Higgsino dark matter in partly supersymmetric models

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Models where supersymmetry (SUSY) is manifest only in a sector of the low-energy spectrum have been recently proposed as an alternative to the MSSM. In these models the electroweak scale is explained by a fine-tuning between different Higgs mass contributions (*split-SUSY models*), or by the localization of the Higgs sector in a point of an extra dimension where all the mass parameters are suppressed by the metric (*partly-SUSY models*). Therefore, the presence of a good dark matter candidate becomes the main motivation for (partial) low-energy SUSY. We study this issue in minimal frameworks where the higgsinos are the only light supersymmetric particles. Whereas in split-SUSY models the higgsino should have a mass around 1 TeV, we show that in partly-SUSY models the lightest higgsino could also be found below M_W.

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I. INTRODUCTION

The stability of the electroweak (EW) scale at the loop level has been the main motivation for supersymmetry (SUSY) during the past 25 years [1]. SUSY *doubles* the spectrum of the standard model (SM) and makes the EW scale *natural*, consistent with the dynamics and not the result of an accidental cancellation between higher scales.

Recently, however, other alternatives have been proposed where SUSY does not play this traditional role. We will consider two frameworks:

(i) Split-SUSY models [2], where the Higgs mass parameters are fine-tuned to the actual values, which provide an EW scale that allows atoms [3]. An analogous argument was used by Weinberg [4] to predict a cosmological constant consistent with the observed value (that allows the formation of structures), and it would be justified by the *landscape* [5] of string theory.

(ii) Partly-SUSY models [6], with the Higgs sector living in a point of an extra dimension (the *TeV brane*) where the Planck scale is red-shifted by the metric to the EW scale. SUSY is then broken in the *Planck brane*. Loop corrections connect the Higgs with Planck-scale physics, but all the contributions are also suppressed by the metric. These models have a 4-dimensional (4D) holographic interpretation where the Higgs is a bound state of size TeV^{-1} and its constituents decouple exponentially at energies above that scale.

Although in these two frameworks SUSY would be part of the complete theory in the ultraviolet, it is not needed to cancel large quadratic corrections and could be broken at very high energies. In both cases, however, the breaking may be such that one is left at low energies with what has been an important phenomenological motivation for SUSY: the presence of a good dark matter candidate [7]. A stable, weakly-interacting particle like the neutralinos of the MSSM could provide a relic abundance $\Omega_\chi = 0.113h^2$ [8], in agreement with cosmological and astrophysical observations.

One can argue that, in both scenarios, the higgsino would be a well motivated lightest SUSY particle (LSP). The additional presence of gauginos at a low scale requires that the breaking of SUSY respects an (approximate) R-symmetry. In [9] it is shown that this can be naturally the case when SUSY is broken by the nonzero D term of a spurion vector superfield. However, in the generic case with D- and F-breaking the gauginos should get large masses. In contrast, in partly-SUSY models SUSY may be broken at a very large scale in the Planck brane, but the μ term (localized in the TeV brane) will always have TeV size. In split-SUSY models a μ term of order TeV could be obtained, for example, in a gauge-mediated scenario [10] where SUSY is broken at a scale $F \approx (10^{11}\ \text{GeV})^2$. For messenger masses of the same order, scalar and gauginos will get large masses $\tilde{m} \approx (\alpha/4\pi)\sqrt{F}$ through gauge interactions, whereas the μ term would be of order TeV if it is induced just by gravitational interactions [11]. It could also be that SUSY is broken at the grand unification (GUT) scale but μ is still protected by flavour symmetries of the superpotential and the Kähler potential. These symmetries (for example, the discrete symmetries related to the topology of the compact space in string models [12]) are suggested by the hierarchies in the quark and lepton masses. Notice that at large scales one may expect several pairs of higgs doublets (per just one gaugino multiplet), so the symmetries could protect (at least) one of them and imply a μ term of order TeV generated by nonrenormalizable operators [13].

Here we explore this *minimal* possibility, with the higgsinos as the only light SUSY particles. We focus our analysis on higher order effects (loops and heavy fields) that may break the degeneracy of the four higgsinos. We show that although split- and partly-SUSY models may look similar, they suggest a very different higgsino dark matter scenario.

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The dark matter candidates in generic split-SUSY models have been analized in [14], with results that do not differ essentially from the ones in the MSSM. Studies of indirect dark matter detection signals can be found in [15]. Arkani-Hamed *et al.* [9] have suggested an interesting possibility where a heavy gravitino decays when the LSP is already out of equilibrium, increasing its cosmic abundance. Here we will just determine the usual relic abundance obtained from a LSP with (approximately) constant number below the freeze-out temperature.

II. HIGGSINOS IN THE SPLIT-SUSY MODEL

Let us start defining the spectrum in the split-SUSY model. We will assume that sfermions and gauginos get masses at the SUSY-breaking scale, much above the EW scale. The Higgs sector contains the usual doublets of chiral superfields, $\mathbf{H}_1 = (\mathbf{h}_1^0\ \mathbf{h}_1^-)$ and $\mathbf{H}_2 = (\mathbf{h}_2^+\ \mathbf{h}_2^0)$, that can be expanded

$$\mathbf{h}_1^0 = h_1^0 + \sqrt{2}\theta\tilde{h}_1^0 + \theta^2 F_{h_1^0}, \tag{1}$$

with h_1^0, $\tilde{h}_1^0$ and $F_{h_1^0}$ the scalar, spinor and auxiliary components of $\mathbf{h}_1^0$ and analogous expressions for the rest of higgs fields. Once the SUSY-breaking terms are included, the light scalar sector will coincide with the one in the SM (all the extra scalars become very heavy). In the higgsino sector, we assume a term $W = \mu\mathbf{H}_1\mathbf{H}_2$ in the superpotential, giving

$$\begin{aligned}\mathcal{L}_0 &= \int \mathrm{d}^2\theta\mu(-\mathbf{h}_1^0\mathbf{h}_2^0 + \mathbf{h}_1^-\mathbf{h}_2^+) + \text{h.c.}\\ &\supset -\frac{1}{2}(\tilde{h}_1^0\quad \tilde{h}_2^0)\begin{pmatrix} 0 & -\mu \\ -\mu & 0\end{pmatrix}\begin{pmatrix}\tilde{h}_1^0\\ \tilde{h}_2^0\end{pmatrix} - \mu\tilde{h}_1^-\tilde{h}_2^+ + \text{h.c.}.\end{aligned} \tag{2}$$

This Lagrangian defines a degenerate spectrum of one charged (Dirac) fermion plus the two neutral fields

$$\begin{aligned}\chi_s &= \frac{i}{\sqrt{2}}(\tilde{h}_1^0 + \tilde{h}_2^0),\\ \chi_a &= \frac{1}{\sqrt{2}}(\tilde{h}_1^0 - \tilde{h}_2^0),\end{aligned} \tag{3}$$

all of them with mass μ (hereafter we assume $\mu > 0$). The most remarkable feature in this new basis $(\chi_s\ \chi_a)$ is that the gauge couplings with the Z boson become nondiagonal:

$$\begin{aligned}\mathcal{L}_Z &= -\frac{g}{2c_W}Z_\mu(\bar{\tilde{h}}_1^0\quad \bar{\tilde{h}}_2^0)\bar{\sigma}^\mu\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}\tilde{h}_1^0\\ \tilde{h}_2^0\end{pmatrix}\\ &= -\frac{g}{2c_W}Z_\mu(\bar{\chi}_s\quad \bar{\chi}_a)\bar{\sigma}^\mu\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}\begin{pmatrix}\chi_s\\ \chi_a\end{pmatrix}.\end{aligned} \tag{4}$$

In the MSSM tree-level mixing with the gauginos and loop (fermion-sfermion and γ/Z-higgsino) corrections [16] introduce mass splittings $\Delta_{0,+}$ between the two neutral states and between the charged and the lightest neutral state (which corresponds to $\chi_0 \approx \chi_a + O(\Delta_0/\mu)\chi_s$ if the mixing with the gauginos dominates). Here, however, sfermions and gauginos decouple, and both top-quark loops and the mixing with the gauginos are negligible. Only the splitting $\Delta_+ \approx \alpha\mu\log(1 + M_Z^2/\mu^2)$ is generated through γ/Z-higgsino loop corrections. Therefore, the typical spectrum in the split-SUSY framework with decoupled gauginos consists of two degenerate neutral higgsinos of mass μ plus a charged field around 1 GeV heavier.

III. HIGGSINOS IN THE PARTLY-SUSY MODEL

At the lowest order there will be few differences between the scenario just described and the partly-SUSY model [6]. The setup is defined in the usual 5D slice of AdS space of the Randall-Sundrum model [17]. It is assumed that the SM fermion and gauge fields live in the bulk of the extra dimension, whereas the Higgs fields are attached to the TeV boundary. SUSY is then broken only in the Planck brane, and the zero Kaluza-Klein (KK) modes of all the SUSY particles in the bulk (sfermions and gauginos) get large masses. The fact that SUSY is not broken in the TeV brane would justify a *little* hierarchy between the typical scale there ($L^{-1} \approx 5$ TeV, for example) and the EW scale, since the (SUSY-breaking) Higgs mass parameters would appear at the loop level suppressed by a factor of $(g/4\pi)^2$. The most remarkable feature in this setup is that the Higgs sector is (up to low-energy corrections) SUSY despite having unsuppressed interactions with other sectors of the theory where SUSY may be broken at the Planck scale. SUSY-breaking contributions in the TeV brane involve loops where a bulk particle propagates from the TeV brane to the Planck brane and back to the initial point, and are then red-shifted by the metric.

A first difference with the spectrum in split-SUSY models is that here the scalar higgs sector is similar to the one in the MSSM, with two neutral and one charged fields in addition to the lightest neutral Higgs.

In the Higgsino sector we assume a μ term (see Eq. (1)) localized on the TeV brane. In addition, the zero modes of sfermions and gauginos are very heavy and decouple, which would imply a spectrum of charginos and neutralinos that coincides (at the lowest order in $1/L^{-1}$) with the one described in the split-SUSY case. However, the partly-SUSY spectrum also includes the KK excitations of all the fields in the bulk. These fields will be localized near the TeV brane, are (approximately) SUSY, and have masses of order L^{-1}. Their effect can be found using the (SUSY) equations of motion to integrate them out. In particular, the KK modes of the vector superfields introduce the operator

$$\mathcal{L}_1 = -\int \mathrm{d}^4\theta\frac{4.1}{L^{-2}}\Big(\sum_a g^2(\mathbf{H}_1^\dagger T^a\mathbf{H}_1 + \mathbf{H}_2^\dagger T^a\mathbf{H}_2)^2 + \frac{g'^2}{4}(-\mathbf{H}_1^\dagger\mathbf{H}_1 + \mathbf{H}_2^\dagger\mathbf{H}_2)^2\Big), \tag{5}$$

where the factor of $4.1/L^{-2}$ was calculated in [6] using the 5D propagator and subtracting out the zero-mode contribution (it corresponds to $\sum_n (f_n^2/f_0^2)/M_n^2$, the sum over all the excitations of the inverse mass-squared weighted by the ratio of wave functions at the TeV brane). We obtain

$$\begin{aligned}\mathcal{L}_1 \supset 2\frac{4.1}{L^{-2}}\bigg(\sum_a g^2(F_{H_1}^\dagger T^a \tilde{H}_1 H_1^\dagger T^a \tilde{H}_1 \\ + F_{H_2}^\dagger T^a \tilde{H}_2 H_2^\dagger T^a \tilde{H}_2 + F_{H_1}^\dagger T^a \tilde{H}_1 H_2^\dagger T^a \tilde{H}_2 \\ + F_{H_2}^\dagger T^a \tilde{H}_2 H_1^\dagger T^a \tilde{H}_1) + gT^a \to g'Y\bigg) + \text{h.c.},\end{aligned} \tag{6}$$

with $F_{H_1}^\dagger = \mu(h_2^0 - h_2^+)$ and $F_{H_2}^\dagger = \mu(h_1^- - h_1^0)$. If $\langle h_1^0 \rangle = v_1$ and $\langle h_2^0 \rangle = v_2$ the operator implies the higgsino mass terms

$$\begin{aligned}\mathcal{L}_1 \supset -\frac{8.2M_Z^2}{L^{-2}}\bigg[\frac{1}{2}(\tilde{h}_1^0 \quad \tilde{h}_2^0)\begin{pmatrix} -\mu\sin 2\beta & \mu\cos 2\beta \\ \mu\cos 2\beta & \mu\sin 2\beta \end{pmatrix} \\ \times \begin{pmatrix} \tilde{h}_1^0 \\ \tilde{h}_2^0 \end{pmatrix} + \mu\cos^2\theta_W \cos 2\beta \tilde{h}_1^- \tilde{h}_2^+\bigg] + \text{h.c.},\end{aligned} \tag{7}$$

where $\tan\beta = v_2/v_1$ and $v = \sqrt{v_1^2 + v_2^2} = 174$ GeV.

In this model the Higgs fields could also interact with massive chiral superfields localized on the TeV brane. These could be the KK modes of bulk fields or purely 4D fields (in both cases the fields are SUSY and with masses of order L^{-1}). If trilinear terms couple the Higgs doublets with these singlet or triplet superfields, integrating them out one obtains the effective operator $W = -(\lambda/L^{-1}) \times (\mathbf{H}_1\mathbf{H}_2)^2$:

$$\begin{aligned}\mathcal{L}_2 &= -\int d^2\theta \frac{\lambda}{L^{-1}}((\mathbf{h}_1^0\mathbf{h}_2^0)^2 - 2\mathbf{h}_1^0\mathbf{h}_2^0\mathbf{h}_1^-\mathbf{h}_2^+ \\ &\quad + (\mathbf{h}_1^-\mathbf{h}_2^+)^2) + \text{h.c.} \\ &\supset -\frac{1}{2}\frac{-2\lambda}{L^{-1}}(h_2^0\tilde{h}_1^0 + h_1^0\tilde{h}_2^0)^2 - \frac{2\lambda}{L^{-1}}h_1^0h_2^0\tilde{h}_1^-\tilde{h}_2^+ + \text{h.c.}\end{aligned} \tag{8}$$

The Higgs vacuum expectation values (VEVs) will then introduce an additional mass $-2\lambda v^2/L^{-1}$ for the neutral higgsino ($\sin\beta\ \tilde{h}_1^0 + \cos\beta\ \tilde{h}_2^0$) and a mass $\lambda v^2 \sin 2\beta/L^{-1}$ for the chargino.

Several observations are here in order.

(i) The new mass terms in Eq. (7) (from the integration of gauge excitations) do not break the degeneracy between the two neutral higgsinos. The new (degenerate) eigenvalue is $m_\chi \approx \mu(1 + 8.2\cos 2\beta M_Z^2/L^{-2})$. In addition, for $\tan\beta > 1$ the mass contribution to the charged higgsino is negative, making it lighter than the neutral states. To get a working scenario we need that these effects are compensated by the second operator.

(ii) The corrections in Eq. (7) are of order $v^2\mu/L^{-2}$, whereas the ones from the integration of chiral superfields (in Eq. (8)) are of order v/L^{-1}. Therefore, if chiral trilinears and gauge couplings are of similar size, for $\mu < L^{-1}$ this second operator will dominate. A little hierarchy $M_Z \approx \mu \approx (g/4\pi)L^{-1}$ is favored in the partly-SUSY model under discussion [6].

(iii) For a positive value of λ (in Eq. (8)), the second operator defines a spectrum where the LSP is a neutral state of mass $m_\chi = \mu - \lambda(1 - \sin 2\beta)v^2/L^{-1}$, the second neutralino is $\Delta_0 = 2v^2\lambda/L^{-1}$ heavier, and the chargino increases its mass to $m_{\chi^+} = \mu + \lambda v^2 \sin 2\beta/L^{-1}$.

In Fig. 1 we plot the three masses for different values of $\tan\beta$. We take $\mu = 80$ GeV, $L^{-1} = 5$ TeV and $\lambda = 5$ (which could be generated by a trilinear coupling with a bulk singlet around 2 times the gauge coupling). We observe that the corrections are able to keep the LSP lighter than the W boson while pushing the chargino mass above the bounds from LEP. As we see in the next section, this would suffice to make the neutral higgsino an acceptable dark matter candidate.

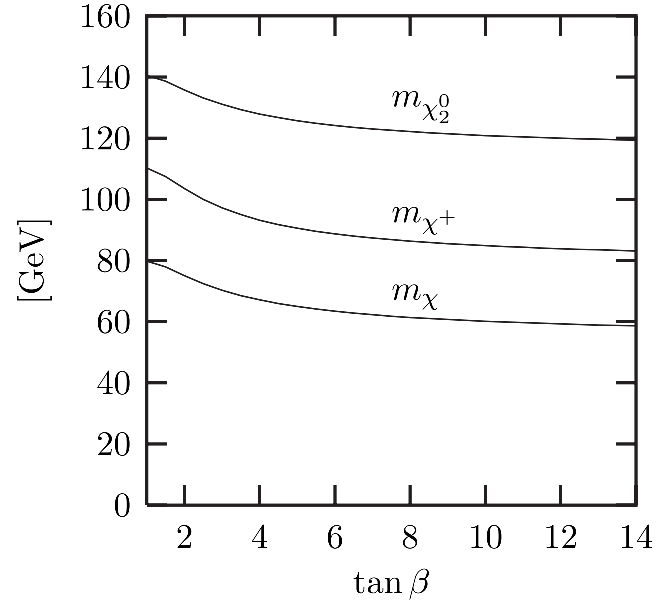

FIG. 1. Masses of the LSP (m_χ), the chargino (m_{χ^+}) and the second neutralino ($m_{\chi_2^0}$) for $\mu = 80$ GeV, $L^{-1} = 5$ TeV and $\lambda = 5$.

IV. DARK MATTER DENSITY

Recent observations [8] indicate that the fraction of critical energy density of the universe provided by dark matter is $\Omega_\chi = 0.113h^2$. In this section we use a modified version of *Dark SUSY* [18] to analyze under what conditions the higgsinos can account for that number.

The relic density of LSP depends crucially on its mass m_χ and on the rate of the reactions that change its number [19]. If the LSP χ is significantly lighter than the other SUSY particles, then the only relevant reaction is its annihilation into SM particles. In our framework, however, there are other particles (χ_2^0 and χ^+) with similar mass and then similar abundances at temperatures below m_χ. These particles can *coannihilate* with χ into SM particles [20,21], decreasing significantly the freeze-out temperature and the relic density of the LSP.

Let us start describing the situation in the split-SUSY case. If $\mu \lesssim M_W$, then the most efficient process reducing the LSP abundance is the coanihilation with χ_2^0 into quarks and leptons mediated by a Z boson. For example, taking $\mu = 75$ GeV we obtain $\Omega_\chi h^2 = 0.0005$ (with no significant dependence on tanβ). Notice that this value of μ would be also excluded by collider bounds on the chargino, which would be just around 1 GeV heavier. If $\mu \gtrsim M_W$ there is also the annihilation into W^+W^- (with the chargino in the t channel) and into ZZ that push Ω_χ to low values. For example, taking $\mu = 95$ GeV we obtain $\Omega_\chi h^2 = 0.0009$. Therefore, the region with a light higgsino in the split-SUSY setup can not provide the observed dark matter density. For larger values of μ the relic abundance increases, reaching $\Omega_\chi h^2 \approx 0.113$ for $\mu = 1.1$ TeV (with no significant dependence on tanβ).

The situation in the partly-SUSY framework could be completely different. In particular, for $\mu \lesssim M_W$ the operator in Eq. (8) can introduce splittings that will suppress the relevance of coannihilations and push the chargino mass above collider bounds. Let us be more definite. If tan$\beta = 1$ the corrections increase the mass of the neutral state $\chi_2^0 = \chi_s$ (in Eq. (3)) to $m_{\chi_2^0} = \mu + \Delta_0$ without changing the mass $m_\chi = \mu$ of the LSP $\chi = \chi_a$. At temperatures below μ the coannihilations of χ and χ_2^0 through a Z will not be relevant because of the mass splitting (that suppresses the abundance of χ_2^0), whereas the annihilations will be suppressed because the antisymmetric state does not couple to the Z boson (the couplings are nondiagonal, see Eq. (4)). In Fig. 2 we show that the corrections are able to increase the relic abundance up to the observed value. We plot $\Omega_\chi h^2$ for $\mu = 75$ GeV and different values of L^{-1} and tanβ. For tan$\beta > 1$ the LSP does not correspond to χ_a, since the corrections in Eq. (8) will mix that state with χ_s. This increases the coupling of the LSP with the Z boson and its annihilation cross section, reducing $\Omega_\chi h^2$. Therefore, low values of tanβ can accommodate larger dark matter densities. For a given value of tanβ, Fig. 2 shows a value of L^{-1} that optimizes the relic density: larger values reduce the mass splittings and increase the relevance of coannihilations, whereas lower values of L^{-1} increase (except for tan$\beta = 1$) the coupling of the LSP with the Z boson and then the rate of its annihilations.

In Fig. 3 we plot $\Omega_\chi h^2$ for different values of μ and tanβ. The maximum value of $\Omega_\chi h^2$ is always achieved for a LSP mass around 75 GeV (larger masses open new annihilation channels, and lower masses increase its coupling to the Z boson), but due to the mass corrections this corresponds to different values of μ (depending on tanβ).

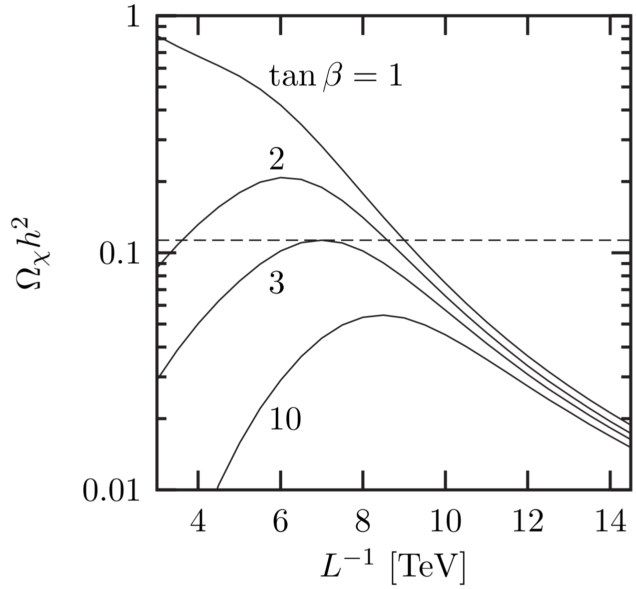

FIG. 2. $\Omega_\chi h^2$ for $\mu = 75$ GeV, $\lambda = 5$ and different values of tanβ.

We observe in Fig. 3 that for $L^{-1} = 5$ TeV and tan$\beta < 3$ the LSP could provide the observed dark matter of the universe. In general, given tanβ and λ there is a value of μ and L^{-1} that optimizes $\Omega_\chi h^2$. For example, the line corresponding to tan$\beta = 3$ increases up to $\Omega_\chi h^2 = 0.137$ if $L^{-1} = 6.5$ TeV and $\mu = 82$ GeV, whereas for tan$\beta = 10$ the maximum value $\Omega_\chi h^2 = 0.093$ (within 3σ deviations of the experimental value) is achieved for $L^{-1} = 5.2$ TeV

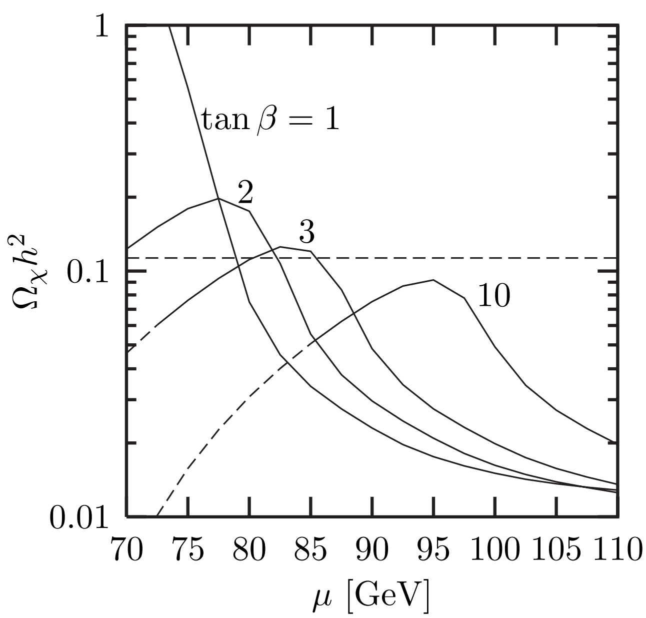

FIG. 3. $\Omega_\chi h^2$ for $L^{-1} = 5$ TeV, $\lambda = 5$ and different values of tanβ and μ. Dashes indicate a chargino excluded by collider bounds.

and $\mu = 95$ GeV. Values of $\tan\beta$ up to 4.7 can reproduce the central value $\Omega_\chi h^2 = 0.113$.

V. SUMMARY AND DISCUSSION

The LSP has been the favorite WIMP candidate to constitute the dark matter of the universe. In particular, the MSSM could explain the value $\Omega_\chi h^2 = 0.113$ if a sneutrino or a neutralino is the LSP. This has been an important phenomenological argument for SUSY, in addition to the basic (and more *formal*) motivation of offering a mechanism to cancel quadratic corrections.

Recently, however, other scenarios have been proposed where SUSY is not the key ingredient to explain the difference between the EW and the Planck scales. We have considered split-SUSY models, where the higgs mass is the result of an accidental cancelation of much larger contributions, and partly-SUSY models, where the higgs sector *sees* the large SUSY-breaking scale redshifted to the EW scale by the metric. In both frameworks SUSY would manifest only in a sector of the theory. Models partially SUSY had not been studied before because, in general, one expects that if SUSY is broken in a nonisolated sector radiative corrections will extend this breaking to the whole theory. This is not the case, however, in the two setups that we have studied. In split-SUSY models the higgsinos could be the only light SUSY fields if their mass is protected by flavor symmetries or, for example, if SUSY breaking is gauge mediated to sfermions and gauginos while the μ term in generated through gravitional interactions. In the partly-SUSY case the higgsinos would naturally be the only light ($\approx (g/4\pi)L^{-1}$) SUSY particles if the rest of SM fields live in the bulk and SUSY is broken in the Planck brane. In both scenarios the presence of higgsinos could well be the only trace of SUSY at energies ≤ 1 TeV.

We have analyzed if these higgsinos could be the dark matter of the universe. In both scenarios the degeneracy of the neutral and the charged higgsino states is the key factor, as coanihilations are then very effective and imply a too low relic density for $\mu < 1$ TeV. In the split-SUSY case the degeneracy is only broken (in a $\leq 1\%$) by EW loop corrections, whereas in the partly-SUSY model there are also effective operators (suppressed by powers of $1/L^{-1}$) that result after integrating out the KK modes of gauge and chiral fields.

Therefore, although they may look at first sight similar, these two models suggest a very different dark matter scenario. A 1 TeV LSP, with extra neutral and charged fermions around 1 GeV heavier, together with a SM content in the scalar sector (no extra higgses), would be an indication of split SUSY. In the partly-SUSY model it would be more difficult (although possible) to accommodate the 1 TeV LSP, since that would introduce a little hierarchy problem. We have shown, however, that this framework may imply a LSP of mass $m_\chi \approx 75$ GeV, a charged higgsino with $m_{\chi^+} = m_\chi + \Delta_+ \approx 100$ GeV and another neutral state at $m_{\chi_2^0} \approx m_\chi + 2\Delta_+ \approx 125$ GeV. Such a higgsino spectrum, with no signs of sfermions or gauginos and a scalar higgs sector that includes the usual charged and neutral fields of the MSSM with a low value of $\tan\beta$ ($\lesssim 4$), would be the clear signature of a partly-SUSY model.

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