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LIGHT NEUTRALINO AS DARK MATTER

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ABSTRACT

Cosmological properties of a light neutralino χ are studied in the context of the minimal supersymmetric model. It is found that the relic mass density of a general superposition of gauginos and higgsinos is generally very small, while for predominantly higgsino-like or gaugino-like neutralinos it is typically close to the critical mass density. The existence of even one light sfermion ($m_{\tilde{f}} \gtrsim m_\chi$) dramatically reduces the relic mass density of gaugino-like relics and makes them cosmologically also less attractive. Other criteria place an upper bound of about 150 GeV on the mass of the lightest neutralino, and exclude also higgsino-like neutralinos.

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Introduction

One of the challenges confronting particle physics and cosmology is the determination of the nature of dark matter (DM) which is believed to account for up to 90% of the matter in the Universe [1]. Among several well-motivated DM candidates that have been proposed, the lightest neutralino χ has emerged as a favourite choice for both the lightest supersymmetric particle (LSP) [2,3] and 'cold' dark matter. Combined LEP [4] and ^{76}Ge data [5] have excluded [6] some other popular candidates, like sneutrinos [7] and heavy neutrinos, both Dirac and Majorana, unless the couplings of the latter ones to the Z^0 are strongly suppressed [8]. In contrast, the lightest neutralino has been only mildly constrained to be heavier than about 13 GeV [9] by combining the results of the ALEPH direct search for neutralinos with the UA2 lower bound on the gluino mass. (This limit is improved [9] to about 20 GeV by the new, preliminary data from CDF.) On the cosmological side, the relic mass density of the lightest neutralino comes out naturally within an order of magnitude of the critical density [10-15,8].

The LSP cosmology has been studied in the context of the Minimal Supersymmetric Standard Model (MSSM) [3,16], with the lightest neutralino as the LSP [11]. In this paper, I reconsider the lightest neutralino as a candidate for DM. I focus primarily on the light LSP case, with $m_\chi < m_W$, and take into account recent experimental limits from LEP and gluino mass limits from UA2 and CDF. This work is complementary to other recent studies [13,14] which emphasize the possibility of χ being heavier than the W -boson. I argue that reasonable assumptions imply an upper bound $m_\chi \lesssim 150 \text{ GeV}$, and exclude higgsino-like LSPs. Similarly, naturalness predicts [17] that the LSP mass should not be much heavier than the W , the mass range to be also directly explored by LEP II. (See also Ref. 18 for a discussion of the prospects for direct searches for light DM.) It has been known [11] that in the considered region, $m_\chi < m_W$, the channel $\chi\chi \rightarrow \bar{f}f$ typically dominates the annihilation cross-section. However, other possible channels, *i.e.*, $\chi\chi \rightarrow$ Higgs pairs (also considered in Ref. 19) and $\chi\chi \rightarrow Z$ -Higgs boson, may have a significant effect in the region of parameter space in which they are kinematically allowed.

I also discuss in detail the dependence of the relic density of LSPs on parameters such as the LSP mass, the top quark mass, and the masses of the sfermion and Higgs bosons. I find a remarkably strong sensitivity of the relic density of the

gaugino-like LSPs to the sfermion masses. In particular, the existence of even one light sfermion ($m_{\tilde{f}} \approx m_\chi$), *e.g.*, the selectron $\tilde{e}$, has a dramatic effect of reducing the relic mass density, and strongly disfavours a gaugino-like LSP below $m_\chi < m_W$ as a DM candidate for natural values of parameters.

Next, I extend the analysis to the region $m_\chi > m_W$, where the LSP annihilation to several new final states (like, for example, vector boson pairs) becomes possible, and argue that even the annihilation channels considered in this paper are efficient enough to give too little dark matter in significant portions of the parameter space, especially those where the LSP contains comparable fractions of both the gaugino and higgsino components, both below and above m_W .

The lightest neutralino

The four neutralinos of the MSSM are the mass states of the linear combinations of the neutral gauginos: the wino $\tilde{W}^3$ and the bino $\tilde{B}$; and the neutral higgsinos: $\tilde{H}_1^0, \tilde{H}_2^0$,

$$\chi_i^0 = N_{i1}\tilde{W}^3 + N_{i2}\tilde{B} + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0, \quad (1)$$

and are labelled in order of increasing mass. Hence $\chi \equiv \chi_1^0$. The mass spectrum [11,3] is defined in terms of $\tan\beta \equiv v_2/v_1$, the higgsino mass parameter μ , as well as the soft masses M_1 and M_2 of $\tilde{B}$ and $\tilde{W}^3$, respectively:

$$\begin{pmatrix} M_2 & 0 & m_Z \cos\theta_W \cos\beta & -m_Z \cos\theta_W \sin\beta \\ 0 & M_1 & -m_Z \sin\theta_W \cos\beta & m_Z \sin\theta_W \sin\beta \\ m_Z \cos\theta_W \cos\beta & -m_Z \sin\theta_W \cos\beta & 0 & -\mu \\ -m_Z \cos\theta_W \sin\beta & m_Z \sin\theta_W \sin\beta & -\mu & 0 \end{pmatrix} \quad (2)$$

The usual GUT relationship between the soft gaugino masses implies

$$M_1 = \frac{5}{3} \tan^2\theta_W M_2 \approx 0.5 M_2 \quad (3)$$

$$M_2 = \frac{g_2^2}{g_s^2} m_{\tilde{g}} \approx 0.3 m_{\tilde{g}}, \quad (4)$$

where $m_{\tilde{g}}$ is the gluino mass. This reduces the number of independent parameters to three: I choose them to be $\tan\beta$, μ and M_2 . It is not restrictive to assume $M_2 > 0$, in which case μ can be either positive or negative.

The mass states of charged gauginos and higgsinos are called charginos. Their masses are given by [11, 3]

$$m_{\chi_{1,2}^{\pm}, \chi_{3,4}^{\pm}} = \frac{1}{2} \left[M_2^2 + \mu^2 + 2m_W^2 \pm \sqrt{(M_2^2 - \mu^2)^2 + 4m_W^4 \cos^2 2\beta + 4m_W^2(M_2^2 + \mu^2 + 2M_2\mu \sin 2\beta)} \right]. \quad (5)$$

I present in Figs. 1 and 2 mass contours of the LSP in the (μ, M_2) plane for two representative choices of $\tan \beta$: $\tan \beta = 2$ (Fig. 1) and $\tan \beta = 8$ (Fig. 2). Experimental searches for supersymmetric particles at LEP (charginos, neutralinos), and by UA2 and CDF (gluino), as well as the precision measurements of the Z line shape at LEP, have considerably constrained the allowed parameter space. First, LEP tells us that the lightest chargino $\chi_1^{\pm}$ is heavier than about 45 GeV [4]. Second, UA2 provides us with a lower bound on the gluino mass, $m_{\tilde{g}} > 79 \text{ GeV}$ [20], which implies, via (4), that $M_2 > 23.5 \text{ GeV}$. (A new preliminary bound of $m_{\tilde{g}} \gtrsim 150 \text{ GeV}$ from CDF [21] is now also available.) Third, Aleph [22] has recently excluded significant fractions of the (μ, M_2) plane on the basis of unsuccessful searches for charginos and neutralinos (those regions are marked in the graphs by 'ALEPH'). Once these constraints are applied, the condition $m_{\chi_{1,2}^{\pm}} > m_{\chi}$ does not restrict the allowed parameter space any further. Finally, recent Higgs searches at LEP imply that $\tan \beta > 1.6$ (see, e.g., [9]).

By combining all the experimental constraints listed above, one obtains a lower bound of about 13 GeV on the mass of the lightest neutralino [9].^{*} This limit is improved to $\approx 20 \text{ GeV}$ by the CDF limit on the gluino mass [9].

Notice the asymptotic behavior of the presented mass contours: for large $|\mu|$, $m_{\chi} \approx M_1$ and the LSP is a nearly pure bino; while for large M_2 , $m_{\chi} \approx |\mu|$ and χ is a nearly pure symmetric (antisymmetric) higgsino $\tilde{H}_S$ ($\tilde{H}_A$), where $\tilde{H}_{S,A} \equiv [\pm \tilde{H}_1 + \tilde{H}_2]/\sqrt{2}$ [13]. In Figs. 1 and 2, I also delineate those regions where the LSP is gaugino-like ($N_{11}^2 + N_{12}^2 \geq p$), and higgsino-like ($N_{13}^2 + N_{14}^2 \geq p$), with

^{*} After the publication of Ref. 9, it has been shown [23] that radiative corrections again allow $\tan \beta$ as small as one. At the same time, however, Aleph [22] has enlarged excluded regions in the (μ, M_2) plane for smaller values of $\tan \beta$, so that the bound of about $10 - 13 \text{ GeV}$ is still expected to hold.

increasing purity p : $p = 0.5, 0.9, 0.98$ and 0.99 . In addition, I also mark those (sub)regions where the LSP is a nearly pure bino or (anti)symmetric higgsino with purity $p = 0.99$.[†] It is clear that between those nearly pure gaugino and higgsino regions, there are still large portions of the (μ, M_2) plane where the LSP consists of significant fractions of both gauginos and higgsinos. I will call such regions 'mixed'.[‡]

An upper bound can also be placed on the mass of the LSP. It follows directly from the relation (4) and the fact that none of the supersymmetric particles is expected to be heavier than about 1 TeV . Above that scale, supersymmetry no longer protects Higgs (and in general scalar) masses from large one-loop radiative corrections. The rough bound $m_{\tilde{g}} \lesssim 1 \text{ TeV}$ implies $M_2 \lesssim 300 \text{ GeV}$ and

$$m_{\chi} \lesssim 150 \text{ GeV}. \quad (6)$$

In addition, it excludes higgsino-like LSPs, as can be seen from Figs. 1 and 2. Below, I will not apply this bound to restrict the LSP parameter space, but I will discuss its consequences at the end.

For completeness, I mention the Higgs sector [16] of the model. It consists of five physical Higgs bosons: two charged scalar fields $H^{\pm}$, with mass $m_{H^{\pm}} > m_W$; two neutral scalar fields h and H , with masses m_h, m_H ($m_h \leq |\cos 2\beta| m_Z < m_Z < m_H$); and a pseudoscalar field A , with mass $m_A < m_H$. All these masses are strongly constrained by supersymmetry and can be given in terms of just two free parameters, which we take to be m_A and $\tan \beta$.

The relic mass density of the LSPs

The relic mass density ρ_{χ} of LSPs can be computed by solving the Boltzmann equation (see, e.g., [24]). For the present purpose, I will use an early approximate

[†] An almost pure bino $\tilde{B}$ with purity p satisfies $N_{12}^2 \geq p$. Analogously, nearly pure symmetric and antisymmetric higgsinos with purity p are those higgsino-like states with purity p (i.e., satisfying $N_{13}^2 + N_{14}^2 \geq p$) for which $(|N_{13}| + |N_{14}|)^2/2 \geq p$. Notice that this definition of purity is more stringent than the one given by Olive and Srednicki [13].

[‡] Olive and Srednicki [13] denote as 'mixed' the whole areas of the (μ, M_2) plane where the LSP is not almost a pure bino or almost pure $\tilde{H}_S$ or $\tilde{H}_A$, even though in significant fractions of their 'mixed' regions the LSP may still be predominantly gaugino- or higgsino-like (especially for smaller values of $\tan \beta$).

solution [25,11]

$$\rho_\chi \simeq 4.5 \times 10^{-40} \left(\frac{T_\chi}{T_\gamma} \right)^3 \left(\frac{T_\gamma}{2.7 K} \right)^3 N_F^{1/2} \left(\frac{GeV^{-2}}{ax_f + \frac{1}{2}bx_f^2} \right) g/cm^3, \quad (7)$$

where $T_\gamma \simeq 2.7 K$ is the relic temperature of the photons; and the reheating factor (T_χ/T_γ) and the effective number of degrees of freedom N_f at the freeze-out temperature T_f can be found in Ref. 11. The scaled freeze-out temperature $x_f \equiv T_f/m_\chi$ is typically very small ($x_f = \mathcal{O}(1/20)$), justifying at low temperatures the approximation

$$\langle \sigma v_{rel} \rangle \simeq a + bx \quad (8)$$

of the thermally-averaged annihilation cross-section $\langle \sigma v_{rel} \rangle$. In computing a and b , I have followed the prescription given in Ref. 26.

I first focus on the channels $\chi\chi \rightarrow \bar{f}f$, where f is a conventional quark or lepton, which occur through the Z -boson exchange in the s -channel, the exchange of sfermions $\tilde{L}, R$ in both t - and u -channels [11,12], and the exchange of Higgs bosons in the s -channel [15]. The resulting expressions for a and b are in general rather complex and will be presented elsewhere [27]. The main features of this process can be summarized as follows:

1. In general, there are eight types of contributions to a and b , corresponding to the eight non-vanishing terms entering the total annihilation amplitude squared. Four of them come from the interference terms between the Z , the sfermion, and the Higgs exchanges. However, it has been checked numerically [28] that these interference terms do not influence the relic density significantly.
2. The Z -boson exchange is important primarily in the 'mixed' and the higgsino-like regions. This is due to the $Z\chi\chi$ coupling which is proportional to $(N_3^2 - N_4^2)$. Notice, however, that in the limit of the LSP being almost pure (anti)symmetric higgsinos $\tilde{H}_{A,S}$, the Z -exchange becomes again suppressed.
3. In general, LSP annihilation through sfermion exchanges is dominant in the gaugino-like regions (unless all the sfermions are very heavy) where the relevant Feynman couplings are comparable to the gauge coupling. On the

other hand, sfermion couplings to higgsino-like LSPs are suppressed by a factor m_f/m_W , and in this case the sfermion exchange is relatively much less important below the top threshold. (For $m_\chi > m_t$ it becomes dominant.)

4. The Higgs exchange contribution [15] to the LSP annihilation into $\bar{f}f$ is never dominant (except around the poles), but in general should not be neglected. The relative importance of the Higgs exchange is bigger for larger $m_{\tilde{f}}$ and smaller Higgs masses. It is suppressed by the Higgs boson couplings to fermions ($\sim m_f/m_W$), except for the pseudoscalar at large values of $\tan\beta$. The Higgs exchange vanishes in the pure gaugino and higgsino limits.

I have also included the other possible final states which may become kinematically allowed below m_W . These are: hh, AA, hA, hH, AH, Zh and ZA . They are of a relatively lesser importance, unless all the sfermions are rather heavy. For simplicity, for each of these final states, I have neglected the interference terms between the various contributing diagrams, assuming that their relative importance is small, similarly as in the case of the LSP annihilation into fermions. Even in this approximation, the resulting formulae for a and b are quite complex and will be presented elsewhere [27].

In the region $m_\chi > m_W$ the LSPs can also annihilate into several new important final states: $WW, ZZ, H^+H^-, HH, W^\pm H^\mp, ZH$, and $t\bar{t}$. In this study, I have included only the LSP annihilation into HH, ZH , and $t\bar{t}$. Thus the relic density in the region above m_W is greatly overestimated, as the neglected channels (especially WW and ZZ) will dramatically diminish the (higgsino-like) domains above m_W , where the indicative results show enough, or too much, dark matter. The purpose of evaluating the relic density above m_W has been, however, to explore where in the parameter space, annihilation into the final states that have been included in the analysis, already gives too little DM.

Results and discussion

The relic density of the LSPs resulting from (7) can be conveniently expressed in terms of the relic abundance $\Omega_\chi h_0^2$, where $\Omega_\chi \equiv \rho_\chi/\rho_{crit}$, and $0.5 \lesssim h_0 \lesssim 0.7$ is a current estimate of the present value of the Hubble parameter in units of $100 km/s/Mpc$ (see, e.g., the second paper of Ref. 1). The upper limit on h_0 holds provided that $\Omega_{tot} = 1$ and that the Universe is at least 10 billion years old. If

LSPs account for most of matter in the Universe then

$$0.25 \lesssim \Omega_\chi h_0^2 \lesssim 0.5. \quad (9)$$

However, definitely excluded on cosmological grounds are only those regions where $\Omega_\chi h_0^2 \gtrsim 1$ (unless the Universe is younger than about 10 billion years). On the other hand, $\Omega_\chi h_0^2$ below about 0.025 are not interesting cosmologically, as they do not account even for enough dark matter in galactic halos.

The results are presented as contours of relic abundance $\Omega_\chi h_0^2$ in the plane (μ, M_2) , for $\tan \beta = 2$ (Figs. 3 and 4) and $\tan \beta = 8$ (Figs. 5 and 6), for several representative choices of m_h and $m_{\tilde{f}}$. All these graphs exhibit a considerable complexity. Nevertheless, several common features can be noticed. Firstly, in the ‘mixed’ regions, both below and above m_W , the relic density is typically rather small ($\Omega_\chi h_0^2 \lesssim 0.1$), often even too small for providing enough DM in galactic halos ($\Omega_\chi h_0^2 \lesssim 0.025$). This deficit of DM in the ‘mixed’ regions is caused by the fact that none of the LSP annihilation channels is suppressed there. The regions of very small relic abundance above m_W are likely to be actually somewhat larger, since the relic density for $m_\chi > m_W$ has been overestimated by neglecting several new final states. Thus the ‘mixed’ regions, although not excluded, are cosmologically not very interesting [8].

Secondly, the strong dependence of the relic density on the sfermion masses in the gaugino-like regions can be seen by comparing Figs. 3 and 4a, or Figs. 5 and 6a. Sfermion masses are assumed here to be all degenerate and equal to 200 GeV (Figs. 3 and 5) or 1 TeV (Figs. 4a and 6a).^{*} Generally, larger values of $m_{\tilde{f}}$ correspond to much larger relic abundance, as expected (propagator suppression), except near the Z- and Higgs poles. I stress, however, that the existence of even one light ($\gtrsim m_\chi$) sfermion (I take the selectron $\tilde{e}$) has a dramatic effect of reducing the relic abundance in the light gaugino region to $\Omega_\chi h_0^2 \lesssim 0.1$, even if all other sfermion exchange channels are effectively turned off. This is clear by comparing Fig. 4a with Fig. 4b, or Fig. 6a with Fig. 6b. Notice that any sfermion would have caused a comparable effect since the coupling of a gaugino-like LSP to sfermions

^{*} When m_χ grows and approaches the chosen value of the sfermion masses $m_{\tilde{f}}$, then $m_{\tilde{f}}$ must start growing with m_χ ($m_{\tilde{f}} = m_\chi$). This results in maximizing the LSP annihilation through sfermion exchange and therefore in minimizing the relic density in the region of m_χ above the initially set sfermion masses.

is not suppressed by the corresponding fermion mass. The relic abundance of light higgsino-like LSPs does not exhibit any sensitivity to sfermion masses (due to the just mentioned suppression by a factor m_f/m_W) until the top quark final state becomes kinematically allowed (I choose $m_t = 150$ GeV). At that point, if the stop is not too heavy ($m_{\tilde{t}} = 200$ GeV), $\Omega_\chi h_0^2$ drops dramatically ($\lesssim 0.025$!) for both higgsino-like and gaugino-like LSPs. For (not so much) larger stop masses the effect becomes suppressed by the stop exchange propagator.

Thirdly, in the light higgsino region (large M_2 and $|\mu| \approx m_W$) the relic abundance $\Omega_\chi h_0^2$ increases with increasing M_2 , and eventually becomes larger than one, except for narrow bands of small $\Omega_\chi h_0^2$ due to Z- and Higgs poles. The process $\chi\chi \rightarrow \tilde{f}\tilde{f}$ is considerably suppressed there (as discussed before), while other kinematically allowed annihilation channels are rather subdominant for higgsino-like LSPs. Of course, once the vector boson final states are taken into account, the relic density will decrease dramatically in the higgsino regions above m_W [13,14], but not below. Asymptotically large values of M_2 are thus cosmologically excluded for m_χ below m_W . Qualitatively similar conclusions have been obtained in Ref. [13] in the limit of a pure (anti)symmetric higgsino but the quantitative pattern of relic density contours below m_W in this approximation is considerably oversimplified, mainly due to neglecting the s-channel exchanges of the Z and the Higgs bosons whose effect is clearly visible in the presented graphs.

The favoured regions (9) (between short-dashed lines) are present for all choices of parameters but are relatively small. Their position and size also vary but typically correspond to $m_\chi \lesssim m_W$ and to the LSP being either almost a pure bino or higgsino. This may have important implications for direct DM searches as well as supersymmetry searches at LEP [8]. Notice that in similar regions just above m_W , the relic abundance will be considerably reduced [13] once the final states of vector boson pairs (higgsino-like LSPs) and charged Higgs boson pairs (bino-like LSPs) are included.

The new final states involving Higgs bosons that become kinematically allowed for larger m_χ are of relatively smaller significance below m_W , but above m_W can be quite important, especially when all the sfermions are heavy. (The effect of varying the Higgs masses can be seen in Fig. 5.) Generally, Higgs-pair final states play a role mostly in the gaugino-like regions, while the Z-Higgs boson channels have an effect in higgsino-like regions but appear to be subdominant to WW and

ZZ channels [14]. The relative importance of those new channels is bigger for bigger $\tan\beta$ and smaller Higgs masses, and critically depends on $m_{\tilde{f}}$. Even one light sfermion $m_{\tilde{f}}$ makes their contribution completely negligible.

Finally, above m_W for large values of $|\mu|$ and M_2 , the relic density grows again due to the increase of $m_{\tilde{\chi}}$, as expected, and cosmological limits [13,14] can be placed on the ultra-heavy LSPs.

The presented graphs reveal a rich structure of relic density domains in the (μ, M_2) plane, particularly in the region $m_{\tilde{\chi}} < m_W$ that we have studied in more detail. Despite the lack of knowledge of, or relatively mild constraints on, the values of several external parameters (at least six in the simplest approach), certain general patterns have been pointed out. Of course, any improvement in constraining the allowed parameter space, notably the discovery of a (presumably) light sfermion (slepton?), will lead to very important cosmological consequences.

Conclusions

I have reconsidered a light neutralino, with $m_{\tilde{\chi}} < m_W$ as a candidate for DM. In the MSSM, there exist significant domains of the parameter space where the relic density of LSPs is naturally close to the critical density. In those regions the LSP is predominantly bino- or higgsino-like. On the other hand, the neutralinos consisting of comparable fractions of both gaugino and higgsino components generally annihilate very effectively and their relic density is typically rather small ($\Omega_{\tilde{\chi}} h_0^2 \lesssim 0.1$), often even too small to account for DM in galactic halos ($\Omega_{\tilde{\chi}} h_0^2 \lesssim 0.025$). If one or more light sfermions ($m_{\tilde{f}} \gtrsim m_{\tilde{\chi}}$) exist, then also light gauginos become much less attractive as DM candidates. For $m_{\tilde{\chi}} > m_W$, the LSP relic density is typically close to the critical density for $m_{\tilde{\chi}} \sim$ several hundred GeV , the mass range for the LSPs that is less appealing. A light higgsino, either $\tilde{H}_S$ or $\tilde{H}_A$, with mass somewhat smaller than m_W (60 to 80 GeV) might be a likely candidate for both the LSP and DM. However, if the gluino is not to be much heavier than 1 TeV , then higgsino-like LSPs are excluded and the LSP must be lighter than about 150 GeV . In addition, if at least one sfermion is relatively light, then the lightest neutralino of minimal supersymmetry may be a much less attractive candidate for DM than previously expected.

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FIGURE CAPTIONS

- 1) Contours of the LSP mass (short-dashed: 25 GeV , long-dashed: 40 GeV , dot-dashed: 60 GeV , solid: m_W) in the (μ, M_2) plane for $\tan\beta = 2$. Also shown are the contours (solid) of constant gaugino purity ($N_1^2 + N_2^2 = p$), with $p = 0.99$ (almost pure gaugino), 0.98 , 0.9 , 0.5 , 0.1 , 0.02 , and 0.01 (almost pure higgsino), as well as the contours of the almost pure bino $\tilde{B}$ and (anti)symmetric higgsino $\tilde{H}_{A,S}$ (short-dashed), with purity $p = 0.99$, as defined in the text. Regions where $0.01 < N_1^2 + N_2^2 < 0.99$ are marked as 'MIXED'. The allowed region is constrained by several experimental data. The results from Aleph and CDF are preliminary.
- 2) Same as Fig. 1, except with $\tan\beta = 8$. Only the most restrictive experimental constraints (from LEP and Aleph) are shown.
- 3) Contours of the LSP relic abundance $\Omega_\chi h_0^2$ in the allowed regions of the (μ, M_2) plane for $\tan\beta = 2$, $m_h = 50\text{ GeV}$, all $m_{\tilde{f}} = 200\text{ GeV}$ or m_χ , whichever is larger; and a) $\mu < 0$, and b) $\mu > 0$. For reference, also marked are the areas recently excluded by Aleph (thick long-dashed), almost pure (purity $p \geq 0.99$) gaugino or higgsino regions and the contour $m_\chi = m_W$ (thick short-dashed); compare Fig. 1. Thick solid lines in the blank areas correspond to $\Omega_\chi h_0^2 = 0.025$, and thin long-dashed lines to $\Omega_\chi h_0^2 = 0.1$. Thin short-dashed lines delimit the theoretically preferred regions where $0.25 < \Omega_\chi h_0^2 < 0.5$. Finally, grey areas encircled by thick solid lines correspond to $\Omega_\chi h_0^2 > 1$ and are cosmologically excluded. The relic abundance above m_W (especially in the higgsino-like regions) is significantly overestimated, as discussed in the text.
- 4) Same as Fig. 3, except in window a) all $m_{\tilde{f}} = 1\text{ TeV}$, and in window b) all $m_{\tilde{f}} = 1\text{ TeV}$, except for $m_{\tilde{e}}$ which is set at m_χ but not less than 40 GeV . Only the case $\mu > 0$ is shown; for $\mu < 0$ the results are almost identical.
- 5) Same as Fig. 3, except $\tan\beta = 8$ and in window a) $m_h = 50\text{ GeV}$, while in window b) $m_h = 80\text{ GeV}$. Only the case $\mu > 0$ is shown; for $\mu < 0$ the results are almost identical.
- 6) Same as Fig. 4, except $\tan\beta = 8$.

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6