hep-ph/9705444
CERN–TH/97-105
UMN–TH–1537/97
TPI–MINN–97/16

Constraints on Neutralino Dark Matter from LEP 2 and Cosmology

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Abstract

A significant lower limit on the mass of the lightest neutralino χ can be obtained by combining the results from sparticle searches at LEP at centre-of-mass energies up to 172 GeV with cosmological considerations, if it is assumed that the χ is stable. Exclusion domains from slepton searches close $m_\chi \sim 0$ loopholes that were left open by previous lower-energy LEP searches for charginos and neutralinos, leading to the lower limit $m_\chi \gtrsim 17$ GeV. The constraints on supersymmetric parameter space are strengthened significantly if LEP constraints on supersymmetric Higgs bosons are taken into account, and further if the relic neutralino density is required to fall within the range favoured by astrophysics and cosmology. These bounds are considerably strengthened if universality at the GUT scale is assumed for soft supersymmetry-breaking scalar masses, including those of the Higgs bosons. In this case, the Higgs searches play a dramatic rôle, and we find that $m_\chi \gtrsim 40$ GeV. Furthermore, we find that if tan$\beta \lesssim 1.7$ for $\mu < 0$, or tan$\beta \lesssim 1.4$ for $\mu > 0$, the cosmological relic density is too large for all values of m_χ.

CERN–TH/97-105
May 1997

1 Introduction

Among the most significant and model-independent accelerator constraints on supersymmetric dark matter candidates are those provided by LEP, thanks to its very clean experimental conditions. Many analyses have been conducted within the context of the minimal supersymmetric extension of the Standard Model (MSSM) with soft supersymmetry-breaking parameters - scalar masses m_i, gaugino masses M_α and trilinear couplings A_{ijk} - originating at some high supergravity scale and evolved down to lower energies using the renormalization group [1]. Further, it is often assumed that R parity is conserved, so that the lightest supersymmetric particle is stable, and often taken to be the lightest neutralino χ [2]. Within this framework, the negative results of LEP 1 searches for $Z^0 \to \chi^+\chi^-$ (where $\chi^\pm$ denotes the lightest chargino) and $Z^0 \to \chi\chi'$ (where χ' denotes a generic heavier neutralino) already established important limits on supersymmetric model parameters, but left open the possibility that the lightest neutralino might be massless [3]. Subsequently, the advent of data from higher-energy LEP runs at energies between 130 and 140 GeV (called here the LEP 1.5 run) [4] complemented LEP 1 data in an elegant manner that almost excluded the possibility of a massless neutralino, at least if the input gaugino masses M_α were assumed to be universal [5].

With these same assumptions, we showed in a previous paper [6] that the remaining loopholes in the experimental analysis could be blocked, and interesting lower limits on m_χ obtained, by combining LEP data with those from other e^+e^- experiments [7]. These bounds could be strengthened by assuming universality between the input slepton and squark masses and imposing the cosmological requirement that the relic neutralino density fall within the interesting range. We also found that the lower bound on m_χ could be further improved if one extended the assumption of universal soft supersymmetry-breaking scalar masses m_i to the Higgs sector, in the context of an implementation of dynamical electroweak symmetry breaking (EWSB) [8].

As the centre-of-mass energy of LEP is increased in steps, this type of lower bound on the neutralino mass can be strengthened progressively, and we have already commented[9] on the potential improvement that could be obtained by taking into account the data produced by LEP close to the W^+W^- threshold at $E_{CM} = 161$ GeV (called here the LEP 2W run) [10]. Recently, results have been announced from the subsequent higher-energy run at $E_{CM} = 170/172$ GeV (LEP 2) [11], and the main purpose of this paper is to consider their implications for the MSSM parameter space and supersymmetric dark matter [for a recent analysis of the chargino and cosmology constraints, see [12]]. The LEP 2 data of particular interest to us are the searches for charginos and neutralinos, new lower limits on the masses of sleptons $\tilde{\ell}$, improved limits on the production of stop squarks $\tilde{t}$ [13], and upper limits on the production rates for the neutral supersymmetric Higgs bosons h, A. The latter constraints are especially important when combined with cosmology and/or Higgs mass universality.

We now find, in contrast to the previous LEP 1.5 analysis, that the experimental searches for $\chi^+\chi^-, \chi\chi'$ and $\bar{\tilde{\ell}}\tilde{\ell}$ production at LEP 2 leave no loopholes for massless or light neutralinos, even in the absence of any other phenomenological inputs apart from gaugino mass universality. This is because slepton searches restrict the possibility for charginos to decay undetected into soft leptons. As shown in Fig. 1, we find a lower bound $m_\chi \gtrsim 17$ GeV, if the input slepton masses are assumed to be universal. Significant extra domains of supersymmetric parameter space are excluded if one takes into account the negative results of LEP searches for supersymmetric Higgs bosons, and assumes that all the input slepton and squark masses are universal, and also if one assumes that the relic neutralino density Ω_χ is large enough to be of astrophysical interest, but does not overclose the Universe: $0.1 \leq \Omega_\chi h^2 \leq 0.3$. The lower bound on m_χ may be strengthened significantly if the universality assumption is extended to the masses of the Higgs bosons that are put into renormalization-group calculations that implement dynamical EWSB, in which case LEP Higgs searches play a more important rôle [1]. Within this wholly universal framework, we find the lower limit $m_\chi \gtrsim 40$ GeV, attained when $\mu < 0$ and $\tan\beta = 2.8$. This constraint is considerably stronger than that inferred indirectly from unsuccessful squark and gluino searches by the CDF and D0 collaborations [15]. For small $\tan\beta$, the Higgs constraints improve the lower limit on m_χ so dramatically that it becomes incompatible with the cosmological upper limit on the relic density $\Omega_\chi h^2 \leq 0.3$. Thus cosmology and LEP 2 data together require the lower limit $\tan\beta \gtrsim 1.7$ for $\mu < 0$ and $\tan\beta \gtrsim 1.4$ for $\mu > 0$. In passing, we point out that the LEP 2 results exclude a large fraction of the domain of parameter space where the neutralino is a higgsino, and that future higher-energy LEP runs will be able to determine the fate of this option.

2 Review of Accelerator Constraints

As a prelude to our analysis, we first summarize the most relevant LEP 2 constraints that we use [11]. The unsuccessful searches for $e^+e^- \to \chi^+\chi^-$ production impose an upper limit on its cross section σ_{+-}, which we conservatively estimate as $\sigma_{+-} < 0.35$ pb in the

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[1] This point was recognized implicitly in [14], where it was noted in section IV that LEP should discover a Higgs boson if $\tan\beta$ is small and $\mu < 0$.

regions of parameter space relevent to our limit on m_χ, except when the sneutrino is lighter than the chargino, in which case we assume zero efficiency, which certainly is true when $|m_{\chi^\pm} - m_{\tilde{\nu}}| < 3$ GeV [2]. There is also an upper limit on the cross section for associated $\chi\chi'$ production, but this is does not exclude a significant extra domain of the MSSM parameter space. In addition to the constraints imposed by the chargino searches, we find that a useful rôle is also played by the upper limit on selectron [3] pair production, conservatively estimated using a rough approximation for the experimental efficiencies and the number of reported candidates: no limit is assumed when $m_{\tilde{e}} - m_\chi < 10\,\mathrm{GeV}$. Among the LEP 2 constraints of most interest to us are those on supersymmetric Higgs production, for which we consider both the $e^+e^- \to hZ$ and $e^+e^- \to hA$ reactions. We implement these constraints as upper limits on the number of events seen in the four LEP experiments, as reported in [11]. To do this, we first calculate the hZ and hA cross sections including initial-state radiation effects, then multiply by the luminosities and divide by the detection efficiencies quoted by the four collaborations in the different search modes, to obtain the total number of events expected in all the LEP experiments. We then compare with the reported results of the four collaborations [11], including the announced candidates in the different channels and taking account of their reported masses and resolution errors [16]. Since we include the full renormalization-group-improved mass formulae [17] for the Higgs boson masses, which are sensitive to the stop mass spectrum, we also implement the latest available constraints on stop production at LEP 2 [13].

3 Parameter Constraints

We start by using the upper limits on σ_{+-} and selectron production to derive a joint constraint in the $(m_{1/2}, m_0)$ plane, assuming a universal input soft supersymmetry-breaking mass m_0 for the the left and right sleptons. We do this by first fixing the value of $\tan\beta$, then, for each value of m_0, varying μ and plotting the minimum value of $m_{1/2}$ for which both the σ_{+-} and selectron constraints are respected. This provides the boundary of the hatched excluded domain, labelled "LEP", shown in Fig. 2 for negative μ and in Fig. 3 for positive μ, for representative choices of $\tan\beta$. We focus attention on the central $\tan\beta = 2$ cases shown in panels (a,b) of these figures, with outlying cases $\tan\beta = \sqrt{2}, 35$ shown in panels (c,d). We also indicate by diagonal hatching in Figs. 2 and 3 the domains of the $(m_{1/2}, m_0)$

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[2] We note that, although the experimental efficiency decreases in the limit $m_{1/2} \gg \mu$ where the mass difference $m_{\chi^\pm} - m_\chi$ becomes small, this case is not relevant for this study.

[3] The limits on $\tilde{\mu}$ and $\tilde{\tau}$ production do not significantly strengthen the bounds obtained from $\tilde{e}$ alone.

plane which are excluded theoretically in this framework because the lightest neutralino χ is heavier than the lighter stau $\tilde{\tau}_R$. It is apparent that the hatched LEP exclusion domain provides a non-trivial lower bound on m_χ, even in the absence of any further theoretical input. Although the LEP curve is somewhat re-entrant when $m_0 \sim 70$ GeV, it is bounded well away from the $m_{1/2} = 0$ axis. Thus, the previous loophole in the ALEPH analysis [5] which allowed $m_\chi \sim 0$ in the neighbourhood of tan$\beta = \sqrt{2}$ is now excluded [4], as is the other previous loophole at large m_0 for tan$\beta \sim 1.01$. The resulting experimental lower limit on m_χ as a function of tanβ is shown by the curve labelled "LEP" in Fig. 1.

The constraints in the $m_{1/2}, m_0$ plane obtainable from squark and gluino searches at Fermilab [15], assuming universality for the gaugino masses, are essentially the same as recorded in Figs. 1 and 3 of our LEP 1.5 analysis [6]. Therefore, for reasons of simplicity, we have not noted them explicitly in Figs. 1 and 3 of this paper. However, they are shown for reference in Fig. 2b, where it is seen that they again play the valuable rôle of excluding parts of the re-entrant regions in Figs. 2 and 3, though this rôle is less important here than in the LEP 1.5 analysis.

Further interesting constraints on the supersymmetric parameter space may be obtained by taking account of the LEP constraints on supersymmetric Higgs bosons [11]. In the absence of further theoretical input, one must allow arbitrarily large values of m_A, rendering the hA search irrelevant and retaining just the hZ search. The tree-level Higgs mass asymptotes to $m_Z |\cos 2\beta|$ for $m_A \gg m_Z$, and for small $\tan\beta$ this lies well below the experimental lower bound. However, the renormalization-group-improved formula for m_h [17] depends on the sfermion masses, in particular the stop and (for very large $\tan\beta$) the sbottom masses, and the constraints on the Higgs mass coming from the $e^+e^- \to hZ$ searches can be satisfied even for low $\tan\beta$ if the sfermion masses are sufficiently large. We henceforth assume that the input values of the soft supersymmetry-breaking squark masses are also equal to m_0. The low-scale renormalized sfermion masses are given by $m^2_{\tilde{f}} = m^2_0 + C_f m^2_{1/2} + m^2_f + O(M^2_Z)$, where the contributions $\propto m^2_{1/2}$ are due to the renormalization group evolution of the soft masses from M_X to M_Z [1]. The Higgs search bound can then be translated into a contour in the $(m_{1/2}, m_0)$ plane, restricting one to large $m_{1/2}$ and/or m_0. Since the radiative corrections to m_h are only logarithmically sensitive to the sfermion masses, the bounds on $m_{1/2}$ and m_0 increase rapidly as $\tan\beta$ becomes small. The Higgs mass can be increased by introducing mixing between stop eigenstates, although this is constrained by current lower limits on the mass of the lightest stop [13], whilst Higgsino loops can provide a small negative contribution

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[4] This possibility may also be constrained by searches for $W^\pm$ decays into charginos and neutralinos: see [18].

to m_h [17] [5].

It is important to note that the extension of the universality assumption to the input stop and sbottom masses constrains the allowed values of other supersymmetric model parameters. Consider first the renormalization group evolution of A_t down from the unification scale. For A_t much larger than $m_{1/2}$, the leading-order running of A_t is given by $dA_t/dt \approx 6\lambda_t^2 A_t/8\pi^2$ [1], so that (for constant λ_t) A_t decreases as a power law with scale, with an exponent that is roughly $1/12$ for $\lambda_t \sim 1$. Thus, A_t is reduced by an order of magnitude in its evolution from M_X to M_Z, and large $A_t(M_Z)$ requires extremely large $A_t(M_X)$ if $m_{1/2}$ is small. On the other hand, A_t itself enters into the running of other soft masses, in particular the stop mass-squared parameters, and extreme values for A_t drive the stop masses negative at M_Z. In practice, we find that $0 \leq A_t \leq 500\,\mathrm{GeV}$ covers the allowed range of A_t for the relevant values of $m_{1/2}$, with the positive gaugino mass contribution to the running of A_t driving $A_t > 0$ even for $A_t(M_X) < 0$. Since the bottom Yukawa is $\ll 1$ for moderate $\tan\beta$, A_b is not so tightly constrained, and we allow $-2\,\mathrm{TeV} \leq A_b \leq 2\,\mathrm{TeV}$, to include all values of A_b which do not lead to charge and/or color breaking in the scalar sector [19]. With the parameters A_t and A_b bounded as above, stop and (for large $\tan\beta$) sbottom mixing now limit the allowed range for μ, since a large value of $|\mu|$ may push the physical mass of the lightest stop (sbottom) below its current experimental limit [13]. At very large $\tan\beta$, where λ_b is not small, A_b is further restricted, but the range of μ allowed by sbottom mixing is quite insensitive to the limits on A_b in this case.

To establish the bound in the $(m_{1/2}, m_0)$ plane coming from Higgs searches, we vary μ, A_t and A_b over the range allowed by the stop and sbottom mass limits, the absence of charge and colour-breaking minima in the scalar potential [19], and the renormalization group evolution of the trilinear couplings. We find that only the regions bounded by the curves labelled "Higgs" in Figs. 2(a,c) and 3(a,c) permit solutions with sufficiently small Higgs production rates. The curves bend to the left at large m_0, where large sfermion masses lead to greater positive radiative corrections to the Higgs mass, and the Higgs curve strikes the chargino bound at sufficiently large m_0. For small $\tan\beta$, where the tree-level Higgs masses are small, the Higgs search constraints provide stronger limits on m_χ than those obtained from the chargino and slepton searches alone, as seen in Figs. 2 and 3. The narrow dips at $m_0 \sim 70\,\mathrm{GeV}$ are excluded [6], and the smallest neutralino masses come from points along the chargino bound at large m_0. This effect is carried over to Fig. 1, where the branch labelled "H" is the lower bound on m_χ due to combining the LEP 2 searches for sparticles

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[5] The corrections also depend upon the top mass, which we take here to have the central value of 171 GeV.

[6] As already mentioned, this rôle is also played by the Fermilab gluino searches [15].

and Higgs bosons. For large $\tan\beta$, the tree-level Higgs mass is already large enough to yield a sufficiently small Higgs production rate (recall that we are free to choose a large value for m_A), and the Higgs searches provide no additional bound on the $(m_{1/2}, m_0)$ plane, hence the absence of a "Higgs" curve in Fig. 2d and 3d. The Higgs searches fail to improve on the constraints coming from chargino, neutralino and slepton searches alone for all $\tan\beta \gtrsim 2.8$ for $\mu < 0$ and $\tan\beta \gtrsim 1.7$ for $\mu > 0$.

4 Incorporation of Cosmological Constraints on Neutralino Dark Matter

We now combine these accelerator bounds with cosmological bounds, assuming that the lightest neutralino is the lightest supersymmetric particle, and is absolutely stable, as in models with a conserved R parity and a relatively heavy gravitino [2].

It is well known that in a considerable domain of the supersymmetric parameter space the neutralino is an interesting dark matter candidate. In what follows, we focus on region of the parameter space in which the relic abundance of neutralinos left over from annihilations in the early Universe contributes a significant though not excessive amount to the overall energy density. Denoting by Ω_χ the fraction of the critical energy density provided by neutralinos, we focus on the region of parameter space in which

$$0.1 \leq \Omega_\chi h^2 \leq 0.3 \tag{1}$$

The lower limit in eq.(1) is motivated by astrophysical relevance. For lower values of $\Omega_\chi h^2$, there is not enough neutralino dark matter to play a significant rôle in structure formation, or constitute a large fraction of the critical density. Regions of parameter space in which the neutralino density fall short of this bound are not excluded, they are simply not of cosmological interest. In Figs. 2 and 3, only the light-shaded regions admit a neutralino with a relic density $\Omega_\chi h^2 > 0.1$.

The upper bound in (1), on the other hand, is an absolute constraint, derivable from the age of the Universe, which can be expressed as

$$H_0 t_0 = \int_0^1 dx \left(1 - \Omega - \Omega_\Lambda + \Omega_\Lambda x^2 + \Omega/x\right)^{-1/2} \tag{2}$$

In (2), Ω is the density of matter relative to critical density, while Ω_Λ is the equivalent contribution due a cosmological constant. Given a lower bound on the age of the Universe, one can establish an upper bound on Ωh^2 from eq.(2). In light of the new Hipparcos data [20], a safe lower bound to the age of the Universe is $t_0 \gtrsim 12$ Gyr, which translates into the upper bound given in (1). This bound is independent of the value of Ω or Ω_Λ, so long as $\Omega + \Omega_\Lambda \leq 1$.

Two generic possibilities for the composition of a possible neutralino dark matter candidate should be distinguished [2]: it may have mainly a gaugino composition, in which case its mass is more sensitive to $m_{1/2}$ than to μ, or it may be mainly a higgsino [21], in which case its mass is more sensitive to μ. Much of the higgsino region has now been excluded by LEP 2 [7]. This is because neutral higgsino dark matter particles should weigh less than 80 GeV, since heavier higgsinos annihilate rapidly into W^+W^-, suppressing the relic density below the relevant range (1) [22]. On the other hand, since $m_{\chi^\pm} - m_\chi$ is small in the higgsino region, the LEP 2 chargino searches now effectively exclude $m_\chi \lesssim 75$ GeV, leaving a narrow allowed range 75 GeV $\lesssim m_\chi \lesssim$ 80 GeV. The fate of this remaining region will soon be decided by higher-energy runs of LEP 2: among other searches, these should be able to probe $m_{\chi^\pm} \lesssim 95$ GeV for $m_{\chi^\pm} - m_\chi \gtrsim 5$ GeV, sufficient to discover or exclude a higgsino dark matter candidate.

An important consequence of the upper limit on $\Omega_\chi h^2$ is the exclusion of a large region in m_0 for at least some range of values of $m_{1/2}$, which results from combining cosmology with the LEP supersymmetric Higgs constraint. Gaugino-type neutralinos annihilate in the early universe predominantly through sfermion exchange into fermion pairs. Large sfermion masses shut off this annihilation channel and lead to large neutralino relic densities, in violation of the upper limit in (1). Since the sfermion masses depend on both m_0 and $m_{1/2}$ via the renormalization group equations, (1) therefore places an upper bound on m_0 and $m_{1/2}$ for gaugino-type neutralinos. In our previous analysis [6], the relic density could have been reduced to an acceptably low value, even for arbitrarily large values of m_0, by choosing a small value of $|\mu|$, which causes the lightest neutralino to become a gaugino/higgsino mixture. Including Higgs production constraints removes this freedom, as regions of low $m_{1/2}$ yield too low a Higgs mass unless μ is taken to be very large. As described above, this is particularly important at low $\tan\beta$, where the tree-level Higgs masses are small. The result of combining the LEP Higgs constraints with $\Omega_\chi h^2 < 0.3$ is shown as the dashed line in Figs. 2(a,c) and 3(a,c). In Fig. 2a, the dashed line turns up at $m_{1/2} \gtrsim 155\,\mathrm{GeV}$, and at $m_{1/2} \gtrsim 164\,\mathrm{GeV}$ for $\mu > 0$ in Fig. 3a, where the Higgs is sufficiently heavy for low $|\mu|$. In Fig 2a, the gap at $m_{1/2} \sim 85\,\mathrm{GeV}$ is due to the presence of a Higgs pole in the neutralino annihation cross-section. Similarly the gaps at $m_{1/2} \sim 95\,\mathrm{GeV}$ and $m_{1/2} \sim 115\,\mathrm{GeV}$ are due to the presence of a Higgs and Z^0 pole respectively in Fig. 3a. For $\tan\beta = 35$, no additional

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[7] Moreover, this higgsino region is not accessible if dynamical EWSB is implemented with universal input parameters, as discussed below.

limit is obtained by combining the Higgs and cosmological constraints.

Of course an alternate way of satisfying the Higgs bound is to take m_0 very large, rather than μ: taking μ sufficiently small then yields again a mixed neutralino for which the upper limit of (1) is easily satisfied. The dashed curves thus bend back to the left at very large m_0 and strike the chargino bound. This intersection occurs at values of m_0 well above the range plotted: for $\mu < 0$ this occurs at $m_0 \sim 700\,\mathrm{GeV}$ for $\tan\beta = 2$, and at $m_0 \sim 2\,\mathrm{TeV}$ for $\tan\beta = \sqrt{2}$. For $\mu < 0$, and for low $\tan\beta$, these large values of m_0 permit the lowest values of $m_{1/2}$ and the lightest neutralinos. In Fig. 1, the branch labelled "C" is the lower bound on m_χ coming from combining the LEP experimental limits with the cosmological constraint $\Omega_\chi h^2 < 0.3$. Comparing curves H and C in Fig. 1, we see that the additional cosmological constraint is in this case only relevant for low $\tan\beta$. The difference in bounds is due to the requirement that μ be sufficiently small to yield a mixed neutralino. If one were to require that $m_0 < 500\,\mathrm{GeV}$, the cosmological constraint would yield much tighter bounds on m_χ at low $\tan\beta$. For $\mu > 0$, a $|\mu|$ sufficiently small to yield a mixed neutralino also gives a small chargino mass, and in contrast to the $\mu < 0$ case, the lowest neutralino masses at low $\tan\beta$ come from the corner between the Higgs bound and the $\Omega_\chi h^2 = 0.3$ contour visible on Fig. 3a. This explains why branch C is significantly higher in Fig. 1b than in Fig. 1a at low $\tan\beta$.

5 Implications of Universal Masses for Higgs Scalars

We now supplement the above experimental and cosmological considerations by extending the theoretical assumption of GUT-scale universality for the input scalar soft supersymmetry-breaking masses to those in the Higgs sector. In this case, renormalization-group calculations leading to dynamical EWSB with the correct Higgs vacuum expectation values fix the previously undetermined parameters $|\mu|$ and m_A, for any given choice of values of $m_0, m_{1/2}$ [8]. These restrictions have the effect of further strengthening the above lower limits on m_χ. First, one is no longer permitted to vary μ to find the lowest possible rates of chargino and selectron production, so that the boundary of the previous hatched LEP exclusion domain in Figs. 2 and 3 is moved to the right, as shown. This change is least important for intermediate values of $\tan\beta \sim 3$, but always tends to fill in the previously re-entrant portion of the LEP region.

The most dramatic effect of the scalar-mass universality assumption appears when it is

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[8] The assumed values of other MSSM model parameters such as the trilinear soft supersymmetry-breaking parameters A are not essential for this argument. In order to implement dynamical EWSB down to the smallest possible value of $\tan\beta \sim 1.2$ as seen in Fig. 1, for this analysis we allow the top mass to be as low as 161 GeV.

implemented for the limits coming from the searches for Higgs bosons. It both constrains the renormalization-group-improved calculation of m_h and enables the hA search to come into play. The former effect causes the hZ search to provide a very important lower limit on $m_{1/2}$, particularly for small tanβ. This effect is so significant for tan$\beta = \sqrt{2}$ that for $\mu < 0$ it requires $m_{1/2} \gtrsim 1$ TeV, far to the right of the corresponding panel in Fig. 2c. The Higgs lower bound with universal input scalar masses is visible in the tan$\beta = 2$ panel of Figs. 2 and 3 labelled "UHM" (for universal Higgs mass). For $\mu < 0$ it becomes of comparable significance to the other bounds when $\tan\beta \sim 3$, and for slightly smaller $\tan\beta$ when $\mu > 0$. The second constraint due to the fixing of m_A becomes significant for large values of tan$\beta \gtrsim 35$, which is of relevance to models in which Yukawa couplings are also assumed to be universal. All of the Higgs bounds bend to the left at sufficiently large m_0. For example, the Higgs curve in Fig. 2b strikes the chargino bound at $m_0 \gtrsim 800\,$GeV. Thus in the absence of an independent constraint on m_0 (see below), the Higgs bound at low $\tan\beta$ is effectively the chargino bound at large m_0. The resulting strengthened lower bound on m_χ is shown as the thin solid line labelled "UHM" in Fig. 1.

6 Combining Cosmology and Universality

After applying separately the cosmological and universality constraints in the two previous sections, we now apply them both simultaneously. A first comment is that higgsino dark matter is not compatible with scalar-mass universality, since dynamical EWSB then fixes $|\mu|$ so that the lightest neutralino is in the gaugino region. The dark shading in Figs. 2 and 3 delimits the region in which the neutralino relic density satisfies (1), and we see that the universality assumption restricts significantly the region of the $m_{1/2}, m_0$ plane in which the relic density lies within the favoured range. Indeed, for tan$\beta = 35$, the favoured region lies at larger values of $m_{1/2}$ not shown. One sees the effects of enhanced annihilation rates through adjacent Higgs and Z poles, which create low-density channels through, and distortions of, the favoured dark-shaded region. In Fig. 2 these are shown in their entirety, but for reasons of clarity in Fig. 3 they are shown only in the regions not already excluded by LEP.

In Fig. 1, the thick branch of the solid UHM line labelled "cosmo + UHM" describes the improvement to the universal scalar mass m_χ bound at low $\tan\beta$ due to the true cosmological constraint $\Omega_\chi h^2 < 0.3$. The thick branch of the solid line labelled "DM + UHM" shows the improvement at high $\tan\beta$ from including the preference that $\Omega_\chi h^2 > 0.1$. The latter provides a significant improvement in the bound, amounting to almost a factor of two at high $\tan\beta$ over the solid grey m_χ bound from the previous section. As in [6, 9], the kink around $\tan\beta \gtrsim 3$ and the tight constraint on m_χ at large $\tan\beta$ for $\mu > 0$ arise from the necessity of being to the right side of the Z pole in order to have a sufficiently high relic density compatible with (1).

Perhaps the most dramatic impact, however, is seen at low $\tan\beta$, where we have already noted that the LEP Higgs constraint imposes a very strong constraint on the $(m_{1/2}, m_0)$ plane if universal scalar masses are assumed. The cosmological bound on the sfermion masses now forbids the large values of m_0 which previously permitted low $m_{1/2}$, and consequently relatively low m_χ, at low $\tan\beta$. As noted above, the Higgs exclusion curve moves rapidly to larger $m_{1/2}$ as $\tan\beta$ is decreased, and the improvement in the m_χ bound at low $\tan\beta$ is commensurately rapid. This explains the different analytic forms of the constraints on m_χ for $\tan\beta \lesssim 2.6$ for $\mu < 0$ and $\tan\beta \lesssim 1.8$ for $\mu > 0$.

This is particularly important because there is an *upper* bound on the value of $m_{1/2}$ for which the cosmological relic density of neutralinos can be kept within the cosmologically interesting range (1) [23], if the universality assumption is extended to Higgs mass parameters, which implies that the lightest neutralino is gaugino-like [9]. As shown in Fig 3(c), for low enough $\tan\beta$, the Higgs bound moves entirely to the right of the dark-shaded region, and for $\mu < 0$, the cosmologically allowed range with $\Omega_\chi h^2 < 0.3$ is actually *incompatible* with the Higgs lower limit on $m_{1/2}$ for $\tan\beta \lesssim 1.7$. This cosmological upper bound on $m_{1/2}$ varies only weakly for $\tan\beta \lesssim 2$. We conclude that there is no range of $m_{1/2}$ compatible with all the constraints provided by the LEP experiments, the upper bound on the cosmological relic density, and the theoretical assumption of scalar-mass universality, for sufficiently small $\tan\beta \lesssim 1.7$. Hence, *there is a lower bound*

$$\tan\beta \gtrsim 1.7 \tag{3}$$

if all these constraints are applied simultaneously. Similarly, for $\mu > 0$, the bound is $\tan\beta \gtrsim 1.4$.

We emphasize that this bound comes from merely imposing an upper bound on the relic density, which is simply due to the lower limit on the age of the universe of 12 Gyr: the constraint (3) does *not* require that $\Omega_\chi h^2 > 0.1$. We also note that, due to the sensitivity to $\tan\beta$ of the Higgs bound on $m_{1/2}$, this bound is quite robust. The dependence of the bound (3) on such input parameters as $A_t(M_X)$ and m_t, as well as any residual uncertainty in the extraction of the Higgs mass, can be parameterized in terms of their effect on m_h: any change which produces a 1 GeV increase in the Higgs mass will decrease the bound (3)

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[9] We emphasize that this bound does not apply to the higgsino-like case, which is possible if Higgs universality is relaxed: see for example [24].

on $\tan\beta$ only by roughly 0.01. As dicussed in Section 3, the value of $A_t(M_Z)$ is relatively insensitive to $A_t(M_X)$, particularly at low $\tan\beta$, where the top Yukawa becomes quite large as it is run to M_X. Therefore the uncertainty in m_h near the limit (3) due to changes in $A_t(M_X)$ is negligible, though the radiative corrections to m_h do increase with m_t. However, for m_t too large, the running of the top Yukawa becomes non-perturbative below M_X. The upper limit this imposes on m_t decreases as $\tan\beta$ becomes small, and at low $\tan\beta$ (i.e., near the bound (3)) we use the largest $m_t \sim 161$ GeV for which the running of the top Yukawa remains perturbative up to M_X. Therefore variations in m_t will not decrease the bound (3), although they can increase it for smaller m_t.

7 Conclusions and Prospects

We have seen in this paper how the recent higher-energy LEP 2 data [10, 11] impose interesting new constraints on the parameter space of the MSSM, in particular on the mass of the lightest neutralino χ, assuming that it is stable. Direct searches indicate that $m_\chi \gtrsim 17$ GeV, and exclude a large fraction of the domain of MSSM parameter space where the lightest neutralino is Higgsino-like [10]. The absolute lower bound on m_χ is increased to 40 GeV if it is assumed that all the soft supersymmetry-breaking scalar (slepton, squark and Higgs) masses are universal at some GUT input scale, and that the relic neutralino density fall within the range (1). Moreover, these assumptions are incompatible with the LEP 2 limits unless $\tan\beta \gtrsim 1.7$ for $\mu < 0$.

In addition to their implications for dark matter detection strategies, the LEP 2 limits are beginning to raise questions for supersymmetric model builders. Models which incorporate Yukawa unification as well as the the universal scalar masses invoked here tend to favour values of $\tan\beta \sim 1.8$ or 56 [see [12] and references therein]. The former option is already strongly constrained by LEP 2, and would become untenable if the further upgrades of the LEP energy that are foreseen fail to reveal a supersymmetric Higgs boson. The combination of this with other LEP 2 searches would have sensitivity to $\tan\beta \lesssim 3$ for $\mu < 0$. Thus model-builders may soon have to envisage the relaxation of at least one of the GUT universality and unification assumptions that are conventionally made in constraining the parameters of the MSSM [8].

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[10] As already noted, future LEP 2 runs should determine the fate of this option.

Acknowledgments

J.E. would like to thank the University of Minnesota for kind hospitality while parts of this work were being done. M.S. is grateful for the use of codes written by Gerardo Ganis. This work was supported in part by DOE grant DE–FG02–94ER–40823.

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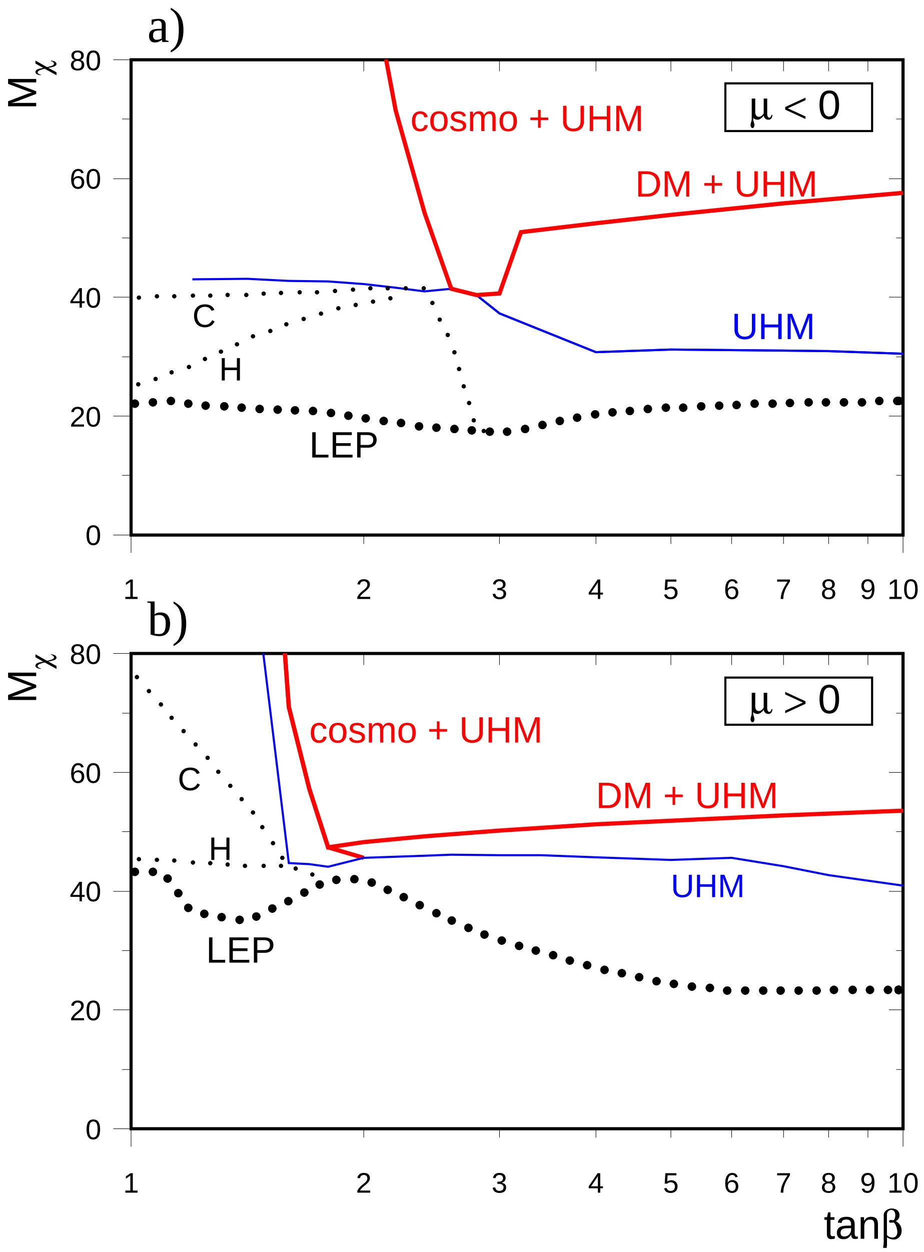

Figure 1: Various lower limits on m_χ (in GeV) obtained using different experimental and theoretical inputs are compared, as functions of $\tan\beta$, for both (a) $\mu < 0$ and (b) $\mu > 0$. The dotted lines labelled "LEP" are obtained by combining the unsuccessful LEP 2 searches for charginos and selectrons, allowing μ to vary over the range allowed by the bounds on A_t discussed in the text. The dotted branches labelled "H" and "C" additionally incorporate the requirements that lightest neutral supersymmetric Higgs boson not be seen at LEP, and also the relic cosmological density $\Omega_\chi h^2 < 0.3$, respectively. The solid lines are bounds incorporating the theoretical assumption of universal scalar masses as GUT inputs into dynamical calculations of the electroweak symmetry-breaking scale. The solid lines include the LEP experimental searches for charginos, selectrons and Higgs bosons, with the branches "cosmo + UHM" and "DM + UHM" incorporating the constraints $\Omega_\chi h^2 < 0.3$ and $0.1 < \Omega_\chi h^2 < 0.3$, respectively.

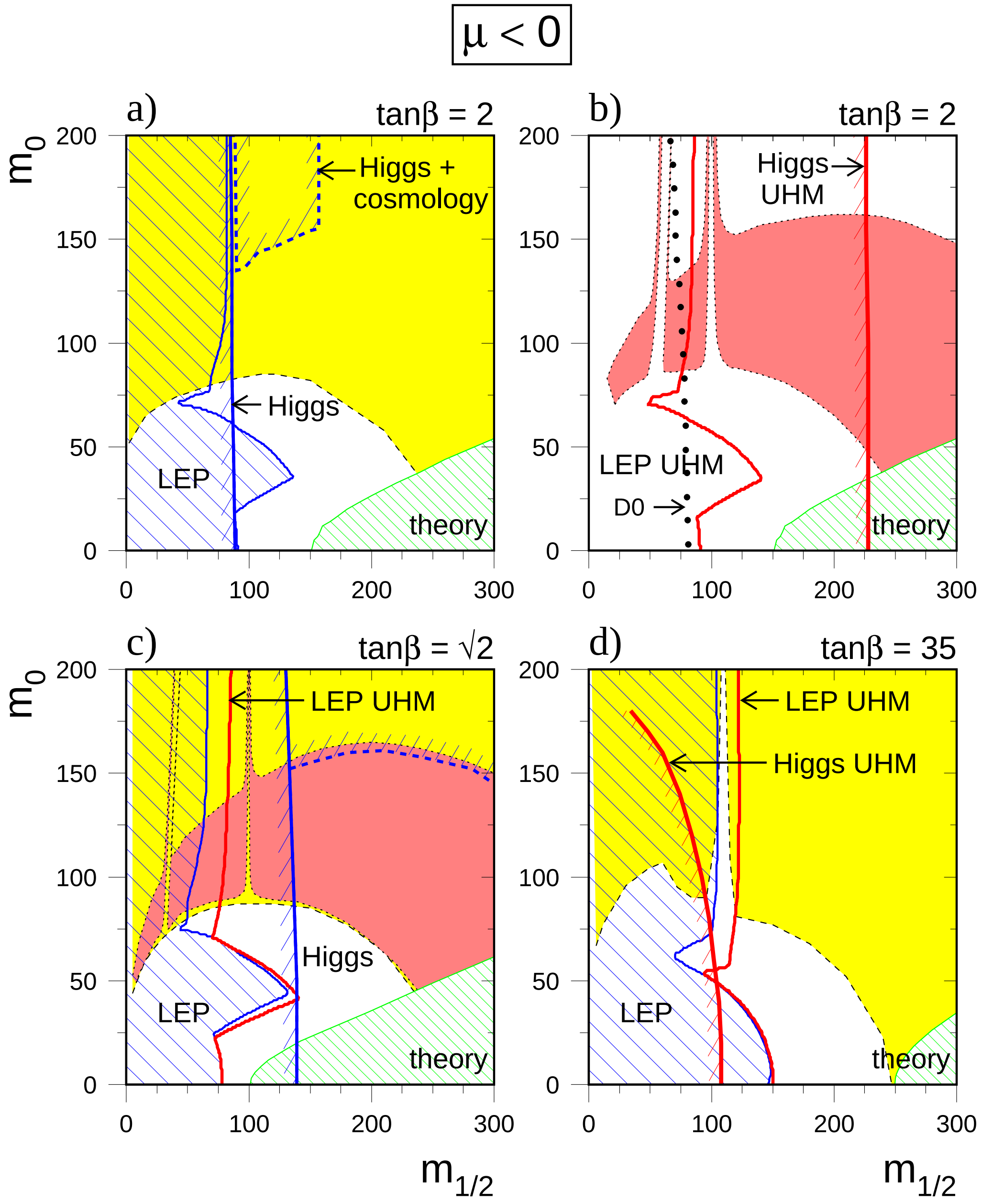

Figure 2: We display for $\mu < 0$ and (a,b) $\tan\beta = 2$, (c) $\sqrt{2}$, (d) 35, the domains of the $(m_{1/2}, m_0)$ plane (in GeV) that are excluded by the LEP 2 chargino and selectron searches, both without (hatched) and with the assumption of Higgs scalar-mass universality. We also display the domains that are excluded by Higgs searches (solid lines) without (a,c) and with (b,d) the assumption of universal scalar masses for Higgs bosons (UHM). Also shown are the regions that are excluded cosmologically because $m_{\tilde{\tau}_R} < m_\chi$, and the domains that have relic neutralino densities in the favoured range (1) with (dark) and without (light shaded) the scalar-mass universality assumption. For clarity, for the case $\tan\beta = 2$ we display separately the bounds without and with the assumption of Higgs scalar-mass universality in Figs. 2b and 2c respectively.

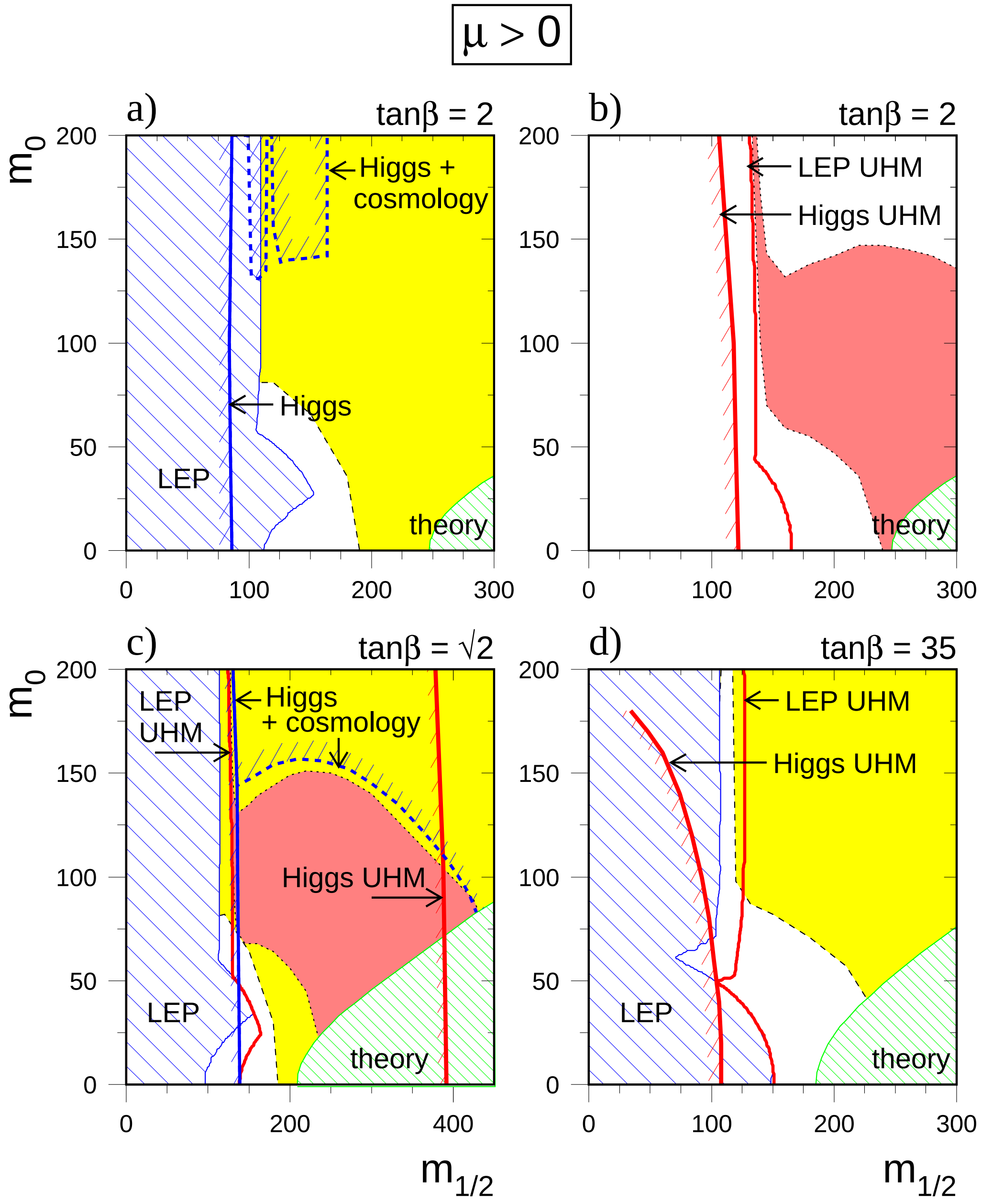

Figure 3: As Fig. 2, but for $\mu > 0$, and with the cosmological density contours suppressed in the domains excluded by LEP 2 searches. Note the different horizontal scale in panel (c), chosen to exhibit the cosmological upper limit on $m_{1/2}$ and its interplay with the assumption of universal scalar masses for Higgs bosons (UHM).