff, Supersymmetric constraints from $B_s \rightarrow \mu^+ \mu^-$ and $B \rightarrow K^* \mu^+ \mu^-$ observables, *J. High Energy Phys.* **08** (2012) 092.
- [80] S. Banerjee *et al.*, Averages of b -hadron, c -hadron, and τ -lepton properties as of 2023, *arXiv:2411.18639*.
- [81] A. Tumasyan *et al.*, Measurement of the $B_S^0 \rightarrow \mu^+ \mu^-$ decay properties and search for the $B^0 \rightarrow \mu^+ \mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* **842**, 137955 (2023).
- [82] R. Aaij *et al.*, Analysis of neutral B-meson decays into two muons, *Phys. Rev. Lett.* **128**, 041801 (2022).
- [83] I. Adachi *et al.*, Evidence for $B^- \rightarrow \tau^- \bar{\nu}_\tau$ with a hadronic tagging method using the full data sample of Belle, *Phys. Rev. Lett.* **110**, 131801 (2013).
- [84] B. Kronenbitter *et al.*, Measurement of the branching fraction of $B^+ \rightarrow \tau^+ \nu_\tau$ decays with the semileptonic tagging method, *Phys. Rev. D* **92**, 051102 (2015).

- [85] A. Heister *et al.*, Search for charginos nearly mass degenerate with the lightest neutralino in e^+e^- collisions at center-of-mass energies up to 209-GeV, *Phys. Lett. B* **533**, 223 (2002).
- [86] G. Aad *et al.*, Combined measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels with the ATLAS detector using $\sqrt{s} = 7, 8$, and 13 TeV pp collision data, *Phys. Rev. Lett.* **131**, 251802 (2023).
- [87] A. M. Sirunyan *et al.*, A measurement of the Higgs boson mass in the diphoton decay channel, *Phys. Lett. B* **805**, 135425 (2020).
- [88] G. Aad *et al.*, Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments, *Phys. Rev. Lett.* **114**, 191803 (2015).
- [89] D. P. Aguillard *et al.*, Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb, 2025.
- [90] R. Aliberti *et al.*, The anomalous magnetic moment of the muon in the Standard Model: An update, 2025.
- [91] B. Abi *et al.*, Measurement of the positive muon anomalous magnetic moment to 0.46 ppm, *Phys. Rev. Lett.* **126**, 141801 (2021).
- [92] T. Aoyama *et al.*, The anomalous magnetic moment of the muon in the standard model, *Phys. Rep.* **887**, 1 (2020).
- [93] G. Aad *et al.*, Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector, *Phys. Rev. D* **93**, 052002 (2016).
- [94] I. Gogoladze, R. Khalid, S. Raza, and Q. Shafi, t - b - τ Yukawa unification for $\mu < 0$ with a sub-TeV sparticle spectrum, *J. High Energy Phys.* **12** (2010) 055.
- [95] H. Baer, T. Krupovnickas, A. Mustafayev, E.-K. Park, S. Profumo, and X. Tata, Exploring the BWCA (bino-wino co-annihilation) scenario for neutralino dark matter, *J. High Energy Phys.* **12** (2005) 011.
- [96] J. Aalbers *et al.*, First dark matter search results from the LUX-ZEPLIN (LZ) experiment, *Phys. Rev. Lett.* **131**, 041002 (2023).
- [97] <https://hpc.lums.edu.pk>.