Right-handed slepton bulk regions for dark matter in a generalized minimal supergravity

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We study the light right-handed slepton bulk regions for dark matter from the generalized minimal supergravity (GmSUGRA) in the minimal supersymmetric Standard Model. In our comprehensive numerical studies, we show that $\mathcal{R}_{\tilde{\phi}} \gtrsim 10\%$ is a conservative criterion to formulate bulk region, where $\mathcal{R}_{\tilde{\phi}} \equiv (m_{\tilde{\phi}} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$. For right-handed stau as the next-to-the-lightest supersymmetric particle (NLSP), we find a large viable parameter space, consistent with the current LHC constraints, Planck2018 dark matter relic density bounds, and direct bounds on neutralino-nucleons scattering cross section that naturally supports the right-handed stau bulk regions for dark matter. In particular, the upper bounds on the masses of the lightest supersymmetric particle neutralino and right-handed stau are about 120.4 and 138 GeV, respectively. This bulk region may be beyond the current LHC reach and could be probed at LUX-ZEPLIN, a next-generation dark matter direct-detection experiment, the Future Circular Collider at CERN, and the Circular Electron Positron Collider. However, the scenario with the right-handed selectron as the NLSP is excluded by the LHC supersymmetry searches.

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I. INTRODUCTION

Even though supersymmetric standard models (SSMs) are the most promising candidate to explain physics beyond the standard model (BSM), experimentally, no concrete evidence has been found so far. In the SSMs, we can achieve gauge-coupling unification [1–6], with R parity, the lightest supersymmetric particle (LSP) as a good cold dark matter (DM) candidate [7,8], a natural solution to the gauge hierarchy problem, and break the electroweak (EW) gauge symmetry radiatively because of the large top-quark Yukawa coupling. Besides, the minimal SSM (MSSM) predicts the lightest CP-even Higgs mass [100,135] GeV [9]. Thus, supersymmetry (SUSY) has been one of the main focuses of the searches being done in the Large Hadron Collider (LHC) to look for the BSM, provides a bridge between the low-energy phenomenology and high-energy fundamental physics, and so is the most promising candidate for the new physics beyond the SM.

However, after the LHC Run-2, we still did not have any sign of SUSY, and LHC searches established strong constraints on the SSMs spectra. The searches that have been done so far elevated low mass bounds on the masses of gluino, first-two generation squarks, stop, and sbottom to around 2.2, 2, 1.25, and 1.5 TeV, respectively [10–14]. Thus, at least the colored supersymmetric particles (sparticles) must be heavy around a few TeV. If the LSP is a binolike neutralino, then the large sfermions masses lead to a small annihilation cross section, as the process mediated by sfermions is suppressed. Thus, in the absence of some other annihilation enhancement or the coannihilation mechanism, the resulting DM relic abundance would be far in excess of the value measured by the Planck (5σ) bound, $0.114 \leq \Omega_{\mathrm{CDM}}h^2(\mathrm{Planck}) \leq 0.126$ [15,16]. Despite these constraints on the squark masses, the current data still leave open the possibility of models for an electroweak-scale bino-dominant LSP and relatively light sleptons with much heavier squarks. SUSY models inspired by the BSM indicate light sleptons mass around a few hundred GeV up to TeV scale; for example, see [17] and the references therein. However, in the standard scenario for the bino-dominant LSP, there are difficulties with obtaining a large enough annihilation cross section to deplete the DM relic density, as the bino DM always annihilates through the process $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$ via t- and u-channel sfermions exchange where $f, \bar{f}$ are standard model fermions; this process is not sufficient because of the intermediate sfermions large masses. However, there are four distinct approaches to the observed DM relic density: (a) Bulk region where sfermions are light; (b) The Z/Higgs resonance or Z/Higgs funnel, where the neutralino LSP mass is about half of the masses of the CP-even Higgs H_0, CP-odd Higgs A_0, SM Higgs, or Z bosons; (c) Coannihilation, where the sfermion masses are closed to the LSP neutralino; or (d) Mixing scenario or well-tempered scenario, where the LSP neutralino has wino- or higgsino component to significantly increase the annihilation cross section; the light sfermion exchange or the bulk region is the most natural version of neutralino DM, wherein no coannihilaiton or resonance annihilation mechanism is necessary to suppress the relic abundance [18]. Thus, the region of parameter space where this works out right is often referred to by the jargon "bulk region." To escape the LHC SUSY search constraints and to be consistent with various experimental results, some of us proposed the electroweak supersymmetry (EWSUSY) [19–21], where the squarks and gluinos are around a few TeV while the sleptons, sneutrinos, bino, and winos are within 1 TeV. The higgsinos (or say, the Higgs bilinear μ term) can be either heavy or light. Especially, the EWSUSY can be realized in the generalized minimal supergravity (GmSUGRA) [22,23]. This article discusses a bulk region in the MSSM from the GmSUGRA. In order to uncover the bulk region in the MSSM via GmSUGRA, we can only consider that the right-light sleptons with all other sfermions must be heavily indicated by the LHC SUSY searches. To determine whether the interaction between sfermions and the LSP is annihilation or coannihilation, the mass difference between the light right-handed sfermions and LSP is important, i.e., the ratio of the mass difference $\mathcal{R}_{\tilde{\phi}} \equiv (m_{\tilde{\phi}} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$ is important, where $\tilde{\phi}$ is $\tilde{e}_R$ (right-handed light selection) or $\tilde{\tau}_1$ (light stau). The $\mathcal{R}_{\tilde{\phi}} \geq 10\%$ is the conservative criterion to observe DM relic density solely via annihilation, and not from coannihilation or resonance, etc. For right-handed stau as the next-to-the-lightest supersymmetric particle (NLSP), we find a large viable parameter space, consistent with the current LHC constraints, Planck2018 dark matter relic density bounds, and direct bounds on neutralino-nucleons scattering cross section that naturally supports the right-handed stau bulk regions for dark matter. In particular, the upper bounds on the masses of the LSP neutralino and right-handed stau are about 120.4 and 138 GeV, respectively. This bulk region may be beyond the current LHC reach and could be probed at LUX-ZEPLIN, a next-generation dark matter direct-detection experiment, the Future Circular Collider (FCC-ee) [24,25] at CERN, and the Circular Electron Positron Collider (CEPC) [26]. However, the scenario with the right-handed selectron as the NLSP is excluded by the LHC supersymmetry searches.

This paper is organized as follows. In Sec. II, we briefly summarize the model and relevant free parameters. In Sec. III, we describe the scanning procedure and range of our grand unified theory (GUT)-scale parameters, and in Sec. IV, we highlight the phenomenological constraints. In Sec. V, we explain the numerical results, and finally we conclude our findings in Sec. VI.

II. THE EWSUSY FROM THE GmSUGRA IN THE MSSM

The EWSUSY can be realized in the GmSUGRA [22,23]. As stated in [19–21], in this framework the sleptons and electroweakinos (charginos, bino, wino, and/or higgsinos) are within 1 TeV while squarks and/or gluinos can be in several TeV mass ranges [19,21]. Apart from this, the gauge-coupling relation and gaugino mass relation at the GUT scale are [22,23]

$$\frac{1}{\alpha_2} - \frac{1}{\alpha_3} = k\left(\frac{1}{\alpha_1} - \frac{1}{\alpha_3}\right), \tag{1}$$

$$\frac{M_2}{\alpha_2} - \frac{M_3}{\alpha_3} = k\left(\frac{M_1}{\alpha_1} - \frac{M_3}{\alpha_3}\right), \tag{2}$$

where k is the index of these relations and is equal to $5/3$ in our simple GmSUGRA. We assume for simplicity that at the GUT scale ($\alpha_1 = \alpha_2 = \alpha_3$), the gaugino mass relation becomes

$$M_2 - M_3 = \frac{5}{3}(M_1 - M_3). \tag{3}$$

It is obvious that the universal gaugino mass relation $M_1 = M_2 = M_3$ in the mSUGRA is just a special case of a general one; that is why we called it GmSUGRA. In this case, there are two independent gauginos rather than three. Thus, Eq. (3) implies for M_2 in terms of M_1 and M_3 as free-input parameters as follows:

$$M_2 = \frac{5}{3}M_1 - \frac{2}{3}M_3. \tag{4}$$

We use Ref. [23] for the general secondary subgrain boundary (SSB) GUT-scale scalar masses. The masses of squarks are obtained in the $SU(5)$ model with an adjoint Higgs field, where we employ slepton masses as a free parameter.

$$m_{\tilde{Q}_i}^2 = \frac{5}{6}(m_0^U)^2 + \frac{1}{6} m_{\tilde{E}_i^c}^2, \tag{5}$$

$$m_{\tilde{U}_i^c}^2 = \frac{5}{3}(m_0^U)^2 - \frac{2}{3} m_{\tilde{E}_i^c}^2, \tag{6}$$

$$m_{\tilde{D}_i^c}^2 = \frac{5}{3}(m_0^U)^2 - \frac{2}{3} m_{\tilde{L}_i}^2. \tag{7}$$

Here, $m_{\tilde{Q}}$, $m_{\tilde{U}^c}$, $m_{\tilde{D}^c}$, $m_{\tilde{L}}$, and $m_{\tilde{E}^c}$ represent the left-handed scalar squark doublets, right-handed up-type squarks, right-handed down-type squarks, left-handed sleptons, and right-handed sleptons, respectively, and m_0^U is the universal scalar mass, as in the mSUGRA. For the light sleptons in the EWSUSY, $m_{\tilde{L}}$ and $m_{\tilde{E}^c}$ are both within 1 TeV. Especially, in the limit $m_0^U \gg m_{\tilde{L}/\tilde{E}^c}$, we get the approximated relations for squark masses: $2m_{\tilde{Q}}^2 \sim m_{\tilde{U}^c}^2 \sim m_{\tilde{D}^c}^2$. In addition, the Higgs soft masses $m_{\tilde{H}_u}$ and $m_{\tilde{H}_d}$, and the trilinear soft terms A_U, A_D, and A_E can all be free parameters from the GmSUGRA [19,23].

III. SCANNING PROCEDURE AND GUT-SCALE PARAMETER RANGE

We employ the ISAJET 7.85 package [27] to carry out a random scan over the parameter space given below. In this package, the MSSM renormalization group equations (RGEs) in the $\overline{DR}$ regularization scheme are evolved for the third-generation Yukawa couplings from the weak scale to $M_{\rm GUT}$ value. We do not enforce the unification condition $g_3 = g_1 = g_2$ at $M_{\rm GUT}$ (where g_3, g_2, and g_1 are the $SU(3)_C$, $SU(2)_L$, and $U(1)_Y$ gauge couplings) strictly since a few percent variations from unification can be allotted to the unknown GUT-scale threshold corrections [28]. All the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale $M_{\rm Z}$, with the boundary conditions given at $M_{\rm GUT}$ (for more detail see [27]). ISAJET employs two-loop MSSM RGEs and defines $M_{\rm U}$ to be the scale at which $g_1 = g_2$. Using the parameters discussed in Sec. II, we have performed the random scans for the following parameter ranges:

$$\begin{gathered}
100\ \text{GeV} \le m_0^U \le 10000\ \text{GeV}, \\
0\ \text{GeV} \le M_1 \le 1200\ \text{GeV}, \\
1000\ \text{GeV} \le M_3 \le 3000\ \text{GeV}, \\
100\ \text{GeV} \le m_{\tilde{L}} \le 5000\ \text{GeV}, \\
0\ \text{GeV} \le m_{\tilde{E}^c} \le 300\ \text{GeV}, \\
0\ \text{GeV} \le m_{\tilde{H}_{u,d}} \le 10000\ \text{GeV}, \\
-10000\ \text{GeV} \le A_U = A_D \le 10000\ \text{GeV}, \\
-5000\ \text{GeV} \le A_E \le 5000\ \text{GeV}, \\
2 \le \tan\beta \le 60.
\end{gathered} \tag{8}$$

Also, we consider $\mu > 0$ and use $m_t = 173.3$ GeV [29]. Note that our results are not too sensitive to one or two sigma variations in the value of m_t [30]. Note, we will use the notations A_U, A_D, and A_E, for A_t, A_b, and A_τ, respectively. In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in [31]. The data points collected are radiative electroweak symmetry breaking (REWSB) compatible with the neutralino being the LSP.

IV. PHENOMENOLOGICAL CONSTRAINTS

The data points collected are the REWSB compatible, with the neutralino serving as the LSP. Besides, we impose the bounds that the LEP2 experiments set on charged sparticle masses ($\gtrsim$100 GeV) [32] for Higgs mass bounds [33] due to the theoretical uncertainty in the calculation of m_h in the MSSM—see, e.g., [34]—we apply the constraint for the Higgs boson mass to our results as $m_h = [122, 128]$ GeV. We use constraint 2.2 TeV on gluino mass decaying into third-generation squarks and lower mass bound of about 1.8 TeV only on first two-generation squark masses (assuming an approximate degeneracy among squark flavor). We use a bound of 2 TeV on squark mass as being more conservative. In these limits, it is usually assumed that LSP neutralino is massless. In our case, the maximum range of neutralino mass is about 350 GeV. In this situation, the above-mentioned limits may be used as lower bounds [35–38]. We also consider the constraints from rare decay processes $B_s \to \mu^+\mu^-$ [39], $b \to s\gamma$ [40], and $B_u \to \tau\nu_\tau$ [41]. Besides, we require the relic abundance of the LSP neutralino to satisfy the Planck2018 bound [15]. More explicitly, we set

$$m_h = 122\text{–}128\ \text{GeV} \tag{9}$$

$$m_{\tilde{g}} \ge 2.2\ \text{TeV}, \qquad m_{\tilde{q}} \gtrsim 2\ \text{TeV} \tag{10}$$

$$0.8 \times 10^{-9} \le \text{BR}(B_s \to \mu^+\mu^-) \le 6.2 \times 10^{-9}\ (2\sigma) \tag{11}$$

$$2.99 \times 10^{-4} \le \text{BR}(b \to s\gamma) \le 3.87 \times 10^{-4}\ (2\sigma) \tag{12}$$

$$0.15 \le \frac{\text{BR}(B_u \to \tau\nu_\tau)_{\rm MSSM}}{\text{BR}(B_u \to \tau\nu_\tau)_{\rm SM}} \le 2.41\ (3\sigma) \tag{13}$$

$$0.114 \le \Omega_{\rm CDM} h^2(\text{Planck}) \le 0.126\ (5\sigma). \tag{14}$$

The above-mentioned branching fractions and neutralino relic density are calculated by ISAJET subroutine IsaTools [42].

V. NUMERICAL RESULTS AND DISCUSSION

The most appealing feature of models with low-energy SUSY is the prediction of thermal relic DM. Indeed, a colorless, stable, neutral weakly interacting massive particle leads to present DM density roughly agreeing with the observation [15]. The SSMs, with the R parity conserved, provide a satisfactory theoretical framework for the existence of such particles [7,8]. In the MSSM, the LSP is a mixture of bino, neutral wino, and higgsinos mass eigenstates. Neutral wino and higgsino state couple directly to SM gauge bosons, and this is complicated by the fact that neutralinos may annihilate too many final states: $f\bar{f}$, W^+W^-, ZZ, ZH, hh, and including H, A, and $H^\pm$ heavy Higgs bosons states. Many processes contribute to each of these final states. It is useful to begin by considering the pure binolike neutralino to investigate the bulk region to avoid resonance annihilation and coannihilation. Thus, we considered the 99.9% binolike neutralino to preclude large annihilation cross sections coming from the higgsino or wino components through the final gauge-boson state processes and three gauge-boson vertices that involve the hypercharge gauge bosons. The bino limit does not disappear for the process that has final $f\bar{f}$ states through a t channel via sfermion exchange, i.e., bino DM always annihilates through the process $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$ via t- and u-channel sfermions exchange where $f, \bar{f}$ are standard model fermions. This process becomes efficient if the mass of the intermediate sfermions is light. Therefore, the electroweak-scale binolike DM is a viable option in our study through the light right-handed sleptons mediating the annihilation, which has long been called the bulk region, the most natural version of neutralino DM, wherein no coannihilation or resonance annihilation mechanism is necessary to suppress the relic abundance to the cosmological-viable range. We also considered the $2m_{\tilde{\chi}_1^0} \ll m_{H^0}, m_{A^0}$ and $2m_{\tilde{\chi}_1^0} \gg m_h$ to avoid the A-funnel/Higgs resonance in our study; while considering the numerical results we employed $\mathcal{R}_{\tilde{\phi}} \gtrsim 10\%$, where $\mathcal{R}_{\tilde{\phi}} \equiv (m_{\tilde{\phi}} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$ to avoid the portion proportional to coannihilation, because the ratio of a mass difference $\mathcal{R}_{\tilde{\phi}}$ is important instead of the absolute mass difference. Thus, to make the coannihilation processes negligible, we employ $\mathcal{R}_{\tilde{e}_R} \equiv (m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} \gtrsim 10\%$, and $\mathcal{R}_{\tilde{\tau}_1} \equiv (m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} \gtrsim 10\%$, as these sleptons ($\tilde{e}_R$ and $\tilde{\tau}_1$) are naturally light. Therefore, our search imposes $\mathcal{R}_{\tilde{\tau}_1} > \mathcal{R}_{\tilde{e}_R}$ while varying the ratio $\mathcal{R}_{\tilde{e}_R}$, and vice versa. Our analysis reveal that the ratio $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$ implies that $m_{\tilde{\chi}_1^0} \leq 120.4$ GeV. In the latter case where we employ $\mathcal{R}_{\tilde{\tau}_1} > \mathcal{R}_{\tilde{e}_R}$ and varied the ratio $\mathcal{R}_{\tilde{e}_R}$, all points with an $\tilde{e}_R$ NLSP are excluded by the ATLAS soft-lepton SUSY search [43]. Then, the only viable MSSM region from the GmSUGRA in the bulk is for the case $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$. All points in Fig. 1 show $\mathcal{R}_{\tilde{\tau}_1}$ vs neutralino graph, which satisfies the experimental constraints mentioned in the previous section.

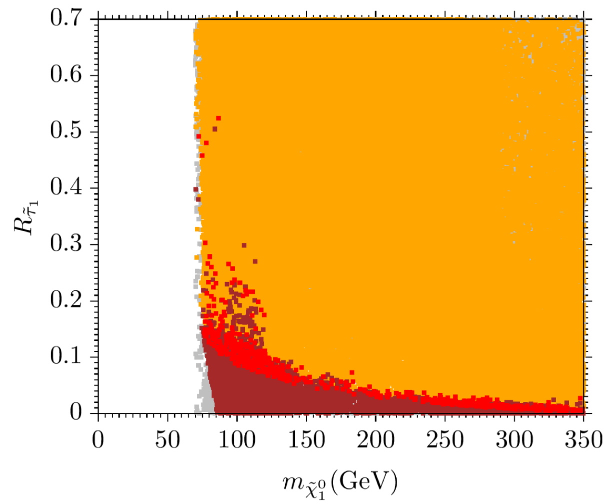

FIG. 1. Gray points satisfy the REWSB and yield LSP neutralino. Orange, brown, and red points are the subset of gray points that satisfy LEP bounds, B-physics bounds, Higgs bound, and sparticles LHC constraints. Also, orange, brown, and red points, respectively, correspond to oversaturated, undersaturated, and saturated DM relic density. In the panel, $\mathcal{R}_{\tilde{\tau}_1} \equiv (m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$.

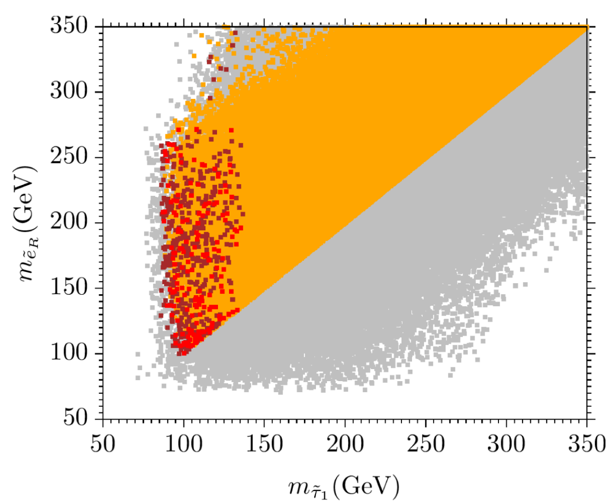

FIG. 2. Gray points satisfy the REWSB and yield LSP neutralino. Orange, brown, and red points are the subset of gray points that satisfy LEP bounds, B-physics bounds, Higgs bound, and sparticles LHC constraints. Also, orange, brown, and red points, respectively, correspond to oversaturated, undersaturated, and saturated DM relic density with $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$.

The $\tilde{\tau}_1$-$\tilde{e}_R$ plane is represented in Fig. 2. Within the bulk region from the GmSUGRA, the upper limit of $\tilde{\tau}_1$ and $\tilde{e}_R$ around 138 and 270 GeV, respectively, recognize that these right-handed sleptons and bino LSP are naturally light.

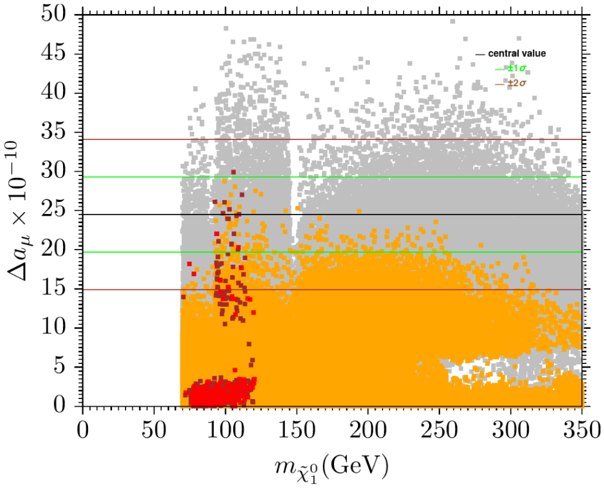

FIG. 3. Gray points satisfy the REWSB and yield LSP neutralino. Orange, brown, and red points are the subset of gray points that satisfy LEP bounds, B-physics bounds, Higgs bound, and sparticles LHC constraints. Also, orange, brown, and red points, respectively, correspond to oversaturated, undersaturated, and saturated DM relic density with $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$. The black line shows the central value of Δa_μ and the green and brown lines, respectively, represent 1σ and 2σ deviation from the central value.

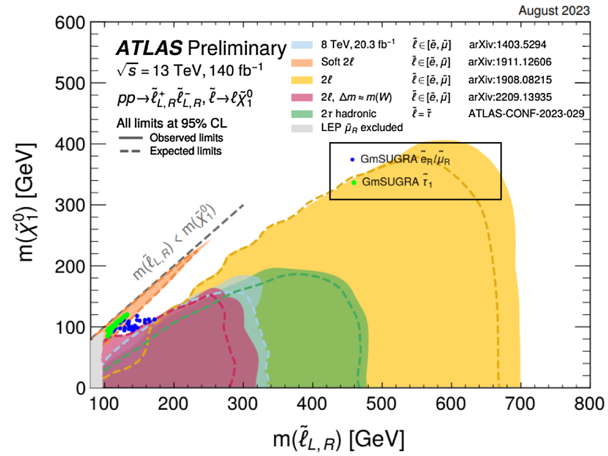

FIG. 4. The bulk region from the GmSUGRA superimposed over the August 2023 ATLAS SUSY updated summary plots [46] for the electroweak production of sleptons [43,47,48,54,55]. The blue point corresponds to the first two generation diright sleptons [a degenerate right-handed selectron ($\tilde{e}_R$) and smuon ($\tilde{\mu}_R$)] while green points correspond to distau ($\tilde{\tau}_1$) in the GmSUGRA. All points are annihilation only, adhere to our requirement $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$, and satisfy the saturated DM relic density. Note that the ATLAS orange-shaded region applies to the first two family sleptons [selection ($\tilde{e}_{L,R}$) and smuon ($\tilde{\mu}_{L,R}$)] only, not to stau ($\tilde{\tau}_1$). The $\tilde{\tau}_1$ constraints are the green-shaded region in the ATLAS, and the GmSUGRA points are comfortably beyond.

Note that we want to comment here that Fermi-Lab Collaboration has recently announced the measurement of muon anomalous magnetic moment results from Run 2 and 3 [44], which strongly suggests new physics around 1 TeV [45]. Figure 3 shows the contribution of our bulk scenario to Δa_μ up to 1σ deviation from the central value. Though our red solutions contribute, up to 1σ and 2σ to Δa_μ have been excluded by the LHC but the brown (undersaturated) and orange (oversaturated) solutions are safe.

The SUSY has been searched extensively at the LHC. The $\pm 1\sigma$ observed and expected exclusion limits from the recent ATLAS SUSY updated summary plots [46] of the [43,47,48] search for direct pair production of sleptons and charginos decaying into final states with two leptons are shown in Fig. 4, with several superimposed benchmark points from the bulk region in the GmSUGRA satisfying the saturated DM relic density bound. All points in Fig. 4 belong to traditional annihilation only and stick to our requirement $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$. The blue points corresponds to the first two generation diright sleptons [a degenerate right-handed selectron ($\tilde{e}_R$ and smuon ($\tilde{\mu}_R$)] while green points correspond to distau ($\tilde{\tau}_1$) in the GmSUGRA. It is important to note that the thin orange-shaded region in the ATLAS graph in Fig. 4 corresponds to the first two family sleptons [selection $\tilde{e}_{L,R}$ and smuon ($\tilde{\mu}_{L,R}$)] only, not to stau ($\tilde{\tau}_1$). The green-shaded region depicts the $\tilde{\tau}_1$ constraints. This paper has not shown that the situation is similar with respect to CMS Collaboration SUSY searches for the EW production of sleptons [49–51]. Our analysis in Fig. 4 revealed that our bulk region is still beyond the LHC approach and, because of the compressed nature of these spectra, this bulk may not be probed at the LHC. It is anticipated from the sensitivity given in Ref. [52] that these light sleptons could be probed when the forthcoming circular colliders, namely the FCC-ee [24,25] at CERN and the CEPC [26] power up their beams.[1] Table I provides two benchmark points highlighting our findings, consistent with the unexplored LHC region under the constraints discussed in the previous section.

In Fig. 5, we display the spin-independent (top) and spin-dependent (bottom) neutralino-proton scattering cross section vs the neutralino mass, adhering to our requirement $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$. In Fig. 5, we display the spin-independent (top) and spin-dependent (bottom) neutralino-proton

[1]We are uncertain about the HL-LHC capability to probe our designated bulk region in light of Ref. [53], which explored a scenario with $m_{\tilde{\tau}_R} = m_{\tilde{\tau}_L}$, a scenario distinct from our investigation, where we consider the case $m_{\tilde{\tau}_R} < m_{\tilde{\tau}_L}$. We plan to address this issue in our future studies.

TABLE I. All the masses are in the unit of GeV where $\mathcal{R}_{\tilde{\tau}_1} \equiv (m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$ and $\mathcal{R}_{\tilde{e}_R} \equiv (m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$.

	Point 1	Point 2
m_0^U	1210	1294
M_1, M_2, M_3	281.1, −1449.5, 2877	267.8, −1287, 2600
m_{E^c}, m_L	125.2, 1054	100.6, 1142
m_{H_u}, m_{H_d}	3012, 901.6	3308, 1024
m_Q, m_{U^c}, m_{D^c}	1105.8, 1558.8, 1303.7	1182, 1668.5, 1386.1
$A_t = A_b, A_\tau$	−7248, −349.2	−6868, −332
$\tan\beta$	21.8	19.6
m_h	125	125
m_H	3545	3109
m_A	3522	3088
$m_{H^\pm}$	3546	3110
$m_{\tilde{\chi}^0_{1,2}}$	−111, 1291	−105, 1147
$m_{\tilde{\chi}^0_{3,4}}$	−3692, 3692	−3164, 3165
$m_{\tilde{\chi}^\pm_{1,2}}$	1297, 3696	1152, 3169
$m_{\tilde{g}}$	5884	5360
$m_{\tilde{u}_{L,R}}$	5222, 5269	4796, 4883
$m_{\tilde{t}_{1,2}}$	3384, 4319	2978, 3902
$m_{\tilde{d}_{L,R}}$	5223, 5205	4797, 4800
$m_{\tilde{b}_{1,2}}$	4308, 4969	3892, 4602
$m_{\tilde{\nu}_1}$	1376	1383
$m_{\tilde{\nu}_3}$	1360	1370
$m_{\tilde{e}_{L,R}}$	1395, 148	1399, 136
$m_{\tilde{\tau}_{1,2}}$	124, 1374	117, 1381
Δa_μ	2.4×10^{-10}	1.5×10^{-10}
$\sigma_{\rm SI}(pb)$	4.6×10^{-14}	1.1×10^{-13}
$\sigma_{\rm SD}(pb)$	2.6×10^{-10}	5.8×10^{-10}
$\Omega_{\rm CDM}h^2$	0.125	0.118
$\mathcal{R}_{\tilde{\tau}_1}$	12%	11%
$\mathcal{R}_{\tilde{e}_R}$	33%	28%

scattering cross section vs the neutralino mass, which we calculate using the package IsaTools [42]. In both panels, the solid black line depicts the current XENONnT [56] and the green line shows the LUX-ZEPLIN(2022) [57]. The blue line represents the 1000-day LUX-ZEPLIN experiment [58]. Plots in the $m_{\tilde{\chi}_1^0}$-$\sigma_{\rm SI}$ plane show that almost all of Planck2018 bound satisfying solutions are below the blue and green lines, except a handful of points. In the figure, we also notice that the 1000-day LUX-ZEPLIN experiment (blue line) [58] is anticipated to probe more of our GmSUGRA bulk. The plots in the $m_{\tilde{\chi}_1^0}$-$\sigma_{\rm SD}$ plane depict that our solutions are consistent with the current research of the direct-detection experiments.

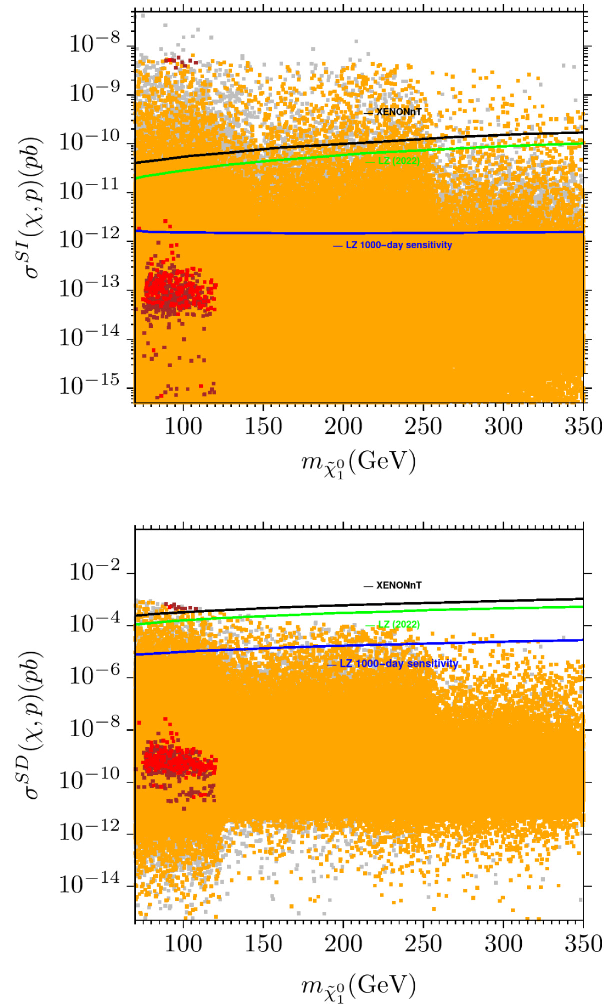

FIG. 5. Gray points satisfy the REWSB and yield LSP neutralino. Orange, brown, and red points are the subset of gray points that satisfy LEP bounds, B-physics bounds, Higgs bound, and sparticles LHC constraints. Also, orange, brown, and red points, respectively, correspond to oversaturated, undersaturated, and saturated DM relic density with $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$. The spin-independent (top) and spin-dependent (bottom) neutralino-proton scattering cross section vs the neutralino mass in reference from current direct-detection experiments, such as XENONnT (solid black line) [56] and LUX-ZEPLIN [solid green line LZ(2022)]. Also with LZ-1000 day sensitivity (solid blue line) [57,58].

VI. CONCLUSION

We have discussed the naturally generated light sfermions and thus a light bino LSP, a scenario we regard as the most natural DM or bulk region via the EWSUSY breaking from the GmSUGRA in the MSSM. We derive a region of parameter space that supports light right-handed sleptons and a light LSP, known as the bulk region, where $m_{\tilde{\chi}_1^0} \leq$ 120.4 GeV with negligible coannihilation correct with

Plank2018 relic bound with a light stau NLSP and upper limits on $m_{\tilde{\tau}_1}$ and $m_{\tilde{e}_R}$ about 138 and 270 GeV, respectively. In particular, we open up the bulk region in MSSM via EWSUSY from the GmSUGRA that allows bino annihilation via t-channel slepton exchange, leading to "supersymmetric DM" at all with respect to DM. Our analysis uncovered that the light right-handed sleptons in the bulk region could be beyond the LHC reach and may be probed in the forthcoming advanced era of circular colliders, such as the FCC-ee at CERN and the CEPC in China. Furthermore, our DM implication is correct with current XENONnT and LUX-ZEPLIN experiments, Planck2018 DM relic density bounds, and could be probed during the presently running 1000-day LUX-ZEPLIN experiment.

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