Implications of purity constraints on light Higgsinos

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The lightest supersymmetric particles could be Higgsinos that have a small mixing with gauginos. If the lightest Higgsino-like state makes up some or all of the dark matter with a thermal freeze-out density, then its mass must be between about 100 GeV and 1150 GeV, and dark matter searches put bounds on the amount of gaugino contamination that it can have. Motivated by the generally good agreement of flavor- and CP-violating observables with Standard Model predictions, I consider models in which the scalar particles of minimal supersymmetry are heavy enough to be essentially decoupled, except for the 125 GeV Higgs boson. I survey the resulting purity constraints as lower bounds on the gaugino masses and upper bounds on the Higgsino mass splittings. I also discuss the mild excesses in recent soft lepton searches for charginos and neutralinos at the LHC, and show that they can be accommodated in these models if $\tan\beta$ is small and μ is negative.

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I. INTRODUCTION

Softly broken supersymmetry (for reviews in conventions and notations consistent with that of the present paper, see Refs. [1,2]) provides a solution to the large hierarchy problem associated with the small ratio of the electroweak mass scale to the Planck scale and other very high-mass scales. The radiative correction sensitivity of the electroweak scale to arbitrarily large mass scales is reduced to a sensitivity to the scale of soft supersymmetry breaking, which is presumed to be many orders of magnitude smaller due to a dynamical origin, for which there is no shortage of proposals.

On the other hand, supersymmetry breaking introduces new possible sources of flavor violation and CP violation. Furthermore, the continuing explorations of the Large Hadron Collider (LHC) are putting lower bounds on superpartner masses, especially in the cases of the strongly interacting superpartners, gluinos, and squarks, which are produced with relatively large cross sections in proton-proton collisions. In recent years, search results are mostly presented in terms of simplified models, and it should be recognized that the simplified models of supersymmetry are not actually supersymmetry. The quoted bounds are therefore often significantly stronger than what would follow from realistic supersymmetric models. Still, the indirect bounds from flavor and CP violation together with the direct bounds from collider searches motivate a scenario [3–6] with a little hierarchy, in which the squarks and sleptons would have multi-TeV or even PeV masses, beyond the reach of the LHC. The proven existence of a Higgs scalar boson with mass near $M_h = 125.1$ GeV gives credence to this possibility, since the tree-level prediction for the mass is less than M_Z, and so it is both necessary and sufficient to have logarithmic corrections to M_h that can easily have the right magnitude if top squarks have multi-TeV or larger masses.

This raises the question of what superpartners could most plausibly still appear at the LHC, and what type of neutral lightest supersymmetric particle (LSP) could be detected in dark matter searches. The accumulation of data at the LHC has arguably reached the point that gluino and squark search improvements are more incremental, and the largest improvements in reach will come in the cases of charginos and neutralinos, which are mixtures of the superpartners of the Higgs bosons (Higgsinos) and the gauge bosons of the Standard Model (gauginos). Many studies have pointed out the intriguing features of light Higgsino-like particles, for which the present LHC bounds are rather weak, and dark matter bounds have not reached the exclusion level. The electroweak scale in supersymmetry is closely tied to the magnitude of the Higgsino mass parameter μ. This makes it interesting to consider the case that among the new mass parameters required in the minimal supersymmetric Standard Model (MSSM), μ is closest to the electroweak scale, with other superpartner masses (perhaps much) larger. Furthermore, a nearly pure Higgsino LSP would make a good candidate for the dark matter that seems to be required by cosmology and astrophysics observations (for some recent reviews, see Refs. [7–9]).

If it makes up a significant fraction of the dark matter, an extremely pure vectorlike spin-1/2 fermion in a doublet of $SU(2)_L$ with weak hypercharge $\pm 1/2$ with a mass splitting between its two neutral mass eigenstates of less than about 200 keV would be ruled out by direct searches from inelastic scattering of the LSP into the higher neutral state, mediated by the Z boson. Fortunately, this kind of simplified Higgsino model is not at all what appears in realistic supersymmetric models, which essentially always have a much larger mass splitting due to the mixing with the gauginos. This impurity of Higgsino-like neutralinos in supersymmetry is both necessary and guaranteed, assuming the gaugino masses are not enormous, since the off-diagonal terms in the neutralino mass matrix in the gauge-eigenstate basis have magnitudes that are bounded from below by electroweak symmetry breaking.

In this paper, I consider a class of supersymmetric models, defined by parameters at the 10 TeV scale [rather than the grand unified theory (GUT) or Planck scale], in which the lightest superpartners are two Higgsino-like neutralinos and a chargino, denoted $\tilde{N}_1$, $\tilde{N}_2$, and $\tilde{C}_1$. These particles have mixing with the bino and wino, yielding further neutralino and chargino states $\tilde{N}_3$, $\tilde{N}_4$, and $\tilde{C}_2$, which are assumed here to be at least somewhat heavier. Inspired by the arguments of [3–6], and by the lack of discovery from the LHC, and by the Higgs boson mass of 125.1 GeV, the squarks, sleptons, gluino, and the other Higgs bosons $A, H, H^\pm$ will be assumed to be practically decoupled, with a common default mass of 10 TeV. This provides a simple framework with only a few parameters having a significant impact on immediately relevant physics considerations, namely the Higgsino mass parameter μ, the bino and wino masses M_1 and M_2, which are assumed to be real and larger in magnitude than $|\mu|$, and $\tan\beta$, the ratio of the Higgs expectation values. Besides simplicity, this framework has the virtues of avoiding both direct detection of superpartners at the LHC and indirect constraints from flavor and CP-violating observables.

It is well-known that the present abundance of a Higgsino-like LSP, assuming thermal freeze-out in the standard cosmology, increases with the mass, and will agree with the best fit of $\Omega_{\rm DM}h^2 = 0.12$ from the results of the Planck experiment [10] if $M_{\tilde{N}_1}$ is about 1.1 TeV. This is illustrated in Fig. 1, which shows the thermal freeze-out prediction for Ωh^2 as a function of $M_{\tilde{N}_1}$, as computed by the public code micrOMEGAs v6.0 [11–14], for two cases with decoupled and not-so-decoupled gauginos. This shows that Ωh^2 has more sensitivity to the gaugino mixing when it is small (for lighter Higgsinos, with $|\mu|$ closer to m_Z).

At least four obvious possibilities present themselves for a Higgsino-like LSP. First, the dark matter could indeed be a Higgsino-like LSP with mass near 1.1 TeV. Second, the mass could be less than 1.1 TeV, and the remaining dark matter could be something else, for example axions. In this case, the rates for dark matter direct detection experiments, for a given LSP-nucleon cross section will be reduced by a factor of

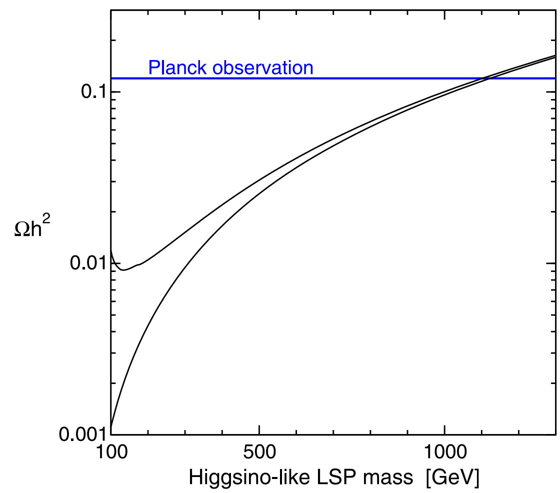

FIG. 1. The thermal freeze-out prediction for Ωh^2 for Higgsino-like LSP dark matter, as a function of the mass. For the illustration, the squark, slepton, and $H, A, H^\pm$ Higgs boson masses are set to 10 TeV. The upper black curve assumes μ: M_1: $M_2 = 1{:}1.5{:}3$ and $\tan\beta = 2$, while the lower black curve assumes $M_1 = M_2 = 10$ TeV and $\tan\beta = 10$. In both cases, agreement with the Planck experiment result [10] of $\Omega h^2 = 0.12$ is obtained if the LSP mass $M_{\tilde{N}_1} \approx 1.1$ TeV, but significant differences arise for smaller masses.

$$\xi \equiv \frac{\Omega_{\rm LSP}h^2}{0.12} \le 1, \tag{1.1}$$

while rates for most indirect detection searches (with the exception of searches for annihilations to neutrinos from equilibrium densities accumulated in the Sun) will be reduced by ξ^2. Third, the mass could again be less than 1.1 TeV, but with other nonthermal freeze-out sources for the Higgsino dark matter. Fourth, the Higgsino might be the lightest among the subset of supersymmetric particles within the MSSM, but it decays to something else, either to Standard Model states through R-parity violating couplings, or to non-MSSM R-parity-odd states such as a singlino (perhaps an axino). In this paper, I concentrate on the first two of these possibilities. The proposal that a Higgsino LSP and an axion combine to give the dark matter density inferred by cosmology has been studied in detail in Refs. [15–18], with an emphasis on fine-tuning considerations that will play no role in the present paper. Other important contributions to our understanding of the Higgsino LSP scenario, including the difficulties in observing them in collider experiments and their possible role as dark matter, can be found in Refs. [19–45].

Dark matter searches of several types impose constraints on the Higgsino-like LSP parameter space. These constraints are nontrivial even if the mass is less than 1.1 TeV and thermal freeze-out governs the density, so that ξ is less than 1. Annihilations of dark matter have been searched for using gamma rays from the center of our galaxy with the HESS ground-based Cherenkov telescope array [46–48], and from annihilations in dwarf galaxies with the Fermi-LAT space-based gamma-ray telescope [49–51]. At present, gamma-ray searches do not exclude the 1.1 TeV thermal Higgsino case [42,52], and are subject to significant uncertainties regarding the dark matter density profile, and become weaker proportionally to ξ^2. In contrast, searches by the IceCube experiment for neutrinos from annihilations in the Sun [53] depend on the equilibrium rate of dark matter accumulations and are proportional to ξ, and give constraints on the spin-dependent LSP-proton cross section. However, at present the preceding constraints on Higgsino-like dark matter with a thermal freeze-out relic abundance are less stringent than those coming from the LUX-ZEPLIN (LZ 2022) [54] direct detection searches, which limit both the spin-independent LSP-xenon nuclear cross section, and (in certain parts of parameter space that may be quite important, as we will see) the LSP-neutron spin-dependent cross section. These constraints scale proportionally to ξ, but are nontrivial even for Higgsino-like LSPs with masses close to 100 GeV, so that ξ is as low as of order 0.01. In general, such direct detection constraints have the effect of requiring that the Higgsino LSP is sufficiently pure (bounding the gaugino contents of the LSP mass eigenstate) in different ways, and to different extents, depending on the mass and other parameters.

In this paper, I will survey the requirements on light Higgsino purity that follow from the LZ 2022 bounds, using the model framework with decoupled scalars outlined above. For fixed values of μ and $\tan\beta$, I obtain lower bounds on the gaugino masses, with consequences for the collider search prospects for the binolike and winolike neutralinos and charginos. These constraints also entail upper bounds on the mass splittings between the mostly Higgsino states $\tilde{N}_1$ (the LSP) and $\tilde{N}_2$ and $\tilde{C}_1$. This has implications for past and future LHC searches, and I will comment in particular on the slight excesses in soft lepton searches observed by the ATLAS and CMS Collaborations [55–57].

II. HIGGSINO MIXING AND COUPLINGS TO HIGGS AND Z BOSONS

In this section, I review the tree-level mixing and mass splitting of neutralinos and charginos in the MSSM. Although these tree-level results are not completely adequate and are not used for the detailed studies in the remaining sections, they can be used to help understand certain qualitative features, notably the dependences on $\tan\beta$ and the sign of μ.

In the gauge eigenstate basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$, the tree-level neutralino mass matrix can be divided into parts that do not and do rely on electroweak symmetry breaking,

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & 0 & 0 \\ 0 & M_2 & 0 & 0 \\ 0 & 0 & 0 & -\mu \\ 0 & 0 & -\mu & 0 \end{pmatrix} + m_Z \begin{pmatrix} 0 & 0 & -s_W c_\beta & s_W s_\beta \\ 0 & 0 & c_W c_\beta & -c_W s_\beta \\ -s_W c_\beta & c_W c_\beta & 0 & 0 \\ s_W s_\beta & -c_W s_\beta & 0 & 0 \end{pmatrix}, \quad (2.1)$$

where s_W and c_W are the sine and cosine of the weak mixing angle, and s_β and c_β are the sine and cosine of the angle β defined by $\tan\beta = \langle H_u^0\rangle/\langle H_d^0\rangle$, the ratio of Higgs expectation values. The neutralino mixing matrix with elements N_{jk} is conventionally defined so that

$$N^* M_{\tilde{N}} N^{-1} = \mathrm{diag}(M_{\tilde{N}_1}, M_{\tilde{N}_2}, M_{\tilde{N}_3}, M_{\tilde{N}_4}), \quad (2.2)$$

and in our case $\tilde{N}_1$ is the LSP and $\tilde{N}_2$ is the other Higgsino-like fermion, and the mass eigenvalues $M_{\tilde{N}_j}$ are always real and positive (no matter what the phases of M_1, M_2, and μ are). For simplicity, suppose that M_1, M_2, are real and positive, and that μ is also real with

$$\sigma \equiv \mathrm{sign}(\mu) = \pm 1. \quad (2.3)$$

Doing perturbation theory in m_Z, one finds that the tree-level mass eigenvalues are (neglecting contributions of order m_Z^4)

$$M_{\tilde{N}_1} = |\mu| - \frac{m_Z^2}{2}(1+\sigma s_{2\beta})\left(\frac{c_W^2}{M_2-|\mu|} + \frac{s_W^2}{M_1-|\mu|}\right) + \cdots, \quad (2.4)$$

$$M_{\tilde{N}_2} = |\mu| + \frac{m_Z^2}{2}(1-\sigma s_{2\beta})\left(\frac{c_W^2}{M_2+|\mu|} + \frac{s_W^2}{M_1+|\mu|}\right) + \cdots, \quad (2.5)$$

$$M_{\tilde{N}_3} = M_1 + s_W^2 m_Z^2 \left(\frac{M_1 + \mu s_{2\beta}}{M_1^2 - \mu^2}\right) + \cdots, \quad (2.6)$$

$$M_{\tilde{N}_4} = M_2 + c_W^2 m_Z^2 \left(\frac{M_2 + \mu s_{2\beta}}{M_2^2 - \mu^2}\right) + \cdots, \quad (2.7)$$

where $s_{2\beta} = \sin(2\beta)$, so that $\tilde{N}_1$ is the LSP for $M_1, M_2 > |\mu|$. The corresponding neutralino mixing matrix can also be straightforwardly evaluated in perturbation theory to order m_Z^2. Of particular interest are the resulting LSP couplings to the lightest Higgs boson, h, and to the Z boson, which respectively give the most important contributions to the spin-independent and spin-dependent LSP-nucleon cross sections, given the assumption of decoupled squarks, sleptons, and $A, H, H^{\pm}$ bosons. They have the form

$$\mathcal{L} = -\sqrt{g^2+g'^2}\left(\frac{1}{2}y_h h\tilde{N}_1\tilde{N}_1 + \text{c.c.} + g_Z Z_\mu \tilde{N}_1^\dagger \bar{\sigma}^\mu \tilde{N}_1\right), \quad (2.8)$$

where

$$y_h = (c_W N_{12}^* - s_W N_{11}^*)(-s_\alpha N_{13}^* - c_\alpha N_{14}^*), \quad (2.9)$$

$$g_Z = (|N_{14}|^2 - |N_{13}|^2)/2, \quad (2.10)$$

in which α is the mixing angle in the neutral Higgs scalar boson sector. Taking the decoupling limit in which $\alpha = \beta - \pi/2$, one finds the following results at leading order in an expansion in m_Z,

$$y_h = -\frac{m_Z}{2}(1+\sigma s_{2\beta})\left(\frac{c_W^2}{M_2-|\mu|} + \frac{s_W^2}{M_1-|\mu|}\right), \quad (2.11)$$

$$g_Z = \frac{m_Z^2}{4|\mu|}c_{2\beta}\left(\frac{c_W^2}{M_2-|\mu|} + \frac{s_W^2}{M_1-|\mu|}\right). \quad (2.12)$$

These both vanish in the limit that m_Z is small compared to $M_2 - |\mu|$ and $M_1 - |\mu|$, corresponding to a pure Higgsino LSP. Two more comments concerning the LSP coupling to the Higgs boson are in order. First, for fixed values of $\tan\beta$ and sign(μ), the coupling has a very simple relation to the LSP mass shift, namely

$$y_h = (M_{\tilde{N}_1} - |\mu|)/m_Z. \quad (2.13)$$

Second, for fixed M_1, M_2, and $|\mu|$, the magnitude of y_h is a monotonically increasing function of $\sigma/\tan\beta$ in the physical range of $\tan\beta > 1$. This means that when all other Higgs bosons and squarks are decoupled, the spin-independent LSP-nucleon coupling, proportional to y_h^2, is minimized for small $\tan\beta$ and negative μ, maximized for small $\tan\beta$ and positive μ, and intermediate for larger $\tan\beta$. Indeed, in the formal limit of $\tan\beta \to 1$ for negative μ, both y_h and g_Z vanish, corresponding [58] to blind spots[1] in both the spin-independent and spin-dependent direct detection cross sections. However, $\tan\beta$ too close to 1 is problematic because it would require a top-quark Yukawa coupling larger than its MSSM infrared fixed-point value, leading to nonperturbative behavior at high energies unless some other new physics intervenes. For somewhat larger $\tan\beta$ and $\mu < 0$, the suppression of the factor $1 + \sigma s_{2\beta}$ for y_h is significantly more robust than that of the factor $c_{2\beta}$ for g_Z. Another potential issue with small $\tan\beta$ is that even for rather large top-squark masses and significant top-squark mixing, it may be difficult to achieve $M_h = 125.1$ GeV in the MSSM. This can be circumvented, if necessary, by introducing vectorlike quark supermultiplets with large Yukawa couplings [61–66], which can substantially raise the lightest Higgs boson mass without affecting other considerations in this paper.

The spin-dependent LSP-nucleon cross sections in the decoupling limit includes a contribution proportional to the coupling g_Z^2. Equation (2.12) shows that the magnitude of g_Z is also proportional to $M_{\tilde{N}_1} - |\mu|$, but is suppressed by an additional factor of $m_Z/|\mu|$ compared to y_h, so that it has relatively enhanced importance for lighter Higgsinos compared to heavier Higgsinos. It also has a different $\tan\beta$ dependent prefactor, which makes it potentially relatively more important than y_h for direct detection for smaller $\tan\beta$ when μ is negative. This is indeed the case as we will see.

The tree-level chargino mass matrix is given in the gauge-eigenstate basis by

$$M_{\tilde{C}} = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix}, \qquad X = \begin{pmatrix} M_2 & \sqrt{2}s_\beta c_W m_Z \\ \sqrt{2}c_\beta c_W m_Z & \mu \end{pmatrix}, \quad (2.14)$$

leading to masses

$$M_{\tilde{C}_1} = |\mu| - m_Z^2 c_W^2\left(\frac{|\mu| + M_2\sigma s_{2\beta}}{M_2^2-\mu^2}\right) + \cdots, \quad (2.15)$$

$$M_{\tilde{C}_2} = M_2 + m_Z^2 c_W^2\left(\frac{M_2 + \mu s_{2\beta}}{M_2^2-\mu^2}\right) + \cdots. \quad (2.16)$$

It follows that the Higgsino-like fermion mass splittings at tree-level are

$$\begin{aligned}\Delta M_0 &\equiv M_{\tilde{N}_2} - M_{\tilde{N}_1} \\ &= \frac{m_Z^2}{2}\left\{[1+\sigma s_{2\beta}]\left(\frac{c_W^2}{M_2-|\mu|} + \frac{s_W^2}{M_1-|\mu|}\right)\right. \\ &\quad \left. + [1-\sigma s_{2\beta}]\left(\frac{c_W^2}{M_2+|\mu|} + \frac{s_W^2}{M_1+|\mu|}\right)\right\} + \ldots, \end{aligned} \quad (2.17)$$

for the neutralinos, and

$$\begin{aligned}\Delta M_+ &\equiv M_{\tilde{C}_1} - M_{\tilde{N}_1} \\ &= \frac{m_Z^2}{2}\left\{[1+\sigma s_{2\beta}]\left(\frac{c_W^2}{M_2-|\mu|} + \frac{s_W^2}{M_1-|\mu|}\right)\right. \\ &\quad \left. - 2c_W^2\left(\frac{|\mu| + M_2\sigma s_{2\beta}}{M_2^2-\mu^2}\right)\right\} + \ldots, \end{aligned} \quad (2.18)$$

for the chargino-LSP mass difference, where the ellipses represent higher orders in the expansion in m_Z. If one now takes the further limit $M_1, M_2 \gg |\mu|$, then we have

[1]Other neutralino direct detection blind spots have been noted in e.g., Refs. [59,60].

$$\Delta M_0 = m_Z^2\left(\frac{c_W^2}{M_2}+\frac{s_W^2}{M_1}\right)+\ldots, \tag{2.19}$$

$$\Delta M_+ = \frac{m_Z^2}{2}\left([1-\sigma s_{2\beta}]\frac{c_W^2}{M_2}+[1+\sigma s_{2\beta}]\frac{s_W^2}{M_1}\right)+\ldots, \tag{2.20}$$

and then in the further limit of large $\tan\beta$, or when $M_1/M_2 = s_W^2/c_W^2$, one finds $\Delta M_0 = 2\Delta M_+$, the relation that has been used in LHC experimental papers [55,57] to define simplified models of Higgsinos used for quoting search bounds. However, it is important that this relation is not always satisfied even approximately, since the relevant hierarchies used to derive it need not hold, even when the Higgsinos are rather pure.

Furthermore, the preceding discussion involves the tree-level neutralino mass matrix, but radiative corrections can be important, especially when the mass splittings are small and/or when there is a significant hierarchy between the gaugino masses and $|\mu|$. In the extreme case of a pure Higgsino with the gauginos completely decoupled so that the m_Z corrections can be neglected, the Higgsinos would all be degenerate at tree level. However, it was shown in Ref. [20] that the charginos get a positive radiative mass splitting from Standard Model electroweak gauge interactions, so

$$\Delta M_0 = 0, \qquad \Delta M_+ = F(|\mu|/m_Z)355\ \text{MeV}, \tag{2.21}$$

where the loop-integral function

$$F(x) = \frac{x}{\pi}\int_0^1 dt(2-t)\ln[1+t/x^2(1-t)^2], \tag{2.22}$$

monotonically increases from about $F(1.10) = 0.724$ for light Higgsinos with mass 100 GeV to an asymptotic value $F(\infty) = 1$ for heavy Higgsinos. Equation (2.21) is used, as a simplified model, in the presentation of experimental search results for quasistable charged Higgsinos manifesting as disappearing tracks [67,68], but it should again be recognized that it will not be generically realized in actual supersymmetric models unless the gaugino masses are of order 10 TeV or much more, depending on the other parameters. For smaller gaugino masses, the tree-level contributions to the mass splittings discussed above are comparable or much larger than this radiative correction.

Another way of estimating the radiative corrections to the Higgsino mass splittings was put forward in Ref. [27], which integrates out the gauginos to define an effective field theory below the gaugino mass scale set by M_1, M_2. This approach works well as long as $M_1, M_2 \gg |\mu|$, and has the advantage of resumming logarithmic correction to the masses using the renormalization group in the effective field theory. However, in the present paper, I am interested in cases where $|\mu|$ is not so small compared to at least one of the gaugino masses. Therefore, below I choose to use the full one-loop corrections to the neutralino and chargino masses, which only includes the leading logarithms but does not neglect subleading terms in $|\mu|/M_1$ and $|\mu|/M_2$ including the tree-level ones. The analytic form of these corrections can be found in Refs. [69–72] in various schemes, and I use the software implementation in the public code SOFTSUSY v4.1.12 [73], which interfaces to micrOMEGAs. I find that the results of SOFTSUSY are in reasonably good agreement with the analytic results found in [72], which in turn approach the results of Ref. [20] in the extreme limit $|\mu| \ll M_1, M_2$ when all scalars except $M_h = 125.1$ GeV are decoupled.

III. GAUGINO MASS BOUNDS FOR HIGGSINO DARK MATTER WITH DECOUPLED SCALARS

The interaction of the LSP with ordinary matter, like the xenon nuclei used in the LZ experiment, relies on the predominantly Higgsino-like state mixing with gauginos. In the limit that the gaugino mass parameters become large, both the spin-independent and spin-dependent cross sections become small. This implies that the observed direct detection limits give lower bounds on the gaugino masses M_1 and M_2, in order to avoid too much mixing. In most of the parameter space, the spin-independent LSP nucleon cross section $\sigma_{\rm SI}$ (corresponding to proton and neutron components weighted by their numbers in the xenon nucleus) give the strongest bound from LZ 2022 [54], which for $M_{\rm LSP}$ scales approximately with the mass, with

$$\left(\frac{\Omega_{\rm LSP}h^2}{0.12}\right)\sigma_{\rm SI} \lesssim \left(\frac{M_{\rm LSP}}{1\ \text{TeV}}\right)2.8\times 10^{-10}\ \text{pb}. \tag{3.1}$$

To illustrate the impact of this bound, I first consider models in which the wino and bino mass parameters at a renormalization scale $Q = 10$ TeV are taken in the ratio $M_2/M_1 = 1.8$, which is approximately the ratio implied by unification of gaugino masses at the scale of apparent gauge coupling unification above $Q = 10^{16}$ GeV. This implies that the Higgsino-like LSP mixes more strongly with the bino, but the wino contamination is still non-negligible. The masses of all squarks, sleptons, and the gluino are also taken to be 10 TeV. I fix the lightest Higgs scalar mass at $M_h = 125.1$ GeV, which is important because of its role in mediating the spin-independent LSP-nuclear cross section. The other Higgs bosons are taken to be in the decoupling limit with masses also at 10 TeV. The physical neutralino and chargino masses and couplings are evaluated using the public code SOFTSUSY v4.1.12 [73]. It is useful to show constraints by plotting the double-scaled cross section

$$\left(\frac{1\ \text{TeV}}{M_{\rm LSP}}\right)\left(\frac{\Omega_{\rm LSP}h^2}{0.12}\right)\sigma_{\rm SI}, \tag{3.2}$$

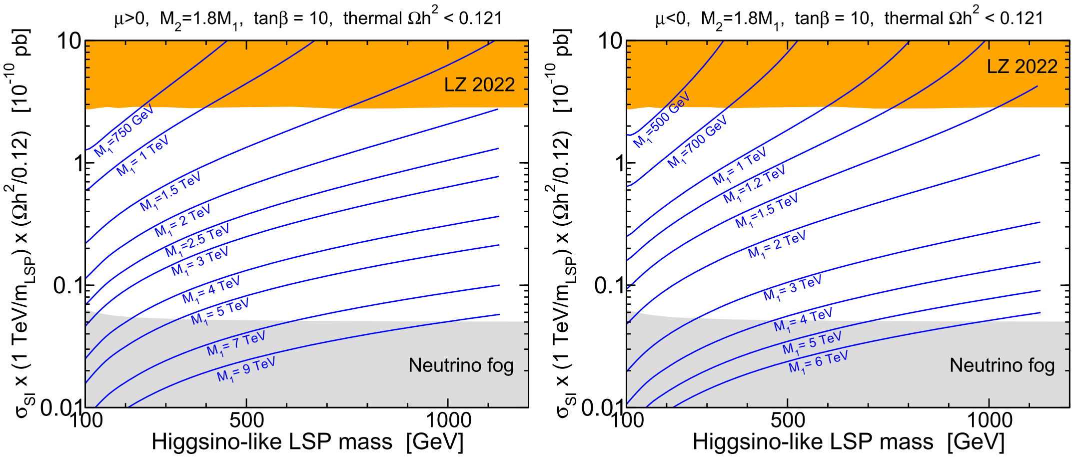

FIG. 2. The spin-independent LSP-nucleon cross section, scaled by factors of (1 TeV$/M_{\mathrm{LSP}}$) and $\Omega h^2/0.12$, as a function of the Higgsino-like LSP mass $M_{\tilde{N}_1}$ (related and comparable to $|\mu|$), for various values of the Lagrangian parameter M_1, as labeled. The wino mass parameter is taken to be $M_2 = 1.8 M_1$, as motivated by models with gaugino mass unification, and $\tan\beta = 10$. The masses of the squarks, sleptons, and gluino, and the heavy Higgs bosons $A, H, H^\pm$ are all set to 10 TeV, and $M_h = 125.1$ GeV is imposed. The left panel shows results for $\mu > 0$, and the right panel for $\mu < 0$. The extent of the curves in the horizontal direction is set by the requirement $\Omega h^2 < 0.121$. The (orange) shaded band at the top is the limit set by LZ 2022 [54]. The (gray) shaded band at the bottom is the expected neutrino fog level as defined in [74].

as the vertical axis, so that σ_{SI} limits (past, present, and future) are very nearly horizontal lines independent of the mass.

The results are shown in Fig. 2 as a function of the LSP mass $M_{\tilde{N}_1}$, for curves corresponding to various fixed values of M_1, with $\tan\beta = 10$, and positive μ in the left panel and negative μ in the right panel. The curves terminate slightly above $M_{\tilde{N}_1} = 1.1$ TeV, due to the requirement $\Omega_{\mathrm{LSP}} h^2 < 0.121$. The shaded (orange) region at top is the LZ 2022 excluded region. These results show that the Higgsino purity constraint requires M_1 to be greater than about 2 TeV for positive μ, and greater than about 1.6 TeV for negative μ, in the case that the Higgsino is all of the dark matter. For lighter LSPs, M_1 can be considerably smaller, as shown, but there are still nontrivial lower bounds on M_1 despite the suppression from ξ. These bounds are reduced to well below 1 TeV if the Higgsino mass is less than a few hundred GeV. It is a general feature that the lower bounds on M_1 are weaker for negative μ, which can be understood from the expression in Eq. (2.11) for the LSP-Higgs coupling.

Also shown in Fig. 2 as the lower shaded (gray) region is the 'neutrino-fog' level at which LSP discovery becomes problematic due to the background from scattering of astrophysical neutrinos [75]. This is not a completely solid floor, because it is subject to neutrino flux uncertainties and might be overcome to some limited extent by improved signal discrimination and statistics. Here, I use the definition for the neutrino-fog level given in Ref. [74]. It can be seen that the unshaded region between the present LZ bound and the neutrino fog corresponds to a large range for M_1 that will be newly probed in future direct detection experiments, up to $M_1 = 9$ TeV for positive μ and $M_1 = 6$ TeV for negative μ. This is far beyond what can be probed at the LHC, even with an energy upgrade. This reach is of course diminished for smaller LSP masses due to the ξ suppression, but is seen to be still substantial.

The situation if the Higgsinos instead mix mostly with winos is shown similarly in Fig. 3. To be specific, I choose $M_1 = 3.2 M_2$ (again at a renormalization scale of 10 TeV), inspired by the gaugino mass relations in models of anomaly mediated supersymmetry breaking (AMSB) [76,77]. As one might expect from the fact that $g > g'$, the lower bounds on the wino mass are stronger than for mixing predominantly with the bino, reaching about 2.4 TeV for $\mu > 0$ and 1.9 TeV for $\mu < 0$, in the case of Higgsinos near 1.1 TeV that provide $\Omega h^2 = 0.12$. Conversely, the future direct detection reach in M_2 above the neutrino fog is greater, exceeding 10 TeV for $\mu > 0$ and 7 TeV for $\mu < 0$.

The results in Figs. 2 and 3 assumed $\tan\beta = 10$ for simplicity, but there is a rather strong dependence on $\tan\beta$. To show how this goes, Fig. 4 gives the minimum allowed binolike neutralino mass $M_{\tilde{N}_3}$ (which is closely correlated with the bino mass parameter M_1), as a function of the Higgsino-like LSP mass $M_{\tilde{N}_1}$, with separate contours for various values of $\tan\beta$ and the sign of μ. Here, I consider two cases. The left panel shows the results assuming the gaugino-mass unification condition $M_2 = 1.8 M_1$, while the right panel shows the results assuming that the wino is thoroughly decoupled at $M_2 = 30$ TeV. In both cases, the squark, slepton, gluino, and other Higgs masses are taken to be nearly decoupled at 10 TeV, while the lightest Higgs

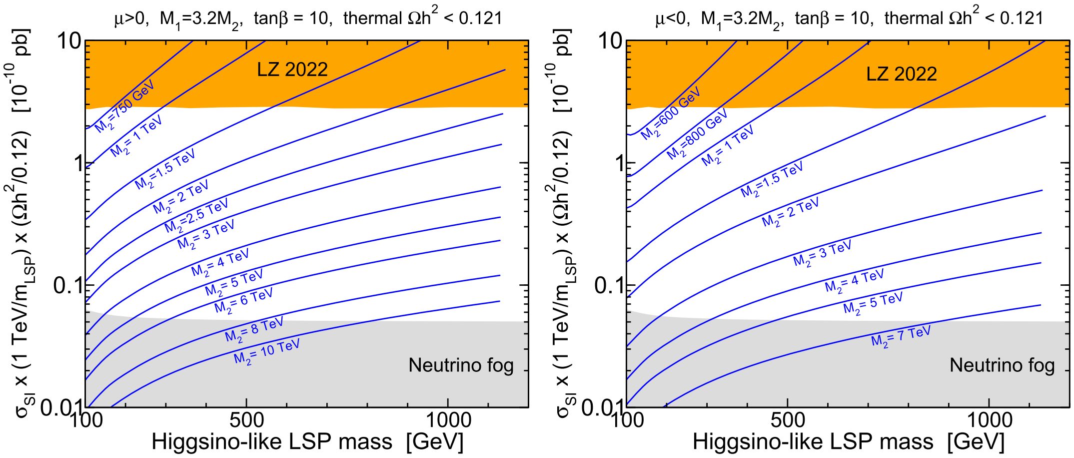

FIG. 3. The spin-independent LSP-nucleon cross section, scaled by factors of (1 TeV$/M_{\rm LSP}$) and $\Omega h^2/0.12$, as a function of the Higgsino-like LSP mass $M_{\tilde{N}_1}$ (related and comparable to $|\mu|$), for various values of the Lagrangian parameter M_2, as labeled. The bino mass parameter is taken to be $M_1 = 3.2 M_2$, as motivated by AMSB models, and $\tan\beta = 10$. The masses of the squarks, sleptons, and gluino, and the heavy Higgs bosons $A, H, H^{\pm}$ are all set to 10 TeV, and $M_h = 125.1$ GeV is imposed. The left panel shows results for $\mu > 0$, and the right panel for $\mu < 0$. The extent of the curves in the horizontal direction is set by the requirement $\Omega h^2 < 0.121$. The (orange) shaded band at the top is the limit set by LZ 2022 [54]. The (gray) shaded band at the bottom is the expected neutrino fog level as defined in [74].

mass is always fixed at 125.1 GeV. For most parameters, the lower bound on M_2 is set by the LZ limit on the spin-independent cross section. However, as we saw in Eq. (2.11), the LSP-Higgs coupling, and therefore $\sigma_{\rm SI}$, are relatively suppressed for negative μ and small $\tan\beta$. Therefore, in some cases with $\tan\beta < 5$ and $\mu < 0$ it turns out that the strongest bound for small Higgsino masses is obtained instead from the LZ limit on the spin-dependent LSP-neutron cross section [54], which to a good approximation is

$$\left(\frac{\Omega_{\rm LSP} h^2}{0.12}\right)\sigma^n_{\rm SD} \lesssim \left(\frac{M_{\rm LSP}}{1\ {\rm TeV}}\right) 4.9 \times 10^{-5}\ {\rm pb} \qquad (3.3)$$

in the relevant mass range above 100 GeV. The cases where the spin-dependent neutron cross-section set the bound are

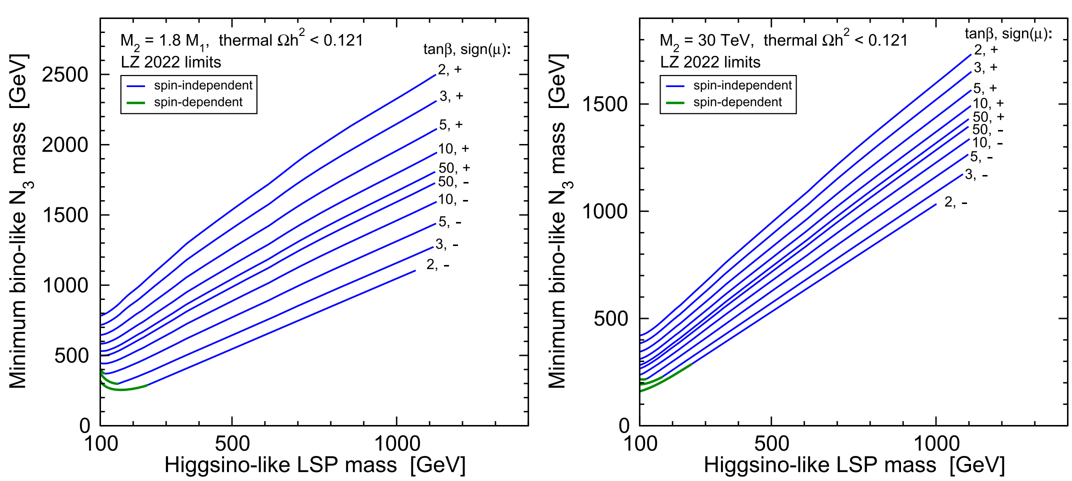

FIG. 4. The minimum binolike neutralino mass $M_{\tilde{N}_3}$ (related to M_1) consistent with the LZ 2022 direct detection limits [54], as a function of the Higgsino-like LSP mass $M_{\tilde{N}_1}$ (related to $|\mu|$). The LSP density is assumed to be the thermal freeze-out prediction for Ωh^2, required to be less than 0.121; this sets the maximum values of $M_{\tilde{N}_1}$. The different lines are the results for various combinations of $\tan\beta$ and sign(μ), as labeled. The lower bound on the bino mass is set by the spin-independent LSP-xenon nucleus cross section, except for the thicker (green) portion of the curves at small $\tan\beta$ and negative μ and small LSP masses, where the spin-dependent LSP-neutron cross section sets the bound. The left panel shows the results assuming $M_2 = 1.8 M_1$ as in models with gaugino mass unification, and the right panel instead takes the winos decoupled, with $M_2 = 30$ TeV. The lightest Higgs boson mass is fixed to $M_h = 125.1$ GeV, and all other superpartner and Higgs boson masses are set to 10 TeV. Note the different vertical scales.

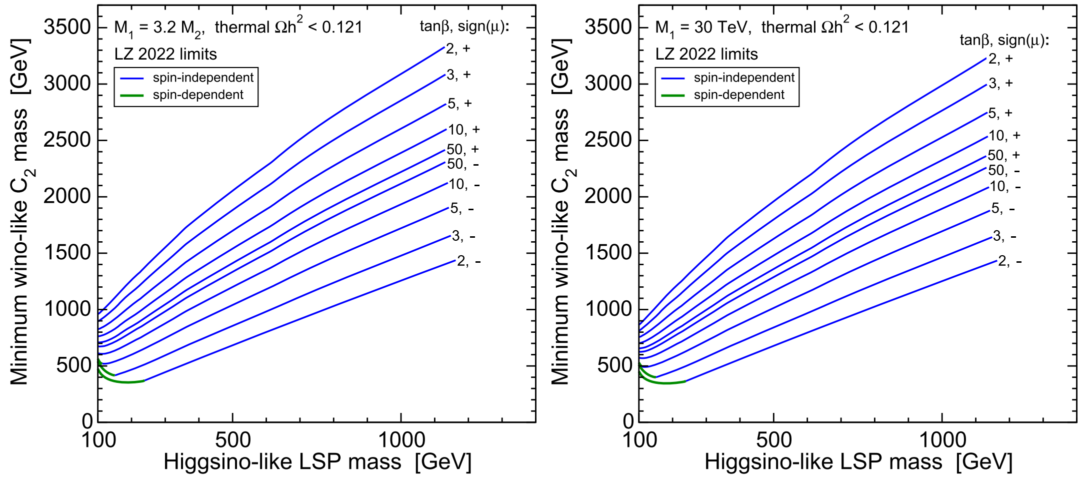

FIG. 5. The minimum winolike chargino mass $M_{\tilde{C}_2}$ (related to M_2) consistent with LZ 2022 direct detection limits [54], as a function of the Higgsino-like LSP mass $M_{\tilde{N}_1}$ (related to $|\mu|$). The LSP density is assumed to be the thermal freeze-out prediction for Ωh^2, required to be less than 0.121. The different lines are the results for various combinations of $\tan\beta$ and $\mathrm{sign}(\mu)$, as labeled. The lower bound on the wino mass is set by the spin-independent LSP-xenon nucleus cross section, except for the thicker (green) portion of the curves at small $\tan\beta$ and negative μ and small LSP masses where the spin-dependent LSP-neutron cross section sets the bound. The left panel shows the results assuming $M_1 = 3.2M_2$ as in AMSB models, and the right panel instead takes the bino decoupled, with $M_1 = 30$ TeV. The lightest Higgs boson mass is fixed to $M_h = 125.1$ GeV, and all other superpartner and Higgs boson masses are set to 10 TeV.

shown in Fig. 4 as the heavier (green) parts of the curves. Note that the small contamination of the heavier wino mixing in the LSP in the left panel results in a stronger lower bound on M_1 compared to the case in the right panel in which the wino is completely decoupled. In general, the lower bounds on M_1 are weakest when $\tan\beta$ is small and μ is negative, and strongest bounds when $\tan\beta$ is small and μ is positive, reflecting the behavior found for y_h in Eq. (2.11). For a thermal dark matter Higgsino-like LSP with mass near 1.1 TeV so that $\xi = 1$, the bino mass is only required to be slightly larger than $|\mu|$ when $\tan\beta = 2$ and $\mu < 0$, but must be over 1.7 TeV for $\tan\beta = 2$ and $\mu > 0$, and at least 2.5 TeV if one assumes gaugino mass unification.

For the case that the Higgsino-like LSP mixes predominantly with the wino, the lower bounds on $M_{\tilde{C}_2}$ (closely related to M_2) are given in Fig. 5, again for various combinations of $\tan\beta$ and $\mathrm{sign}(\mu)$. The left panel shows the AMSB-inspired case of $M_1 = 3.2M_2$, while the right panel shows the case where the bino is essentially completely decoupled, with M_1 fixed at 30 TeV. As can be seen from the figure, the lower bound on M_2 is only slightly weakened by completely decoupling the bino, compared to the AMSB case in the left panel. These bounds are stronger than for predominantly bino mixing, especially for positive μ. One can conclude that for Higgsino-like thermal dark matter with $\xi = 1$ and mixing predominantly with the wino, M_2 can be as small as less than 1.5 TeV if $\tan\beta = 2$ and μ is negative, but the lower bounds exceed 3 TeV when μ is positive. The more relevant scenario for a possible future discovery at the LHC obviously occurs when $|\mu|$ is less than a few hundred GeV, with the most optimistic cases arising for negative μ.

IV. BOUNDS ON HIGGSINO MASS SPLITTINGS

The purity constraints on Higgsino-like LSPs as part of the dark matter are also reflected in upper bounds on the mass splittings. This is particularly important for LHC and future hadron collider searches, which typically rely on either having mass splittings large enough for the decay products of the heavier Higgsinos to pass cuts, or small enough so that quasistable Higgsinos can leave disappearing tracks or displaced vertices. Between those two cases is a regime that is especially difficult to probe at hadron colliders [24], and for which the current exclusion reach is very modest. In fact, the present official exclusion reach from the LHC experimental collaborations is minimal for the LSP mass above 100 GeV when ΔM_0 is between about 1 and 3 GeV, but it has been suggested [78] that this gap might be closed with existing monojet searches [79,80]. For ΔM_0 less than about 40 GeV, the expected exclusion reach from soft leptons is presently limited to Higgsino masses below about 200 GeV, and the observed exclusion is less. As we will now see, in the case of decoupled MSSM scalars (other than the 125 GeV Higgs boson), the mass splittings for Higgsinos are required by LZ 2022 to be not too large, and are in a difficult but interesting region for LHC searches, if the dark matter abundance is set by thermal freeze-out.

Figure 6 shows the Higgsino-like chargino-LSP mass splitting ΔM_+, as a function of the LSP mass, for models in which the neutral Higgsinos mix with a heavier bino. Here, it is assumed that there is approximate gaugino mass unification at the GUT scale, so that $M_2 = 1.8M_1$ at a renormalization scale $Q = 10$ TeV, so that the wino

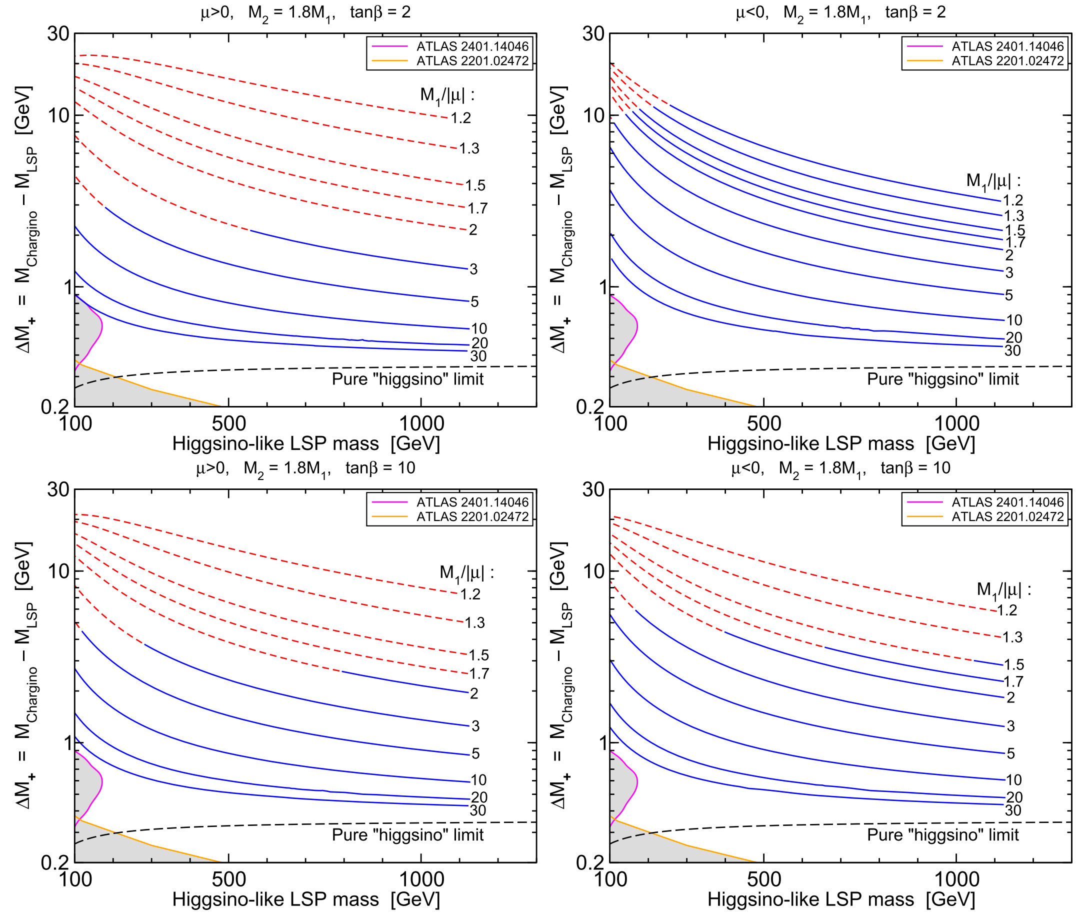

FIG. 6. The mass splitting $\Delta M_+ \equiv M_{\tilde{C}_1} - M_{\tilde{N}_1}$ for mostly Higgsino-like charginos and neutralinos, as a function of the LSP mass $M_{\tilde{N}_1}$, for various ratios $M_1/|\mu| = 1.2, 1.3, 1.5, 1.7, 2, 3, 5, 10, 20$, and 30, as the labeled curves. In each case, the Higgsino mixes more strongly with the bino than the wino, with $M_2 = 1.8M_1$ as motivated by models with gaugino mass unification. The dark matter density Ωh^2 is assumed to be the thermal freeze-out result, and is required to be < 0.121; this sets the horizontal range of the curves. The lightest Higgs mass is fixed at 125.1 GeV. The squark, slepton, gluino, and heavy Higgs boson $A, H, H^\pm$ masses are set to 10 TeV. The solid (blue) portions of the curves satisfy the LZ 2022 limits [54] on both spin-independent and spin-dependent cross sections, while the dashed (red) portions do not. The four panels show results for $\tan\beta = 2$, 10 and $\mathrm{sign}(\mu) = \pm$. In each panel, the shaded (gray) regions at the lower left are constraints from ATLAS searches for low-momentum mildly displaced tracks [81] and disappearing tracks [68]. There is a very similar result to the latter from CMS [67]. Also shown is the mass-splitting prediction [20] for pure Higgsinos, in the idealized case that the gauginos are taken to be absent or completely decoupled.

contamination is smaller but non-negligible. The left panels have positive μ, and the right panels have negative μ, and the upper panels have $\tan\beta = 2$ while the lower panels have $\tan\beta = 10$. As before, the squarks, sleptons, gluino, and the heavy Higgs scalars $A, H, H^\pm$ have masses set to 10 TeV. The different curves show results for constant ratios $M_1/|\mu|$ ranging from 1.2 to 30, as labeled. The dashed parts of the curves have $\sigma_{\rm SI}$ in excess of the LZ 2022 bound, taking into account the fact that the dark matter density is lower than the value implied by the Planck experiment observations ($\xi < 1$). This means that only the solid parts of the curves are nominally allowed, which accordingly limits the range of ΔM_+.

Also shown in Fig. 6 are the current exclusion region from disappearing tracks from ATLAS and CMS, as well as a recent exclusion from mildly displaced tracks, obtained by ATLAS [81] following the suggestion of [33]. Although these searches set nontrivial limits on pure Higgsino simplified models, the disappearing track searches typically do not affect the parameter space of actual MSSM Higgsinos unless the hierarchy $M_1/|\mu|$ is considerably larger than the highest choice of 30 shown in the plot. This holds more generally except for a small region in parameter space where one can tune the tree-level mass splitting ΔM_+ in Eq. (2.18) to very small values. The ATLAS mildly displaced track search probes more moderate gaugino/Higgsino mass hierarchies, but for the choices shown this search only grazes the boundary of the region obtained with $M_1/|\mu| = 30$ for $\tan\beta = 2$ and positive μ.

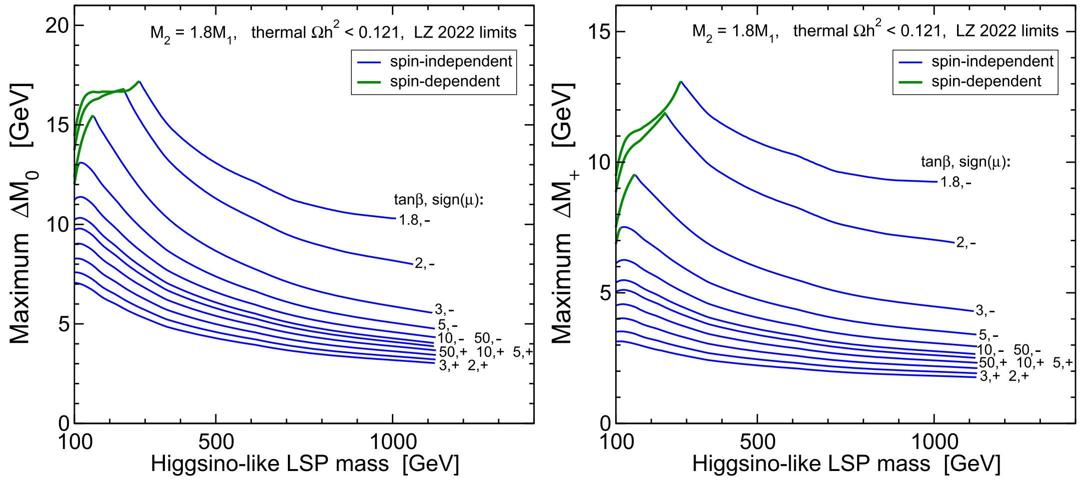

FIG. 7. The maximum Higgsino-like mass splittings $\Delta M_0 \equiv M_{\tilde{N}_2} - M_{\tilde{N}_1}$ (left panel) and $\Delta M_+ \equiv M_{\tilde{C}_1} - M_{\tilde{N}_1}$ (right panel), as functions of the Higgsino-like LSP mass $M_{\tilde{N}_1}$, for models that satisfy the direct detection limits from LZ 2022 [54], for various combinations of $\tan\beta$ and sign(μ) as labeled. The gaugino masses are taken to satisfy $M_2 = 1.8 M_1$ at $Q = 10$ TeV, as motivated by models with gaugino mass unification, so that the small mixing of the Higgsino is mostly with the bino, but with a non-negligible wino contamination. The lightest Higgs mass is fixed at 125.1 GeV. The squark, slepton, gluino, and heavy Higgs boson $A, H, H^\pm$ masses are set to 10 TeV. The dark matter density is assumed to be the thermal freeze-out result, and is required to satisfy $\Omega h^2 < 0.121$; this sets the horizontal extent of the curves. The upper bounds on the mass splittings are set by the spin-independent LSP-xenon nucleus cross section, except for the thicker (green) portions of the curves at small $\tan\beta$ and negative μ and small LSP masses, where it is the spin-dependent LSP-neutron cross section that sets the bounds.

For larger mass splittings, the region allowed by LZ 2022 is significantly constrained. This is shown in more detail in Fig. 7, which gives the maximum mass splittings ΔM_0 (left panel) and ΔM_+ (right panel), as a function of the LSP mass. Different curves show the results for various combinations of $\tan\beta$ and sign(μ). As remarked several times above, the LZ 2022 $\sigma_{\rm SI}$ constraints are considerably weakened for negative μ and small $\tan\beta$. In this case, for small enough LSP mass, it is actually the spin-dependent LSP-neutron cross section $\sigma^n_{\rm SD}$ that sets the bound. For $\tan\beta = 1.8$, the nominal bounds are about $\Delta M_0 < 17$ GeV and $\Delta M_+ < 13$ GeV, although in the present experimentally critical regime of LSP masses less than 300 GeV, the bound on ΔM_+ is stronger. One can also read off the plot the maximum mass splittings for Higgsino-like particles with $M_{\tilde{N}_1}$ near 1.1 TeV, corresponding to $\Omega h^2 = 0.12$. The bounds shown reflect the 90% confidence level LZ 2022 limits, but it should be noted that there are significant uncertainties from nuclear matrix elements and from the local dark matter profile, so these bounds might be relaxed somewhat.

ATLAS and CMS have presented results for searches sensitive to Higgsinos with moderate mass splittings, using signal regions involving two or three soft leptons, which could arise from the decays $\tilde{N}_2 \to Z^{(*)} \tilde{N}_1$ and $\tilde{C}_1 \to W^{(*)} \tilde{N}_1$. For both experiments, the observed exclusions are weaker than expected, indicating a mild excess with respect to the estimated backgrounds. It has also recently been pointed out [78] that monojet searches [79,80] may also have an excess in a kinematically consistent region. As a matter of opinion, I think that it may be too early to make more detailed fits of supersymmetric model parameters to such a mild excess. Doing so would be made more difficult because the published experimental search results make kinematic assumptions that need not hold in real supersymmetric models. In particular, Refs. [55,57] show search limits for Higgsinos based on the assumption $\Delta M_+ = 0.5 \Delta M_0$, while Ref. [56] shows results based on $\Delta M_+ = \Delta M_0$. As noted above, these are not expected to hold accurately for light Higgsinos with significant mass splittings. The efficiencies of searches in the soft lepton regime might be quite sensitive to those kinematic assumptions in ways that may make it difficult to extrapolate reliably. However, it seems worthwhile to make some comments regarding the possibility of accommodating the possible excess with the light Higgsino models of the type considered in this paper.

To this end, in Fig. 8 I show the ATLAS and CMS expected and observed limits in the plane of ΔM_0 and $M_{\tilde{N}_2}$. The region of excesses has ΔM_0 larger than about 10 GeV. As we have seen in Figs. 6 and 7, accommodating sizeable mass splittings consistently with LZ 2022 limits, in MSSM models with sfermions, the gluino, and heavy Higgs bosons decoupled, requires negative μ and small $\tan\beta$. Accordingly, I display some selected model lines with negative μ and $\tan\beta = 2$ (left panel) and $\tan\beta = 1.5$ (right panel), focusing on the region with

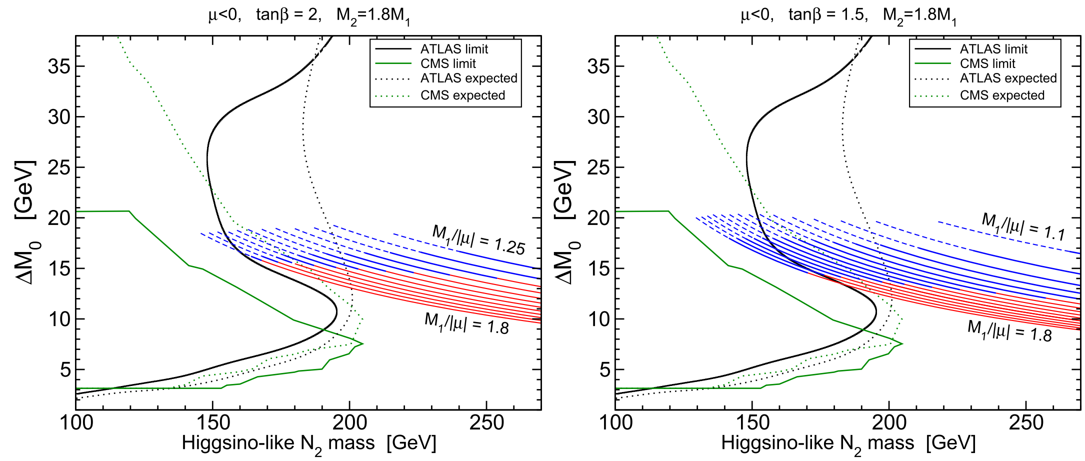

FIG. 8. The Higgsino-like mass splitting $\Delta M_0 = M_{\tilde{N}_2} - M_{\tilde{N}_1}$, as a function of $M_{\tilde{N}_2}$, for models with $\mu < 0$ and $\tan\beta = 2$ (left panel) and $\tan\beta = 1.5$ (right panel). Also shown are the ATLAS [55] and CMS [57] Higgsino soft lepton search limits (solid curves) and expected limits (dotted curves) assuming $M_{\tilde{C}_1} = 0.5(M_{\tilde{N}_1} + M_{\tilde{N}_2})$. In both panels, $M_2 = 1.8M_1$ at a renormalization scale $Q = 10$ TeV, as motivated by models with gaugino mass unification at high scales. The model lines take the ratio $M_1/|\mu|$ in increments of 0.05, from 1.25 to 1.8 (left panel) and 1.1 to 1.8 (right panel). The solid portions of these lines are allowed by the nominal LZ 2022 [54] direct detection searches, while the dashed portions relax the spin-dependent LSP-neutron cross section limits by a factor of 2, in recognition of the significant uncertainties in neutron matrix elements and dark matter profiles. The lightest Higgs mass is fixed to be 125.1 GeV, and the squark, slepton, gluino, and $H, A, H^{\pm}$ Higgs boson masses are set to 10 TeV. The lighter (red) parts of the model lines correspond to the nominal ATLAS exclusion region [82] for pair-produced winos decaying to Higgsinos, although the decay branching ratios and kinematics differ.

$M_{\tilde{N}_2}$ less than 270 GeV, with curves along constant values of $M_1/|\mu|$ as labeled. The solid portions of these lines obey the nominal LZ 2022 constraints, and the dashed portions relax the spin-dependent LSP-neutron cross section by a factor of 2, in recognition of the significant systematic uncertainties in nuclear matrix elements and dark matter profiles. In these plots I assumed $M_2 = 1.8M_1$, as motivated by gaugino mass unification at high scales.

It is apparent from the plots in Fig. 8 that these models may accommodate the LHC excess region within the LZ 2022 bounds, but only for ΔM_0 in the lower part of the excess region, with ΔM_0 at most about 20 GeV. Some caution is in order here, because the published experimental limits shown here assumed $\Delta M_+/\Delta M_0 = 0.5$, while I find that the model predictions for $M_2 = 1.8M_1$ instead, giving this ratio in the range from about 0.65 to 0.75. (More general ratios are possible for different assumptions about M_2/M_1.) The production cross section for $\tilde{C}_1\tilde{N}_2$ will therefore be slightly lower in the actual models than in the experimental exclusion assumptions, while the chargino decay products will have higher energy. Therefore, the true exclusion region that would follow from a dedicated analysis of the experimental data (certainly beyond the scope of this paper) might well differ from that shown. The production cross sections for Higgsinos are very roughly in the right range (a substantial fraction of a pb), but it seems premature to attempt a more definitive statement about fitting rates in light of the quite tentative nature of the excesses.

An interesting feature of these models is that the wino-like states (which are $\tilde{N}_4$ and $\tilde{C}_2$, assuming the mass ordering $|\mu| < M_1 < M_2$ as here) may also be within the kinematic reach of the LHC, and therefore can also be a promising target for searches. The winos decay have only suppressed couplings to the lighter bino, and so decay mostly to the Higgsino-like states, with

$$\tilde{N}_4 \to W^{\pm}\tilde{C}_1^{\pm}, \qquad \mathrm{BR} = 0.51 \tag{4.1}$$

$$\tilde{N}_4 \to Z\tilde{N}_{1,2}, \qquad \mathrm{BR} = 0.27 \tag{4.2}$$

$$\tilde{N}_4 \to h\tilde{N}_{1,2}, \qquad \mathrm{BR} = 0.19 \tag{4.3}$$

and

$$\tilde{C}_2 \to h\tilde{C}_1, \qquad \mathrm{BR} = 0.48 \tag{4.4}$$

$$\tilde{C}_2 \to W\tilde{N}_{1,2}, \qquad \mathrm{BR} = 0.33 \tag{4.5}$$

$$\tilde{C}_2 \to Z\tilde{C}_1, \qquad \mathrm{BR} = 0.17 \tag{4.6}$$

where the numerical values shown are for the case $\tan\beta = 2$, with $\mu = -180$ GeV, $M_1 = 270$ GeV, and $M_2 = 480$ GeV at the renormalization scale $Q = 10$ TeV, but

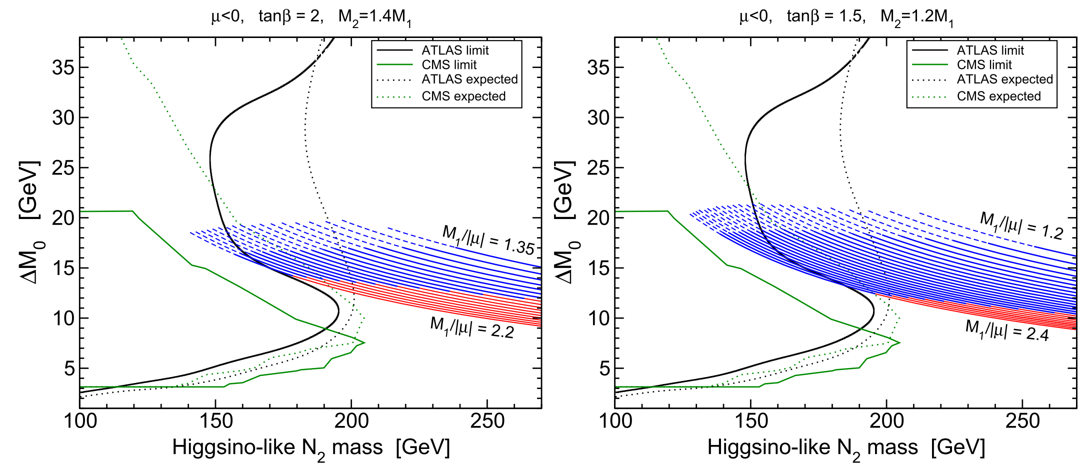

FIG. 9. The Higgsino-like mass splitting $\Delta M_0 = M_{\tilde{N}_2} - M_{\tilde{N}_1}$, as a function of $M_{\tilde{N}_2}$, for models with $\mu < 0$ and small $\tan\beta$. Also shown are the ATLAS [55] and CMS [57] Higgsino soft lepton search limits (solid curves) and expected limits (dotted curves) assuming $M_{\tilde{C}_1} = 0.5(M_{\tilde{N}_1} + M_{\tilde{N}_2})$. The model lines in the left panel have $\tan\beta = 2$ and $M_2 = 1.4M_1$ with $M_1/|\mu| = 1.35$ to 2.2 in increments of 0.05, while the right panel has $\tan\beta = 1.5$ and $M_2 = 1.2M_1$ with $M_1/|\mu| = 1.2$ to 2.4 in increments of 0.05. The solid portions of the model lines are allowed by the nominal LZ 2022 [54] direct detection searches, while the dashed portions relax the spin-dependent LSP-neutron cross section limits by a factor of 2, in recognition of the significant uncertainties in neutron matrix elements and dark matter profiles. The lightest Higgs mass is fixed to be 125.1 GeV, and the squark, slepton, gluino, and $H, A, H^{\pm}$ Higgs boson masses are set to 10 TeV. The lighter (red) parts of the model lines correspond to the nominal ATLAS exclusion region [82] for pair-produced winos decaying to Higgsinos, although the decay branching ratios and kinematics differ.

significant variations occur for other parameters. LHC search bounds for pair-produced winolike states decaying to Higgsino-like states can be found in Ref. [82], but neglecting the effects of bino mixing and using $\tan\beta = 10$ and $\mu > 0$. Although this is not directly comparable because of the different branching ratios and kinematics, and is an indirect constraint since it involves the winos rather than the Higgsinos whose masses are plotted in Fig. 8, I have used a lighter red line to indicate the portions of the model lines that are nominally in the exclusion region of Ref. [82]. (It is claimed in Ref. [82] that the limits are not overly sensitive to variations in $\tan\beta$ and sign(μ), despite significant variations in the wino branching ratios.) Bounds on winos decaying to Higgsinos are more easily evaded when M_2 is not too large compared to $|\mu|$; this gives a larger mass splitting among the Higgsinos, but crucially a more compressed wino-Higgsino mass splitting. Accommodation of the soft lepton excess is therefore found to be easier for smaller $\tan\beta$ and smaller gaugino mass ratio M_2/M_1. This is illustrated in Fig. 9, in which I show selected model lines for $\tan\beta = 2$ with $M_2/M_1 = 1.4$, and for $\tan\beta = 1.5$ with $M_2/M_1 = 1.2$. Even smaller ratios M_2/M_1 may further enlarge the relevant parameter space. Avoiding possible constraints from wino pair production can also be done by simply choosing M_2 larger than 1 TeV, but I find that although this may still accommodate the soft lepton excess, it is more difficult because it decreases the mass splittings among the Higgsinos. Therefore, continuing searches for winos decaying to Higgsinos should be of particular interest. This should include searches for same-sign-W pairs without a large amount of hadronic activity or b-tags, coming from $pp \to \tilde{N}_4\tilde{C}_2$ followed by $\tilde{C}_2 \to W\tilde{N}_{1,2}$ and $\tilde{N}_4 \to W\tilde{C}_1$, as suggested in Ref. [83].

It should also be noted that it is not mandatory to impose the LZ 2022 dark matter constraints at all. For example, a light Higgsino that is apparently the LSP could actually decay on a length scale far larger than the physical size of the collider detectors, for example to a gravitino/goldstino, or to a lighter axino, or to Standard Model states via small R-parity violating interactions. In that case, with no dark matter constraints to implement, it is much easier to accommodate the mass splittings that correspond to the soft lepton excess region. This would correspond, for example, to the dashed portions of the lines in Fig. 6, with no obvious preference for particular values of $\tan\beta$ or sign(μ). I know of no reason to discount this possibility.

At the other extreme, one could consider the possibility that all of the dark matter is the Higgsino-like LSP with $\Omega_{\rm LSP}h^2 = 0.12$. For masses much less than 1.1 TeV, this would require some nonthermal source, such as out-of-equilibrium decays of some heavier particle(s) after freeze-out but before nucleosynthesis [84,85]. This is an attractive possibility on general grounds, but with $\xi = 1$, and therefore no density suppression of the spin-independent or spin-dependent LSP nucleon cross sections, the LZ 2022 direct detection constraints on Higgsino purity become much more severe, and it seems very unlikely to be able to have Higgsino mass splittings large enough to accommodate the LHC soft lepton excess.

The discussion of the soft lepton excess and the potentially overlapping monojet excess in Ref. [78] takes the option of not imposing requirements based on dark matter. A very recent paper [86] imposes dark matter constraints in a similar way to that done here, but with somewhat different assumptions about parameters, and so comes to a different conclusion regarding the possibility of accommodating it with light Higgsinos. In that paper, μ and M_2 are assumed to have the same sign, and the consistency with the $\sigma_{\rm SI}$ limit from LZ 2022 relies on an amplitude cancellation [87] between neutral Higgs h and H contributions, which, as pointed out in those papers, entails other debilitating constraints from $H/A \to \tau^+\tau^-$ and the observed Standard Model-like nature of h production and decay. In contrast, in this paper I have assumed that the heavy Higgs bosons $H, A, H^\pm$ are all safely and thoroughly decoupled,[2] and the required suppression of $\sigma_{\rm SI}$ comes about from having low $\tan\beta$ and negative μ, which can be seen as due to the $1 + \sigma s_{2\beta}$ factor in y_h in Eq. (2.11). In the region of parameter space critical to the soft lepton excess, the limiting factor on the mass splittings therefore usually arises from the less constrained, but less suppressed, $\sigma^n_{\rm SD}$.

V. OUTLOOK

In this paper, I examined the implications of dark matter direct detection bounds from LZ 2022 on the purity of light Higgsinos, assuming that the LSP is stable and makes up at least a fraction of the dark matter, with a density set by thermal freeze-out. Motivated by the good agreement of the Standard Model with flavor- and CP-violating observables, I concentrated on the case that the scalars of the MSSM are heavy enough to be effectively decoupled. The resulting purity constraints give lower bounds on the gaugino masses, while allowing for a significant reach in future direct detection experiments before the neutrino fog is reached. Depending on the parameters, this reach corresponds to wino and bino masses well above 10 TeV, with the strongest present bounds and greatest future reach occurring for small $\tan\beta$ and positive μ, and the weakest present bounds and future reach also occurring for small $\tan\beta$ but negative μ. I used default settings in micrOMEGAs 6.0 for nuclear matrix elements, and it should be recognized that there is a significant uncertainty associated with these and with the local dark matter profile.

The same purity constraints give rise to upper bounds on the mass splittings among the Higgsinos. The remaining parameter spaces are a particularly difficult challenge for the LHC. In particular, I considered the compatibility of scalar-decoupled light-Higgsino models with the excess that currently exists in LHC soft lepton searches for charginos and neutralinos. In the case that the LSP is stable with a thermal relic abundance, this points to a region of parameter space with negative μ and small $\tan\beta$ (of order 3 or less). If, instead, the LSP is unstable or has a relic abundance smaller than predicted by thermal freeze-out, then accommodation of the soft lepton excess is much easier due to the lack of a dark matter constraint, and may not prefer any particular $\tan\beta$ range or sign(μ). Of course, there can also be other completely different scenarios to explain the excess, as in [78,86]. In any case, more data will settle the issue.

Whether or not it makes up a portion of the dark matter, collider searches for light Higgsinos should be an important component of the future LHC experimental program, especially given the meager constraints that exist at present, and subjective but interesting theoretical motivations based on naturalness (see e.g., Refs. [25,29,32] and references therein). Simplified models do not capture the physics variety of these models, or supersymmetric theories more generally. Detection efficiencies can be particularly sensitive to small and moderate mass splittings of realistic models of neutralinos and charginos. One possible remedy for this problem is to simply increase the variety of simplified models for which the experimental collaborations present results, so that any given realistic model is closer to some simplified model. An even more ambitious approach might be to change the paradigm by which experimental search results are presented, so that a publicly available software tool, validated and provided directly by the collaborations based on their knowledge of experimental realities and analysis methods, could provide (or decline to provide, if parameters are not in appropriate ranges) p-values for any input parameter file. If feasible, the case of charginos and neutralinos with decoupled scalars might be an ideal testing ground for such an approach to dissemination of search results.

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[2]Of course, relaxing this assumption could further enlarge the parameter space consistent with the LZ 2022 limits and relevant to the soft lepton excesses.

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