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Current Status and Prospects of Light Bino-Higgsino Dark Matter in Natural SUSY

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Abstract

Given recent advancements in dark matter (DM) search experiments, particularly the latest LUX-ZEPLIN (LZ) direct detection (DD) results, we systematically investigate the light bino–higgsino DM scenario within the natural supersymmetric framework. Requiring the electroweak fine-tuning parameter $\Delta_{\rm EW} < 30$ fixes the higgsino mass parameter in the range $|\mu| \in [100, 350]$ GeV, while we extend the bino mass to $M_1 \in [10, 350]$ GeV. Incorporating constraints from Higgs physics, rare B decays, LEP limits, and DD experiments, we find that part of the parameter space remains viable. However, the relic density of neutralino DM necessarily lies below the observed Planck value, contributing at most $\sim$2% of the total DM abundance. Some of the surviving parameter space is already excluded by current 13 TeV LHC searches, while the future 14 TeV HL-LHC with 3000 fb^{-1} luminosity will probe the remaining region.

Keywords: dark matter; supersymmetry; neutralino; direct detection; LHC; naturalness

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1. Introduction

Cosmological observations provide compelling evidence for the existence of dark matter (DM), yet its particle nature remains one of the foremost challenges in particle physics and cosmology [1]. Additionally, the discovery of the Higgs boson at the Large Hadron Collider (LHC) [2,3] has intensified the need to address the hierarchy problem, which arises from the large disparity between the electroweak scale and the Planck scale, necessitating fine-tuned cancellations to maintain the observed Higgs mass. This issue challenges the naturalness of the Standard Model (SM), motivating the exploration of new physics models that stabilize the electroweak scale.

Weak-scale supersymmetry (SUSY), particularly the Minimal Supersymmetric SM (MSSM), is a leading framework to address these issues at the TeV scale [4]. The MSSM resolves the hierarchy problem by introducing SUSY, which cancels quadratic divergences in the Higgs mass, thereby enhancing naturalness [5]. It also provides a compelling dark matter candidate in the form of the lightest supersymmetric particle (LSP) [6,7], stabilized by R-parity [8,9] conservation. Within this framework, natural SUSY is a well-motivated approach that minimizes fine-tuning by predicting light stop and higgsinos with masses near the electroweak scale, while allowing heavier masses for other superpartners [10–14]. This hierarchy aligns with the observed Higgs mass of approximately 125 GeV and remains consistent with LHC constraints [2,3].

In natural SUSY, the LSP is typically a neutralino, and a light higgsino-like LSP is common due to the small μ parameter required for low fine-tuning. However, a pure higgsino LSP often yields a thermal relic density below the observed value of $\Omega h^2 \approx 0.12$ due to its large annihilation rate [15,16]. Mixed bino-higgsino neutralino as the LSP in natural SUSY allow a light bino by relaxing the gaugino mass unification assumption. This scenario achieves the correct relic density through enhanced annihilation channels mediated by higgsino components [15,17–26]. Current direct detection (DD) experiments, especially the limits reported by the 2025 LUX-ZEPLIN (LZ) results [27], impose stringent constraints on the weakly interacting massive particle (WIMP) parameter space. LHC searches for electroweakinos also strongly constrain this parameter space. Indirect detection experiments are not effective in this region since the annihilation is p-wave suppressed.

In this work, we investigate the light bino-higgsino dark matter scenario in natural SUSY, focusing on its compatibility with recent DD constraints from LZ and LHC. We explore the light dark matter regime ($m_{\tilde{\chi}_1^0} < 350$ GeV) and determine the parameter space limit for the LSP that constitutes all or some portion of DM, i.e., DM relic density can be smaller than observed value. The small μ parameter in natural SUSY enhances bino-higgsino mixing, impacting the spin-independent (SI) and spin-dependent (SD) neutralino-nucleon scattering cross sections. Additionally, we evaluate the potential to probe this scenario through electroweakino searches at the 14 TeV LHC.

The paper is organized as follows: in Section 2, we discuss the bino-higgsino neutralino parameter space in natural SUSY; in Section 3, we present our parameter scan regions, adopted constraints, and likelihoods; in Section 4, we give obtained results; and in Section 5, we summarize our conclusions.

2. Light Neutralino DM

The two neutral higgsinos ($\tilde{H}_u^0$ and $\tilde{H}_d^0$) and the two neutral gauginos ($\tilde{B}$ and $\tilde{W}^0$) are combined to form four mass eigenstates called neutralinos. In the gauge-eigenstate basis ($\tilde{B}$, $\tilde{W}^0$, $\tilde{H}_d$, $\tilde{H}_u$), the neutralino mass matrix takes the form:

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta s_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta s_W m_Z & -\mu & 0 \end{pmatrix}, \tag{1}$$

where $s_\beta = \sin\beta$, $c_\beta = \cos\beta$, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, M_1 and M_2 are the soft-breaking mass parameters for bino and wino, respectively. $M_{\tilde{\chi}^0}$ can be diagonalized by a 4×4 unitary matrix. In the limit of $M_1 < \mu \ll M_2$, the lightest neutralino is bino-like (with some higgsino mixture), while the second and third neutralinos are higgsino-like. The LSP interacts with nuclei via the exchange of squarks and Higgs bosons (SI scattering) and via Z boson and squarks exchange (SD scattering).

We introduced the problems that SUSY models can address, one of which is the widely discussed naturalness problem. In SUSY models, the mass of the W boson can be explained [28] by

$$\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2, \tag{2}$$

where $m_{H_d}^2$ and $m_{H_u}^2$ represent the soft symmetry-breaking parameters for the electroweak scale fields H_d and H_u, respectively. Σ_d and Σ_u correspond to their radiative corrections. μ is the mass parameter associated with the higgsino, and $\tan\beta = v_u/v_d$. Equation (2) is derived from the Higgs potential in the weak-scale MSSM, with all parameters evaluated at the scale $Q = M_{\text{SUSY}}$. The observed values are obtained under the condition that there is no large cancellation between the terms on the right-hand side of Equation (2), meaning that none of these terms is larger than M_Z^2 in magnitude. Electroweak fine-tuning can be quantified by [29]

$$\Delta_{\text{EW}} \equiv \max_i |C_i| \Big/ \left(\frac{M_Z^2}{2}\right), \tag{3}$$

with $C_{H_d} = m_{H_d}^2/(\tan^2\beta - 1)$, $C_{H_u} = -m_{H_u}^2\tan^2\beta/(\tan^2\beta - 1)$, and $C_\mu = -\mu^2$. Also, $C_{\Sigma_u^u(k)} = -\Sigma_u^u(k)\tan^2\beta/(\tan^2\beta - 1)$ and $C_{\Sigma_d^d(k)} = \Sigma_d^d(k)/(\tan^2\beta - 1)$, where k labels the various loop contributions included in Equation (2). Any upper bound on Δ_{EW} from electroweak naturalness considerations sets a corresponding limit on μ^2 [30]. Imposing the upper limit of $\Delta_{\text{EW}} < 30$ [31–33] leads to the limit of $|\mu| \lesssim 350$ GeV [34].

3. Prior, Constraints and Likelihoods

In our numerical calculations, we vary the relevant parameters in the ranges of

$$\begin{aligned} &100\ \text{GeV} \le |\mu| \le 350\ \text{GeV}, \quad 10\ \text{GeV} \le M_1 \le 350\ \text{GeV}, \\ &|A_T| \le 4000\ \text{GeV}, \quad 5 \le \tan\beta \le 50, \quad \text{others} = 3\ \text{TeV}. \end{aligned} \tag{4}$$

The lower limit on μ comes from LEP charged particle searches [35]. We set to M_1 a lower limit of 10 GeV, where DM would already be overabundant, and the upper limit of 350 GeV is chosen to match the μ upper bound, so that we can study light neutralino DM. In this case, DM can be either bino-like or higgsino-like, and mixed bino-higgsino LSP with mass $\sim \mathcal{O}(10\ \text{GeV})$ may also produce the right DM relic abundance.

We adopt the Markov Chain Monte Carlo (MCMC) method based on the Metropolis-Hastings algorithm to perform the scan of MSSM parameter space with likelihood $\propto \exp(-\chi^2_{\text{tot}}/2)$. The package `MicroMEGAS-5.2.30` [36] is used for DM relic density and DD cross section calculations, `SuperIso-4.0` [37] is used for obtaining B-physics predictions, `HiggsTools` [38] (unification of `HiggsBounds-5` [39] and `HiggsSignals-2` [40]) is used to constraint SM-like and extra Higgs bosons at colliders. The total χ^2_{tot} is defined as the sum of individual χ^2 values of PLANCK relic density, B-physics, DM DD, and Higgs constraints from `HiggsSignals`:

$$\chi^2_{\text{tot}} = \chi^2_{\Omega h^2} + \sum_i \chi^2_{B-\text{physics}} + \chi^2_{\text{DD}} + \chi^2_{\text{HiggsSignals}}. \tag{5}$$

The χ^2 of DM relic density is taken to be zero if the predicted value is below the central value of observed data of 0.1186 ± 0.002, and calculated with the formula

$$\chi^2 = \frac{(\mu_t - \mu_0)^2}{\sigma^2_{\text{theo}} + \sigma^2_{\text{exp}}} \tag{6}$$

otherwise. Where μ_t is predicted from the theoretical value. μ_0, σ_{exp} and σ_{theo} are experimental central value, we take the theoretical uncertainty of $0.1\mu_t$.

Constraints from B-physics are Gaussian distributed, the χ^2 for each observable take the form of Equation (6). Experimental central value, experimental and theoretical uncertainty given in Table 1, and theoretical uncertainty of $0.1\mu_t$ is assumed if not provided in the table.

Table 1. B-physics experimental data.

Observable	Value	Reference
$\text{BR}(B \to X_s\gamma)$	$(3.27 \pm 0.14) \times 10^{-4}$	[41]
$\text{BR}(B_s^0 \to \mu^+\mu^-)$	$(3.34 \pm 0.27) \times 10^{-9}$	[42]
$\text{BR}(B^+ \to \tau^+\nu_\tau)$	$(1.09 \pm 0.24) \times 10^{-4}$	[42]

The estimation of χ^2 for the DM-nucleus SI DD cross section χ^2_{DD} is

$$\chi^2_{\text{DD}} = \left(\frac{\sigma^{\text{SI}}_{\chi p}}{\sigma^{\text{SI},90\%}_{\chi p}/1.64} \right)^2, \tag{7}$$

where $\sigma^{\text{SI}}_{\chi p}$ and $\sigma^{\text{SI},90\%}_{\chi p}$ are predicted from the theoretical value and upper limits of the cross sections for a given DM mass at 90% confidence level from LZ [27], respectively. By assuming null detection, we can take the central value as zero and the number 1.64 is the unit of 90% confidence level (C.L.) [43].

For the LHC constraints, we consider null results from SUSY searches with two or three leptons plus missing transverse momentum at the 13 TeV LHC with 36.1 fb^{-1} [44,45] and 139 fb^{-1} [46–48]. We also include projections for the 14 TeV HL-LHC with 3000 fb^{-1} [49]. Signal processes $pp \to \chi_1^+\chi_1^-$ and

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$pp \to \chi_1^{\pm}\chi_{2,3}^0$ are generated using `MadGraph5_aMC-v3.5.2` [50] with the default parton distribution function set [51], and rescaled with a K-factor of 1.5 to include next-to-leading corrections. Events are showered and hadronized with `PYTHIA-8.2` [52], detector effects simulated with `DELPHES-3.5.0` [53], and analyses recast with `CheckMATE-2.0.37` [54]. A sample is excluded at 95% C.L. if the event ratio $r = \max(N_{S,i}/S^{95\%}_{\mathrm{obs},i})$ exceeds unity, where $N_{S,i}$ is the number of the events for the i-th signal region and $S^{95\%}$ is the corresponding observed 95% C.L. upper limit.

4. Results

In Figure 1, we show all samples satisfy the $\chi^2_{\mathrm{tot}} < 6$ limit in SI and SD DM-nucleon cross section vs. DM mass space. f indicate the ratio of the predicted DM relic density to the value observed by Planck, i.e. $f = \Omega_{\tilde{\chi}_1^0} h^2/0.118$. Red crosses are excluded by current electroweakino searches at the 13 TeV LHC at 95% C.L., while blue stars are projected to be searched at the 14 TeV HL-LHC with luminosity of 3000 fb^{-1} at 95% C.L.. Red solid lines denote the 90% C.L. upper limits from LZ (2025) experiments [27], which gives current strongest scattering cross section limit among the DD experiments at the DM mass of ~ 10 GeV to 10 TeV range. Some points remain below the neutrino floor, beyond the reach of DD experiments, however next generation high-luminosity LHC (HL-LHC) with the luminosity of 3000 fb^{-1} will probe all the parameter space of the light bino-higgsino neutralino in the natural SUSY.

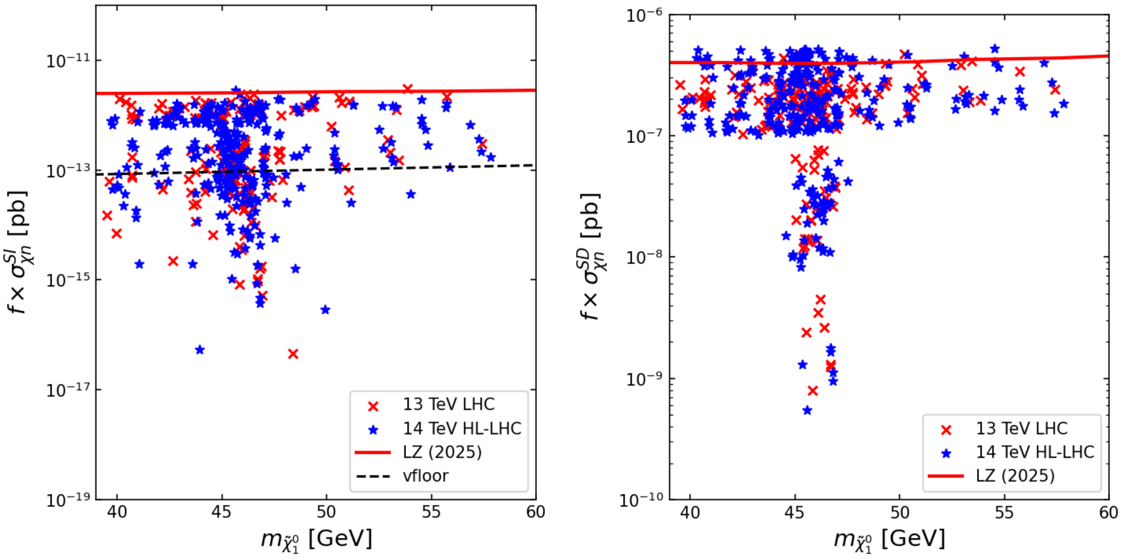

Figure 1. Spin-independent/dependent DM-nucleon cross sections. All samples satisfy the $\chi^2_{\mathrm{tot}} < 6$ constraint. Red crosses are excluded by current electroweakino searches at the 13 TeV LHC at 95% C.L., while blue stars are projected to be searched at the 14 TeV HL-LHC with luminosity of 3000 fb^{-1}. Red solid lines are 90% C.L. upper limits from LZ (2025) experiments [27]. Black dashed line is the neutrino floor. f represent the ratio of the predicted DM relic density to the value observed by Planck.

The left panel of Figure 2 shows the sample on the MSSM soft parameters μ vs. M_1 space. Requiring $\chi^2_{\mathrm{tot}} < 6$ constrains M_1 to lie near the Z-funnel, while the lower bound on $|\mu|$ is ~ 170 GeV. Current 13 TeV LHC data raise this limit to ~ 200 GeV. Contribution to the χ^2_{tot} mainly come from strong LZ (2025) DD limit, and it pushes the coupling $g_{h\chi_1^0\chi_1^0}$ to the small enough value so that Higgs funnel is excluded. While small SI cross sections is due to the both blind spot [21], where negative sign of M_1/μ leads to suppressed $g_{h\chi_1^0\chi_1^0}$, and small fraction of f, small SD cross section is solely due to the small f.

On the right panel of Figure 2, upper limit of ~ 0.02, and a lower limit of $\sim 5 \times 10^{-5}$ have obtained for f, i.e. bino-like DM in this paper at most constitute 2% of all the DM relic. While upper limit of f is also due to the strong LZ limit, for smaller f we need stronger DM annihilation cross section at the early universe, and it has upper limit. Annihilation cross section near Z-boson resonance proportional to the product of coupling constant $g_{Z\chi_1^0\chi_1^0}$ and resonance factor, and which have upper limits determined by bino DM mass and components, $\tan\beta$, and Z-boson decay width. Hence, f can be smaller when DM is closer to the half mass of Z-boson, and it is shown on the right panel of Figure 2.

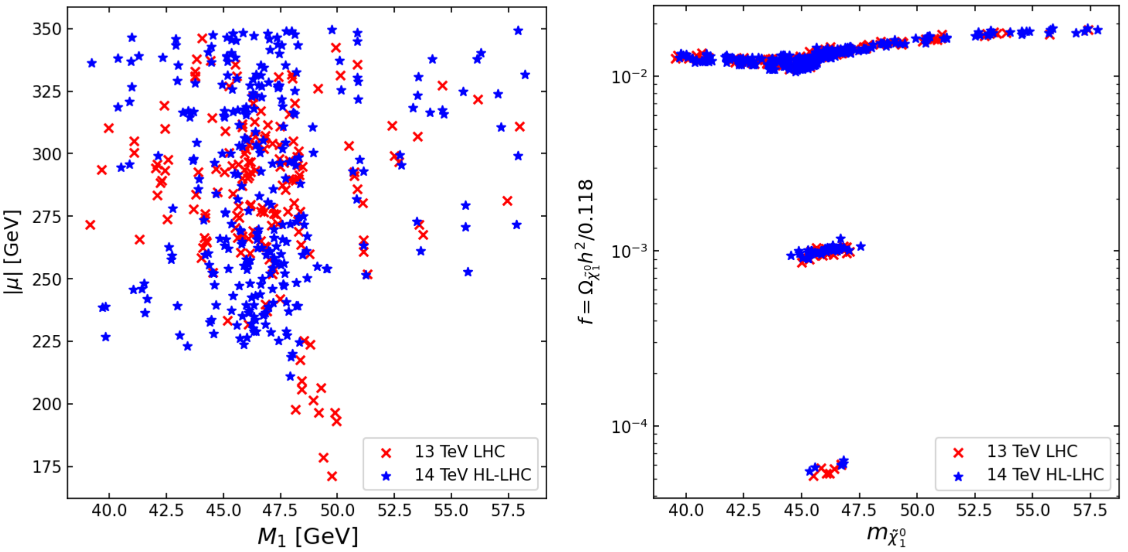

Figure 2. Same as Figure 1, but shown in the μ vs. M_1 plane (left panel) and the f vs. $m_{\tilde{\chi}_1^0}$ plane (right panel). Here, f denotes the ratio of the predicted dark matter relic density to the value observed by Planck.

In addition, recent analyses of the Muon $g-2$ experiment at Fermilab report the value of $a_\mu^{\text{exp}} = 1165920715(145) \times 10^{-12}$ [55], while theoretical SM prediction is $a_\mu^{\text{SM}} = 116592033(62) \times 10^{-11}$ [56]. This suggests no significant discrepancy remains between experiment and theory. The electroweakinos contribution to the muon $g-2$ in this scenario is about 10^{-11}, consistent with the experimental-theory difference of $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 38(63) \times 10^{-11}$ reported in Ref. [56].

5. Conclusions

We have examined the light bino–higgsino dark matter scenario in the framework of natural SUSY, motivated by both electroweak naturalness and the latest experimental results. Requiring $\Delta_{\text{EW}} < 30$ restricts the higgsino mass parameter to $|\mu| \in [100, 350]$ GeV, while we extended the bino mass to $M_1 \in [10, 350]$ GeV. After imposing constraints from Higgs data, rare B decays, LEP limits, direct detection searches, and the observed relic density, we find that only a small fraction of the parameter space remains viable. In particular, the neutralino relic density is always well below the Planck value, contributing at most ∼2% of the total dark matter abundance.

Our analysis shows that current 13 TeV LHC electroweakino searches already exclude part of the parameter space, while the future HL-LHC with 3000 fb^{-1} luminosity will be able to probe the remaining region. Direct detection experiments such as LZ have already reached strong sensitivity, and future improvements may probe most of the surviving points, except for those lying below the neutrino floor. Moreover, in this scenario, the electroweakino contribution to the muon $g-2$ is of order 10^{-11}, consistent with the latest Fermilab measurement and its reduced discrepancy with the Standard Model prediction.

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Abbreviations

The following abbreviations are used in this manuscript:

MSSM	Minimal Supersymmetric Standard Model
LSP	Lightest Supersymmetric Particle
DM	Dark Matter
SI	Spin-Independent
SD	Spin-Dependent
LHC	Large Hadron Collider
HL-LHC	High-Luminosity LHC
LZ	LUX-ZEPLIN
MCMC	Markov Chain Monte Carlo

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