

Status and prospects of light bino–higgsino dark matter in natural SUSY

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Abstract Given the recent progress in dark matter direction detection experiments, we examine a light bino–higgsino dark matter (DM) scenario ($M_1 < 100$ GeV and $\mu < 300$ GeV) in natural supersymmetry with the electroweak fine tuning measure $\Delta_{EW} < 30$. By imposing various constraints, we note that: (i) For $\text{sign}(\mu/M_1) = +1$, the parameter space allowed by the DM relic density and collider bounds can almost be excluded by the very recent spin-independent (SI) scattering cross-section limits from the XENON1T (2017) experiment. (ii) For $\text{sign}(\mu/M_1) = -1$, the SI limits can be evaded due to the cancelation effects in the $h\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling, while rather stringent constraints come from the PandaX-II (2016) spin-dependent (SD) scattering cross-section limits, which can exclude the higgsino mass $|\mu|$ and the LSP mass $m_{\tilde{\chi}_1^0}$ up to about 230 and 37 GeV, respectively. Furthermore, the surviving parameter space will be fully covered by the projected XENON1T experiment or the future trilepton searches at the HL-LHC.

1 Introduction

Scrutinizing the mechanism for stabilizing the electroweak scale becomes more impending after the Higgs discovery at the LHC [1, 2]. Besides, there is overwhelming evidence for the existence of dark matter from cosmological observations. Identifying the nature of dark matter is one of the challenges in particle physics and cosmology.

The weak scale supersymmetry is widely regarded as one of the most appealing new physics models at the TeV scale. It can successfully solve the naturalness problem in the Standard Model (SM) and also provide a compelling cold dark matter candidate. Among various supersymmet-

ric models, the natural supersymmetry is a well motivated framework (see for example [3–11]), which usually indicates the presence of light higgsinos in the spectrum [12]. If unification of the gaugino mass parameters is further assumed, the current LHC bound on the gluino ($m_{\tilde{g}} \gtrsim 2$ TeV [13]) would imply correspondingly heavy winos and binos, resulting in a higgsino-like lightest supersymmetric particle (LSP). However, the thermal abundance of light higgsino-like LSP is typically lower than the observed value of the dark matter in the universe, due to the large higgsino–higgsino annihilation rate. These considerations motivate us to explore the phenomenology of neutralino dark matter in natural SUSY by giving up the gaugino mass unification assumption. One of the possibilities is to allow for the light bino in natural SUSY. Such a mixed bino–higgsino neutralino dark matter can solve the above-mentioned problems of a pure higgsino LSP without worsening the naturalness in natural SUSY. The studies of bino–higgsino dark matter have also been carried out in [14–33].

In this work, we will confront the light bino–higgsino dark matter scenario in natural SUSY with the recent direct detection data. In particular, we focus on the light dark matter regime ($m_{\tilde{\chi}_1^0} < 100$ GeV) and attempt to address the lower limit of the mass of LSP that saturates the dark matter relic abundance. In natural SUSY, a small μ parameter leads to a certain bino–higgsino mixing, so that the spin-independent/dependent neutralino LSP–nucleon scattering cross sections can be enhanced. We will utilize the recent XENON1T [34] and PandaX-II [35] limits to examine our parameter space. Since the couplings of the LSP with the SM particles depend on the relative sign ($\text{sign}(\mu/M_1)$) between the mass parameters μ and M_1 , we will include both of $\text{sign}(\mu/M_1) = \pm 1$ in our study and show the impact on the exclusion limits for our scenario. Besides, we explore the potential to probe such a

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scenario by searching for the trilepton events at 14 TeV LHC.

The structure of this paper is organized as follows. In Sect. 2, we will discuss the light bino–higgsino neutralino parameter space in natural SUSY. In Sect. 3, we will perform the parameter scan and discuss our numerical results. Finally, we draw our conclusions in Sect. 4.

2 Light bino–higgsino neutralino in natural SUSY

In the MSSM, the minimization of the tree-level Higgs potential leads to the following equation [36]:

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2, \tag{1}$$

where $m_{H_{u,d}}^2$ denote the soft SUSY breaking masses of the Higgs fields at the weak scale, respectively. It should be noted that the radiative EWSB condition usually imposes a non-trivial relation between the relevant soft mass parameters at the high scale in a UV model, such as mSUGRA. However, the scenario we studied in our work is the so-called low energy phenomenological MSSM, in which a successful EWSB is always assumed and in this case the above mentioned strong correlation between parameters from radiative EWSB condition in UV models is not applicable. Using the electroweak fine tuning measure Δ_{EW} [6], one can see that the higgsino mass parameter μ should be of the order of $\lesssim 300$ GeV to satisfy the requirement of $\Delta_{EW} < 30$ [37–40]. The light higgsinos have been searched for through chargino pair production in the LEP-2 experiment [41], which indicates $\mu \gtrsim 100$ GeV. We will use this LEP-2 limit as a lower bound for the higgsino mass. However, the relic abundance of thermally produced pure higgsino LSP falls well below dark matter measurements, unless its mass is in the TeV range. In order to provide the required relic density, several alternative ways have been proposed, such as the multi-component dark matter on introducing the axion [42]. On the other hand, without fully saturating the relic density (under-abundance), the higgsino-like neutralino dark matter in radiatively driven natural supersymmetry with $\Delta_{EW} < 30$ [43] or the natural mini-landscape model [44] has been confronted with various (in-)direct detections and is also expected to be accessible via the Xenon1T experiment. In our study, we achieve the correct dark matter relic density by allowing the light bino to mix with the higgsinos.

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

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta s_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \tag{2}$$

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 N . 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 can interact with nuclei via exchange of squarks and Higgs bosons (spin-independent) and via exchange of Z boson and squarks (spin-dependent). Given the strong LHC bounds on the squarks and non-SM Higgs bosons, one can neglect their contributions to the scattering cross section. Then the couplings of the LSP with the Higgs boson can be written

$$C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \approx -\sqrt{2}g_1N_{11}^2 \frac{M_Z s_W}{\mu} \frac{M_1/\mu + \sin 2\beta}{1 - (M_1/\mu)^2}, \tag{3}$$

where N_{11} denotes the bino component of the lightest neutralino mass eigenstate. It can be seen that the SI scattering cross section depends on the relative sign of M_1 and μ . When $\text{sign}(M_1/\mu) < 0$, the coupling $C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$ can be suppressed and even vanish if $M_1/\mu = -\sin 2\beta$ so that the strong LUX SI limits can be escaped. For the SD scattering cross section, it should be noted that the coupling $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ can appear via the higgsino component in the LSP. The pure bino/wino LSP will not have interactions with the Z boson, while the pure higgsino LSP can only have the non-zero coupling $Z\tilde{\chi}_1^0\tilde{\chi}_2^0$. Another blind spot in SD scattering may occur in the limit of $\tan \beta = 1$, where the left–right parity is restored and the parity-violating Z coupling will vanish [16]. However, a low value of $\tan \beta$ is disfavored by the observed Higgs mass in the MSSM.

3 Parameter scan and numerical results

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

$$100 \text{ GeV} \leq |\mu| \leq 300 \text{ GeV}, \quad 30 \text{ GeV} \leq |M_1| \leq 100 \text{ GeV}, \quad 10 \leq \tan \beta \leq 50. \tag{4}$$

We scan the values of M_1 up to 100 GeV since we are interested in light DM region and attempt to address the lower limit of the LSP mass. For higher upper values of μ and M_1 , a heavy mixed higgsino–bino LSP may also produce the right DM relic abundance [20], while the result for lower bound of LSP mass obtained in the following calculation will not change. The stop and gluino can contribute to the naturalness at loop level, which are expected to be $m_{\tilde{t}_1} \lesssim 2.5$ TeV

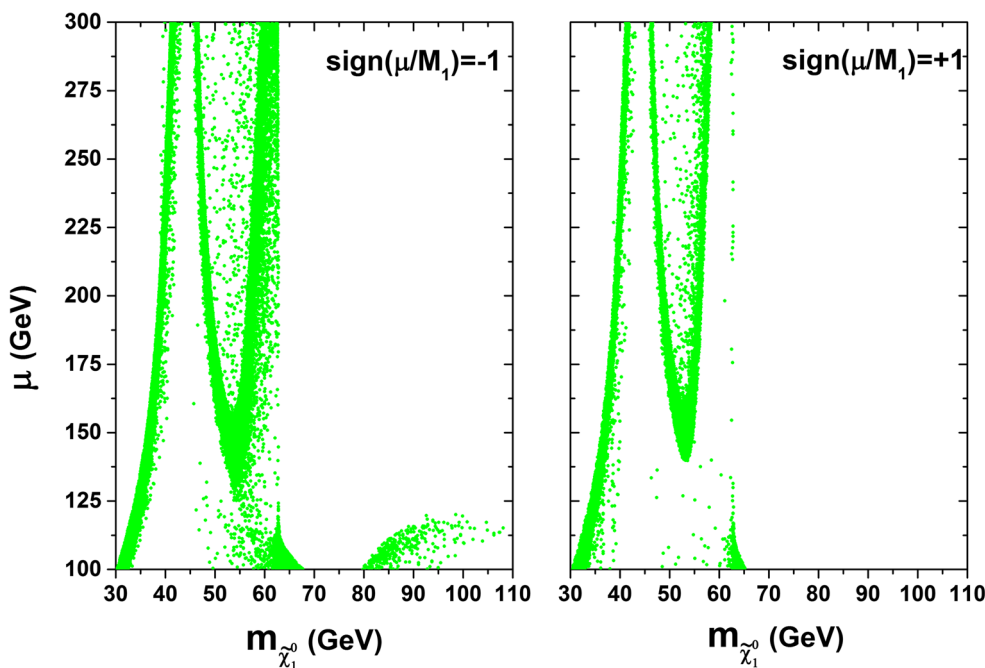


Fig. 1 Scattering plot of samples satisfying the dark matter relic density

and $m_{\tilde{g}} \lesssim 3 - 4$ TeV for $\Delta_{EW} < 30$ [37,45]. By recasting the LHC Run-2 with $\sim 15 \text{ fb}^{-1}$ of data, it is found that the lower bounds of stop mass and gluino mass are about 800 GeV [46–51] and 1.5 TeV [52] in natural SUSY, respectively. Given the irrelevance of the third generation parameters for our neutralino dark matter, we fix the third generation squark soft masses as $M_{\tilde{Q}_{3L}} = 3$ TeV, $M_{\tilde{t}_{3R}} = M_{\tilde{b}_{3R}} = 1$ TeV and vary the stop trilinear parameters in the range $|A_t| < 2$ TeV for simplicity. The physical stop mass $m_{\tilde{t}_1}$ has to be less than 2.5 TeV to satisfy $\Delta_{EW} < 30$. We also require that each sample can guarantee the correct Higgs mass and the vacuum stability [53,54]. For the first two generations, the squark and all slepton soft masses are assumed to be 3 TeV. Other trilinear parameters are fixed as $A_f = 0$. We also decouple the wino and gluino by setting $M_{2,3} = 2$ TeV. We impose the following constraints in our scan:

- (1) The light CP-even Higgs boson masses of our samples should be within the range of 122–128 GeV. The package SuSpect [55] is used to calculate the Higgs mass.
- (2) The samples have to be consistent with the Higgs data from LEP, Tevatron and LHC. We use the packages HiggsBounds-4.2.1 [56,57] and HiggsSignals-1.4.0 [58] to implement the constraints.
- (3) The relic density of neutralino dark matter $\Omega_{\tilde{\chi}} h^2$ is computed by MicrOMEGAs 4.3.2 [59]. Including 10% theoretical uncertainty, we require our samples to satisfy the observed value 0.1186 ± 0.0020 [60] within 2σ range.

- (4) If $m_{\tilde{\chi}_1^0} < m_h/2$, the SM Higgs boson can decay to $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ invisibly. We require the branching ratio $Br(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 24\%$, which has recently been given by the CMS collaboration at 95% C.L. [61].
- (5) The invisible width of the Z boson is required to be less than 0.5 MeV to satisfy the LEP limit.
- (6) The LEP searches for $\tilde{\chi}_1^0 \tilde{\chi}_{2,3}^0$ associated production gives an upper limit, $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_{2,3}^0) \times Br(\tilde{\chi}_{2,3}^0 \rightarrow \tilde{\chi}_1^0 Z^*) < 100$ fb.

In Fig. 1, we show the samples satisfying the dark matter relic density for $\text{sign}(\mu) = \pm 1$. Since a bino-like LSP has rather small couplings with the SM particles, a certain portion of higgsino components is required to meet the observed relic density. Otherwise, the universe will be overclosed. Therefore, except for the two resonance regions $m_{\tilde{\chi}_1^0} \simeq m_Z/2$ and $m_h/2$, the higgsino mass parameter μ is expected to be as low as possible in our scan ranges. It should be noted that the difference of $\text{sign}(\mu/M_1) = \pm 1$ in calculating the relic abundance mainly happens around and after the Higgs resonance region, in which more samples are allowed for $\text{sign}(\mu/M_1) = -1$. This is because the negative sign of μ/M_1 can reduce the coupling of the LSP with the Higgs boson and the suppress the enhanced annihilation cross section of $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ by the Higgs resonant effect. When $m_{\tilde{\chi}_1^0} > m_h/2$, the LSP for $\text{sign}(\mu/M_1) = \pm 1$ is still bino-like so that the relic density easily exceeds the observed value. But if M_1 is close to μ , the LSP for $\text{sign}(\mu/M_1) = -1$ can have sizable higgsino components, which allows samples in

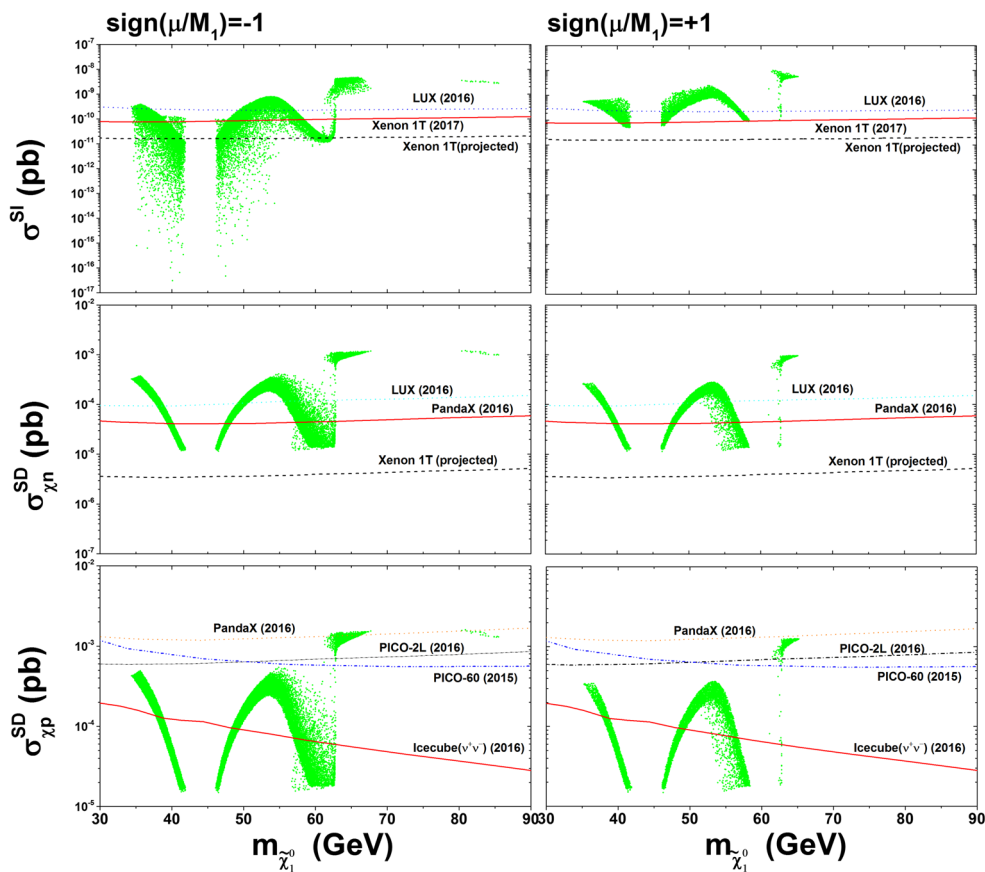


Fig. 2 Spin-independent/dependent neutralino LSP-nucleon scattering cross sections. All samples satisfying the constraints (1–6). The observed 90% C.L. upper limits from Xenon1T (2017) [34], PandaX (2016) [35], LUX (2016) [62,63], PICO-2L (2016) [64], PICO-60

(2015) [65], IceCube (2016) [66] and the projected XENON1T sensitivity limits [67] are plotted. For indirect limits, we assume that LSP annihilates exclusively to some specific final state, with a canonical thermal annihilation cross section $\langle\sigma v\rangle_0 = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

the lower right corner on the left panel of Fig. 1. However, such a region will be excluded by the dark matter direct detections as shown in the following.

In Fig. 2, we present the spin-independent/dependent neutralino LSP-nucleon scattering cross sections, which are calculated by using MicrOMEGAs 4.3.2 [59]. All samples satisfying the constraints (1–6). The neutron and proton form factors are taken as $f_d^p \approx 0.132$ and $f_d^n \approx 0.140$. It can be seen that the very recent SI cross-section limits from XENON1T experiment can almost exclude the whole parameter space of $\text{sign}(\mu/M_1) = +1$. While for $\text{sign}(\mu/M_1) = -1$, a large portion of our samples can escape the SI limits since the $h\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling is suppressed by the cancellation effect in Eq. (3).

On the other hand, the SD cross section is largely determined by Z-boson exchange and is sensitive to the higgsino asymmetry, $\sigma_{SD} \propto |N_{13}^2 - N_{14}^2|^2$. The relic density constraint requires a large higgsino asymmetry so that the SD cross section is enhanced. Therefore, a strong bound on such a scenario comes from the PandaX-II (2016) SD neutralino

LSP–neutron scattering cross-section limits, which can rule out about 70% of our samples and exclude the higgsino mass $|\mu|$ and the LSP mass $m_{\tilde{\chi}_1^0}$ up to about 230 and 37 GeV, respectively. Such lower limits will not changed even if we extend the scan ranges of M_1 and μ to larger values. The current SD neutralino LSP–proton limits from PandaX and PICO are still weak. Both of $\text{sign}(\mu) = \pm 1$ scenarios can be completely covered by the projected XENON1T experiment in the future.

Besides the direct detections, the neutralino annihilation in the Sun to neutrinos can also be enhanced by the higgsino component in the LSP. The null results from the neutrino telescopes, such as IceCube, have produced a strong bound on the SD neutralino LSP–proton scattering cross sections and has excluded a sizable portion of the parameter space for $\text{sign}(\mu) = -1$. Next, we discuss the LHC potential of probing the current parameter space of our scenario allowed by the constraints (1)–(6) and the above direct/indirect detections.

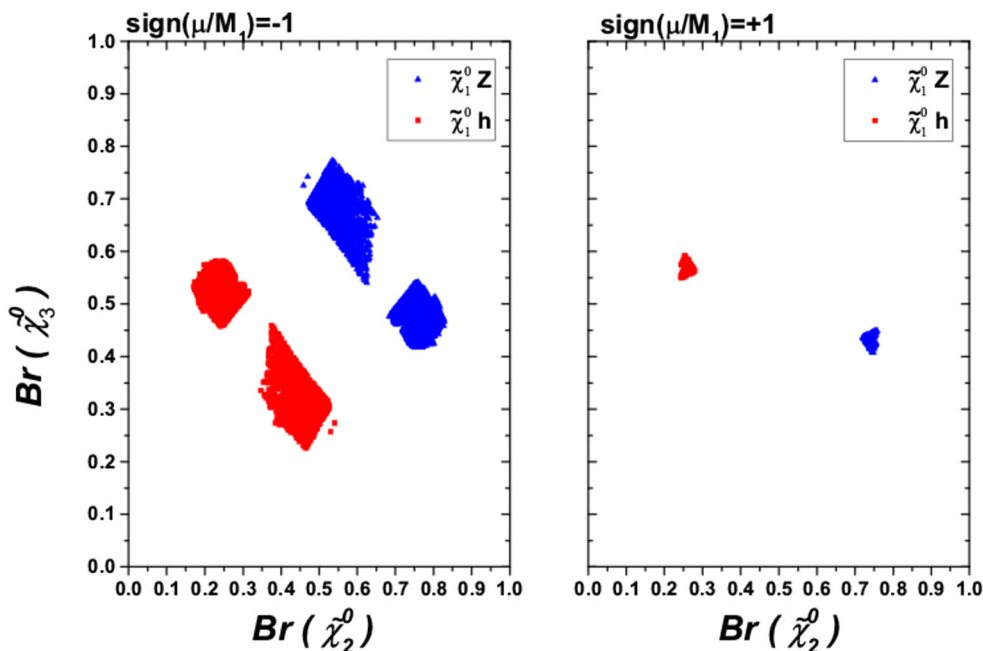


Fig. 3 Scatter plots of the samples allowed by the constraints (1–6) and by the XENON1T (2017) and PandaX (2016), showing $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ decay branching ratios

Table 1 Recast LHC-8 TeV analyses with 20.3 fb^{-1} of data and corresponding signals in our scenario

Final states	Source of signal in our scenario
3lepton + \cancel{E}_T [77]	$pp \rightarrow \tilde{\chi}_1^\pm (\rightarrow W^\pm \tilde{\chi}_1^0) \tilde{\chi}_{2,3}^0 (\rightarrow Z \tilde{\chi}_1^0)$
1lepton + h + \cancel{E}_T [78]	$pp \rightarrow \tilde{\chi}_1^\pm (\rightarrow W^\pm \tilde{\chi}_1^0) \tilde{\chi}_{2,3}^0 (\rightarrow h \tilde{\chi}_1^0)$
$\ell^+ \ell^- + \cancel{E}_T$ [79]	$pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$

In Fig. 3, we plot the decay branching ratios of $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$. For $\text{sign}(\mu) = -1$, we can see that the neutralinos $\tilde{\chi}_{2,3}^0$ mainly decay to $\tilde{\chi}_1^0 Z$. When $Br(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z)$ increases, $Br(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 Z)$ decreases because of the Goldstone theorem [25]. A similar correlation can be seen in the decay channel $\tilde{\chi}_{2,3}^0 \rightarrow \tilde{\chi}_1^0 h$. But for $\text{sign}(\mu) = +1$, the neutralino $\tilde{\chi}_2^0$ still dominantly decay to $\tilde{\chi}_1^0 Z$, while the neutralino $\tilde{\chi}_3^0$ preferably decay to $\tilde{\chi}_1^0 h$. This indicates that the samples with negative sign of μ/M_1 will produce more trilepton events through the process $pp \rightarrow \tilde{\chi}_{2,3}^0 (\rightarrow Z \tilde{\chi}_1^0) \tilde{\chi}_1^\pm (\rightarrow W^\pm \tilde{\chi}_1^0)$ than those with positive sign of μ/M_1 , and can be more easily excluded by the null results of searching for electroweakinos at the LHC.

Given the above decay modes, we first recast the LHC searches for the electroweakinos listed in Table 1 with CheckMATE2 [68–70]. We generate the parton level signal events by MadGraph5_aMC@NLO [71] and per-

form the shower and hadronization procedure by Pythia-8.2 [72]. The fast detector simulation are carried out with the tuned Delphes [73]. We implement the jet clustering by FastJet [74] with the anti- k_r algorithm [75]. We use Prospino2 [76] to calculate the QCD corrected cross sections of the electroweakino pair productions at the LHC. Then we estimate the exclusion limit by evaluating the ratio $r = \max(N_{S,i}/S_{obs,i}^{95\%})$, where $N_{S,i}$ is the event number of signal for i th signal region and $S_{obs,i}^{95\%}$ is the corresponding 95% C.L. observed upper limit. A sample is excluded at 95% C.L. if $r > 1$. After checking all surviving samples, we find that the LHC data in Table 1 cannot further exclude the parameter space because of the strong direct detection bound on higgsino mass parameter $\mu > 230 \text{ GeV}$.

In Fig. 4, we show the prospect of testing our surviving samples through searching for electroweakino pair production in the trilepton final states at 14 TeV LHC with the luminosity $\mathcal{L} = 3000 \text{ fb}^{-1}$. Such an analysis [80] has been implemented in CheckMATE package. In order to reduce the Monte Carlo fluctuations, we generate 200,000 events for each signal point. In Fig. 4, we can see that all red triangles allowed by the constraints (1)–(6) and the XENON1T (2017) and PandaX (2016) experiments can be excluded by the HL-LHC at 95% C.L. Therefore, we conclude that our light bino–higgsino neutralino dark matter scenario will be fully tested by either future XENON1T or HL-LHC experiments.

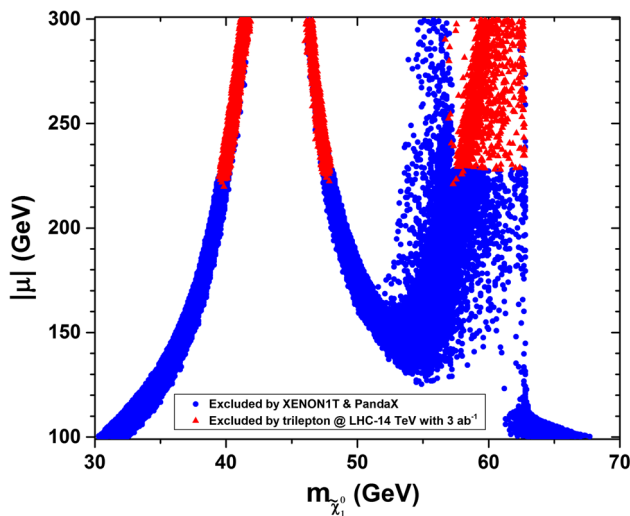


Fig. 4 Scatter plots of the samples allowed by the constraints (1–6) on the plane of $|\mu|$ versus $m_{\tilde{\chi}_1^0}$. The blue bullets are excluded by the XENON1T (2017) and PandaX (2016). The red triangles are expected to be excluded by the trilepton searches at 95% C.L. at the HL-LHC

4 Conclusion

In this work, we examined light bino–higgsino neutralino dark matter in natural SUSY by imposing various constraints from the LEP, dark matter and LHC experiments. We found that the relative sign between the mass parameters μ and M_1 can significantly affect the dark matter and LHC phenomenology of our scenario. For $\text{sign}(\mu/M_1) = +1$, the very recent SI limits from the Xenon1T (2017) experiment can almost exclude the whole parameter space allowed by the relic density and collider bounds. But for $\text{sign}(\mu/M_1) = -1$, the SI limits can be avoided due to the cancellation effects in $h\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling. In this case, a strong bound comes from the PandaX-II (2016) SD neutralino LSP–neutron scattering cross-section limits, which can exclude the higgsino mass $|\mu|$ and the LSP mass $m_{\tilde{\chi}_1^0}$ up to about 230 and 37 GeV, respectively. Furthermore, the surviving parameter space will be fully covered by the projected XENON1T experiment or the future trilepton searches at 14 TeV LHC with the luminosity $\mathcal{L} = 3000 \text{ fb}^{-1}$.

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