

Supersymmetric Dark Matter - How Light Can the LSP Be?

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Abstract

Using a very minimal set of theoretical assumptions we derive a lower limit on the LSP mass in the MSSM. We only require that the LSP be the lightest neutralino, that it be responsible for the observed relic density and that the MSSM spectrum respect the LEP2 limits. We explicitly do not require any further knowledge about the MSSM spectrum or the mechanism of supersymmetry breaking. Under these assumptions we determine a firm lower limit on the neutralino LSP mass of 18 GeV. We estimate the effect of improved limits on the cold dark matter relic density as well as the effects of improved LEP2-type limits from a first stage of TESLA on the allowed range of neutralino LSP masses.

I. INTRODUCTION

One of the most puzzling experimental observations in astrophysics has for a long time been the dominance of the invisible cold dark matter in the universe. Experiments measuring the cosmic microwave background [1], high red-shift supernovae [2], galactic clusters and galactic rotation curves [3] have found that the matter density of the universe is $\Omega_M \simeq 0.3-0.4$. In contrast, constraints from big-bang nucleosynthesis indicate that the baryonic matter density must be well below this number [4]. Last but not least, the observed density of luminous matter is very small, $\Omega_L < 0.01$ [5]. Therefore, the vast majority of the mass in the universe is dark. In addition, cosmic microwave background studies and large scale structure formation requires that the majority of the dark matter be cold (non-relativistic) [1,6].

Starting from a completely different set of experiments and looking at collider-oriented high energy physics, the challenge for the next generation of experiments is to understand how electroweak symmetry is broken and masses are generated. Electroweak precision studies [7] clearly point into the direction of spontaneous electroweak symmetry breaking — a mechanism which creates masses for fermions and gauge bosons but which also automatically yields a scalar Higgs boson. Furthermore, precision experiments prefer a light Higgs boson with a mass below ~ 250 GeV. Unfortunately, the mass of a light Higgs boson in the Standard Model is not stable in perturbation theory, but this mass hierarchy problem can be naturally solved by adding supersymmetry to the gauge symmetries on which the Standard Model is based. We emphasize that supersymmetry does not accidentally cancel the divergences in the Higgs boson mass nor does it have a complicated array of mechanisms to get rid of them. The hierarchy problem is solved by the most basic idea of a supersymmetry between fermionic and bosonic fields [8].

The most general supersymmetric Lagrangean, however, induces flavor-changing neutral interactions which are experimentally very well constrained [9]. The simplest way to avoid these constraints is an exact or approximate R symmetry which translates into the conservation of a supersymmetric spectrum quantum number [10]. Although being inspired by flavor physics constraints, this R symmetry has a huge impact on astrophysics: it leads to the existence of a stable lightest supersymmetric particle (LSP). One possible experimental signature of LSPs with masses of the order of the weak scale could be the measured amount of cold dark matter. Which MSSM particle the LSP is depends on the model parameters. Again there might be other theories with a discrete symmetry which for that very reason lead to cold dark matter [11]. However, in the MSSM the existence of the LSP is not at all ad-hoc but the natural consequence of flavor physics constraints.

II. SUPERSYMMETRIC DARK MATTER

If supersymmetry is to provide us with a suitable dark matter candidate, we can say some things about the nature of the LSP. First, it must be colorless and neutral to avoid observation [12]. Although it may be possible for a colored or charged particle to form bound states with Standard Model particles, searches for exotic isotopes have ruled out exotic charged bound states over a large mass range [13]. Neutral exotic bound states, consisting of squarks or gluons and Standard Model particles, could possibly evade this type of detection, but would also need to be very heavy or be carefully designed to evade collider searches. On the other hand these collider searches usually assume that these strongly interacting superpartners decay to a weakly interacting LSP [14,15].

A second class of constraints on a SUSY dark matter candidate comes from the limits placed by direct elastic scattering experiments. Sneutrinos with relatively large elastic scattering cross sections can be probed by these experiments. By now, all of sneutrino LSP parameter space has been ruled out by direct and indirect searches [16].

This leaves the lightest neutralino as the neutral and colorless SUSY dark matter candidate [17]. Generally, it has a small enough elastic scattering cross section to be missed by experimental searches. Moreover, the mass and annihilation cross section for a neutralino LSP lie naturally in a region which yields a thermal dark matter relic density in agreement with observation. In these LSP annihilation processes light superpartners, such as scalar tau leptons, play an important role as t channel propagators. We calculate the neutralino LSP relic density using the full cross section, including all resonances and thresholds, and solving the Boltzmann equation numerically [18,19]. The issue of neutralino co-annihilation with other light superpartners will be discussed in detail later in this letter.

III. THEORETICAL ASSUMPTIONS

Of all supersymmetric parameters, the mass difference between the LSP and heavier MSSM states has a particularly crucial impact on collider searches at hadron colliders as well as at TESLA. The question we attempt to answer in this paper is straightforward: how light can the LSP be assuming nothing about the unknown SUSY breaking mechanism?

A huge number of constraints on the MSSM spectrum have been accumulated over the last years. Using these constraints, observables like the light Higgs boson mass, the LEP limits on chargino and slepton masses, the squark and gluino mass limits from the Tevatron and flavor physics constraints like the $b \rightarrow s\gamma$ rate can be translated into limits on the LSP mass. However, all of these links rely on theoretical

assumptions, usually on the assumption of unified Majorana fermion or scalar masses at some GUT scale, as it is suggested by the gauge coupling unification [20,21]. A very instructive discussion of these issues can be found, for example, in Ref. [22]. More recently, some effort has been put into the effect which breaking the weak gaugino mass and the gluino mass unification can have on the detection of supersymmetric dark matter [23]. Speculative relations between MSSM parameters can for example stem from the attempt to link features of an unknown underlying string theory to the current experimental results [24]. Top-down approaches to the MSSM spectrum can only be a first step to understand the interplay between different assumptions and observables. For example the effect of non-universal Higgs masses should be and has been explored in detail [25]. A preliminary scan over the supersymmetric parameter space including non-universal gaugino masses can be found in Ref. [26], and a more complete analysis seems to produce similar results to the ones we will show in this letter [28]. In general less model-dependent analyses become increasingly promising the more hard data becomes available [22].

In the setup of our analysis we try to minimize the effects of MSSM model building. Instead we start from a completely general non-unified MSSM spectrum only assuming R parity, since without R parity the LSP as a cold dark matter candidate ceases to exist. The LSP we assume to be the lightest neutralino $\tilde{\chi}_1^0$. On top of that we only assume a very minimal set of general LEP2 limits for charginos, sleptons and sneutrinos, and the measured relic density $0.05 < \Omega_\chi h^2 < 0.3$. We note, however, that the assumption of a general LEP2 mass limit implicitly assumes an $SU(2)$ relation between the mass of the left handed slepton and the sneutrino in each generation. We do not consider the possible effects of complex soft supersymmetry breaking terms [27].

IV. EXPERIMENTAL LIMITS

The present density of dark matter has been measured to be $\Omega_{\text{CDM}} h^2 = 0.12 \pm 0.04$ [29]. This result is the combination of data from measurements of the cosmic microwave background, type Ia supernova red-shifts, 2dFGRS and SDSS galaxy red-shifts and data from the Hubble Space Telescope. In order to provide a suitable dark matter candidate, a set of SUSY parameters must yield an LSP with a relic density similar to these observations. We will, however, consider models in which somewhat larger or smaller densities ($0.05 < \Omega_{\text{CDM}} h^2 < 0.30$) are produced, acknowledging the possibility that one or more of the pieces of the contributing cosmological evidence is not fully understood theoretically [30].

Since in this letter we want to determine an as general as possible limit on the neutralino LSP mass, we limit ourselves to a few experimental results which have turned out to be particularly hard to circumvent. The single most limiting collider result is probably the LEP2 search for supersymmetric particles such as charginos and sleptons [31,32]. It would be far beyond the scope of this letter to discuss in detail all LEP2 limits. Instead we require all scalar leptons and charginos to be heavier than 103 GeV. For particles which decay to leptons and the neutralino LSP this is a direct experimental bound, while for sneutrinos in most cases it requires a very basic $SU(2)$ symmetry between the supersymmetry breaking masses of the left handed slepton and the sneutrino of one lepton flavor. The effect of slightly reduced mass limits (for example from background effects at LEP which might push the mass limits below the kinematic boundary) will be discussed later and the numerical impact can easily be determined. Specific properties of the MSSM spectrum are claimed to have significant effects on the mass limits and we discuss them in greater detail in Section VI. Generally, the LEP2 limits become even harder to circumvent for a very light neutralino LSP

which is what we require in the following analysis¹.

Since the question how light the LSP can actually be does not directly depend on the squark and gluino masses, we decouple these particles and avoid their, in principle, very powerful mass limits [14,15]. This choice of heavy squark masses also means that stop–neutralino co-annihilation can be neglected in our analysis [33]. We also decouple the charged Higgs boson and essentially avoid the $b \rightarrow s\gamma$ constraints (which we still check for all our parameter points) [34,35]. Generally, these additional parameters will not have a major direct impact on the minimum LSP mass in a general non-unified MSSM. However it has been shown that the impact through further theoretical assumptions on the MSSM spectrum can be very significant, in particular once the mass spectrum includes mass degeneracies.

For light neutralinos, in particular, the limit on the invisible Z decay width can become important. We require that Z decays to neutralino LSPs contribute less than one standard deviation to the measured neutrino contribution, which agrees with the Standard Model prediction, *i.e.* $\Gamma_{Z \rightarrow \chi\chi} < 4.2$ MeV. This invisible width limit has a major impact on another additional LEP2 search channel: the single photon production. The Standard Model background process is $e^+e^- \rightarrow Z^{(*)} \rightarrow \nu\nu$ with an additional photon radiated off the initial state. The total cross section for the production of $Z\gamma$ at LEP2 is less than 31 pb for a minimum 1 GeV transverse momentum cut on the photon. The supersymmetric signal process is the production of two lightest neutralinos and an additional photon, which can be radiated off the incoming electrons or the t channel selectron. For light Higgsinos, the dominating process is again $Z\gamma$ production, but with a decay of the Z to neutralinos. Hence the upper limit on the invisible Z decay width translates into a suppression factor, $S/B < 8 \cdot 10^{-3}$, which does not allow for a significant signal at LEP2. Any additional initial state radiation tends to lead to a far forward photon and we have checked that it will not increase this approximate result by more than a factor of two. The situation is different for light gauginos, in which case the dominating diagram is photon radiation off the t channel selectron. We checked typical parameter points from our analysis assuming that the selectron be heavier than 103 GeV and we find cross sections below 0.13 pb. This translates into $S/B < 0.02$ or $S/\sqrt{B} < 0.9$ before cuts and for irreducible backgrounds only. We therefore conclude that the single photon channel does not pose any obvious limits on the parameter points we find in our analysis. The bottom line that there are no experimental limits on the neutralino LSP mass without any additional constraints is in agreement with a more complete analysis presented in the context of the KARMEN time anomaly [36].

As described in Section II and as we will also see in our analysis later, the limit on the neutralino LSP mass does only mildly depend on the selectron mass value. In contrast a large selectron mass alone could lead to a decoupling of the single photon signature. We emphasize that in our analysis we do not decouple the selectrons to respect the current experimental limits on single photon production. All our parameter points even with a low selectron mass automatically obey the LEP2 limits.

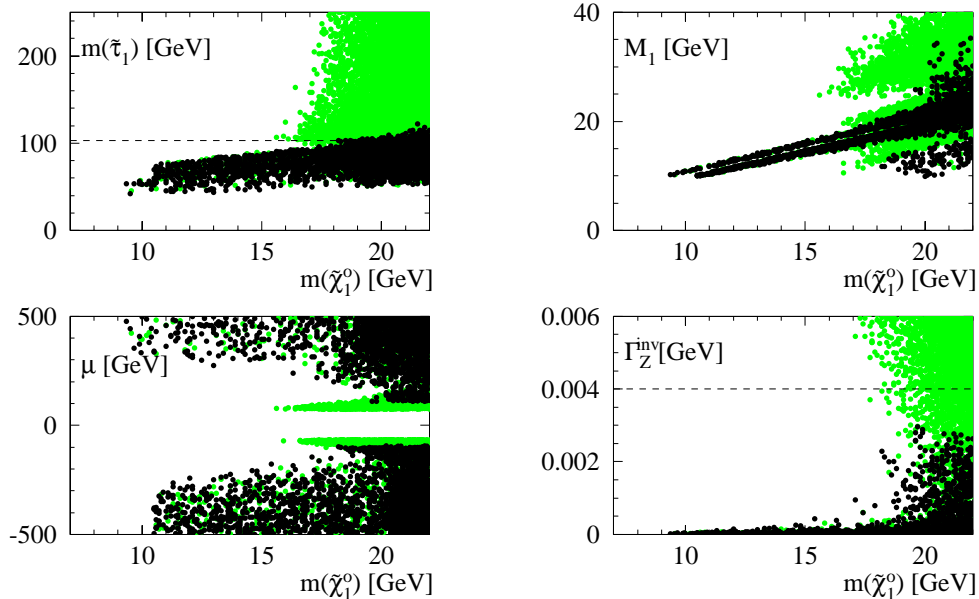


Figure 1. The MSSM data points with the neutralino LSP mass on one axis. The other axis' in the four panels show the lightest slepton mass, the bino mass parameter M_1 , the Higgsino mass parameter μ and the contribution of the decay $Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ to the invisible Z decay width. The color coding corresponds to the light chargino mass with only the black points respecting $m_{\tilde{\chi}_1^+} > 103$ GeV. The dashed lines are the assumed experimental limits. Note that in contrast to the black points, not all of the green (grey) points with too small chargino masses are included in the frames. Moreover the black points might hide green (grey) points below them.

V. SUPERSYMMETRIC PARAMETER SPACE

To probe the supersymmetric parameter space, we use a Monte Carlo scan assuming that squarks, gluinos and heavy Higgs bosons are decoupled with masses of 1 TeV. We scan over the relevant neutralino mass parameters $M_2 = 50$ to 500 GeV, $|\mu| = 50$ to 500 GeV and $M_1 = 10$ to 40 GeV. Moreover we scan over a slepton mass parameter from 100 GeV to 250 GeV. As we will argue later in this section the most relevant parameter is the lightest slepton mass, *i.e.* the mass of the lighter stau $\tilde{\tau}_1$. We do scan over $\tan \beta$ but we do not find any dependence of the neutralino LSP mass on $\tan \beta$ after imposing all other constraints. Its impact on the light stau mass is washed out by the simultaneous scan over μ . Negative values of M_1 which are often ignored and which, for example, decouple neutralino mediated decays of sleptons or squarks [37], have no impact on our analysis. A second run was conducted with similar parameter ranges, but allowing M_1 as large as 60 GeV and the common slepton mass parameter as large as 400 GeV. This second set is used in Fig. 3. Last but not least, for all plots we add ~ 100 data points with slepton and chargino masses right at the LEP2 limits and very low neutralino LSP masses to model the envelope around

¹The reach of the scalar tau search at LEP should for example improve in a light LSP regime: for the decay $\tilde{\tau}_1 \tilde{\tau}_1^* \rightarrow \tau \bar{\tau} + \cancel{E}$ two light LSPs make it easier to distinguish the $2\tilde{\chi}_1^0 4\nu$ missing transverse momentum from the 4ν background. If we compare the signal to the chargino searches $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \ell \ell' + \cancel{E}$ we see that they are identical. The only complication would be the acceptance for low values of \cancel{E} which the light LSP will help to avoid.

the lowest allowed neutralino LSP masses. We emphasize that in all plotted parameter points, the strongly interacting MSSM partners are assumed to be heavy and all non-tau sleptons respect the LEP2 mass limit.

All points in the supersymmetric parameter space allowed by the relic density $\Omega_\chi h^2 = 0.05$ to 0.3 are given in Fig. 1. The green (grey) points have a too small light chargino mass $m_{\tilde{\chi}_1^+} < 103$ GeV while the black points obey the LEP2 limit $m_{\tilde{\chi}_1^+} > 103$ GeV. In the upper left panel of Fig. 1, we see the correlation between the light chargino and the lightest slepton mass: once the neutralino LSP becomes very light the relic density increases rapidly beyond the allowed limit $\Omega_\chi h^2 < 0.3$. The only way to reduce this relic density is the annihilation of two LSPs to leptons. The dominant diagram for the annihilation of gaugino LSPs is the t channel exchange of the lightest slepton (the lighter stau) in the process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tau\tau$. A too large $\tilde{\tau}_1$ mass will immediately lead to an over-closing of the universe. The effect of the stau mass limit is shown in Fig. 1. In our analysis, we generally assume that the lighter stau be the lightest scalar lepton. All arguments, however, translate trivially to any other lightest slepton case. The black points which respect the chargino mass limit clearly prefer a light stau, which is experimentally ruled out. Balancing the limit on the relic density with the stau mass limit gives a minimum LSP mass of $m_{\tilde{\chi}_1^0} \lesssim 18$ GeV. For a fixed chargino mass limit the effect of a relaxed stau mass limit can also be read off this figure: for example a reduced mass limit $m_{\tilde{\tau}_1} > 80$ GeV already allows an LSP mass of ~ 10 GeV.

The only way to avoid the correlation described above would be a Higgsino LSP which can annihilate through an s channel Z boson. The next two panels however show how it is the bino mass parameter M_1 which drives the LSP mass to low values. In the third panel of Fig. 1, we do see two tails of light LSP masses at small $|\mu|$ values, which we deliberately limit to $|\mu| > 50$ GeV. The reason is that these point represent light Higgsino dark matter and are firmly ruled out by the chargino mass limit. The lower right panel of Fig. 1 shows how the chargino mass works together with the invisible Z width measurement: all black parameter points with sufficiently heavy charginos render a gaugino LSP which does not couple to the Z boson and, therefore, automatically avoids the invisible Z width bound. Once we move towards a lighter Higgsino LSP, the invisible Z decay limit is immediately violated. This shows how the LEP2 chargino mass limit, as well as the invisible Z width measurement, firmly rule out light dark matter with a non-negligible Higgsino content [38].

To illustrate the interplay between the chargino and the stau mass limits, we once more print all the points in Fig. 1, but with a different color coding: in Fig. 2 the black points obey the mass limit $m_{\tilde{\tau}_1} > 103$ GeV, all other points are printed in green (grey). As described above, a heavier stau leads to an over-closed universe, unless the LSP is a Higgsino. The behavior which can be seen in the left panel of Fig. 2 reflects the lower limit $|\mu| > 50$ GeV in our scan. The allowed black data points show a strong correlation of the gaugino LSP mass and the relic density, this time for a fixed limit of the light stau mass: the allowed relic density clearly determines the minimum LSP mass under the condition that the stau mass limit is not violated. Again, the way to obtain a light LSP is the admixture of Higgsino content, to couple to the s channel Z annihilation diagram. But then small LSP masses yield a small chargino mass, and in the right panel of Fig. 2 we again see the few points which respect both LEP2 mass limits and again find a minimum LSP mass $m_{\tilde{\chi}_1^0} \lesssim 18$ GeV. We also see how small LSP masses can be realized with very heavy chargino masses $m_{\tilde{\chi}_1^+} \gtrsim 300$ GeV. This seems to be a slight asymmetry between the chargino mass and the scalar tau mass dependence: since the $\tilde{\tau}_1$ mass directly enters the dominating neutralino LSP annihilation diagram, the relation of its mass with the neutralino LSP mass is very smooth, as can be seen in the first panel of Fig. 1. The chargino mass in contrast has to be heavier than a certain value for any given LSP mass but its actual allowed values are not strongly correlated with the neutralino LSP mass.

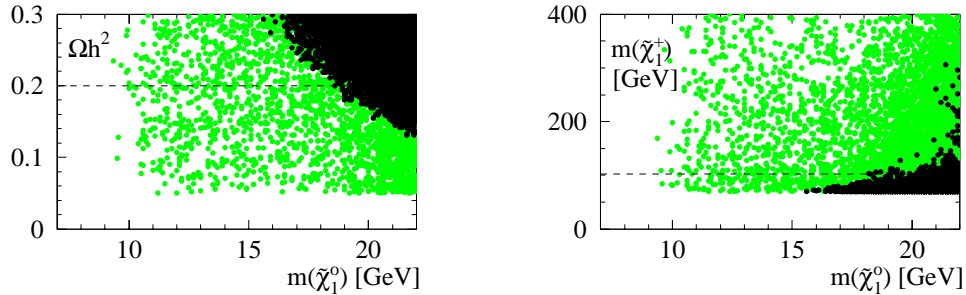


Figure 2. The MSSM data points with the neutralino LSP mass on one axis. The other axis' in the two panels show the LSP relic density and the lighter chargino mass. The color coding corresponds to the lighter stau mass with only the black points respecting $m_{\tilde{\tau}_1} > 103$ GeV. The dashed lines are the experimental limits on the chargino mass and a possible improved limit on the relic density. Note that in contrast to the black parameter points, not all of the green (grey) points with too small chargino masses are included in the frames. Moreover the black points might hide green (grey) points below them.

The only non-trivial assumption in the analysis presented above is the $SU(2)$ relation between the left handed slepton masses and the corresponding sneutrino mass. As always, we implicitly assume that the lighter stau be the lightest slepton, but it is obvious from the discussion above that for very small neutralino LSP masses, all slepton masses have to be right at the LEP limit of 103 GeV. Explicitly we first check what happens if only one lepton generation is available in the annihilation process, *i.e.* if, for example, the selectrons and smuons are completely decoupled: this decoupling changes the mass limit on the neutralino LSP from 18 GeV to 25 GeV, independent of which lepton generation is available. In contrast, the decoupling of all sneutrinos has no significant effect on the LSP mass limit. This can be understood by comparing the different couplings $\ell\tilde{\ell}\tilde{B}$ for left and right handed sleptons and for sneutrinos. The sneutrino coupling is indeed suppressed. As expected from this argument, limiting the neutralino LSP annihilation to sneutrino mediated processes only yields an increase in the mass limit from 18 GeV to 27 GeV. In this sense, a slight violation of the $SU(2)$ symmetry between the masses in one lepton generation, which can yield slightly lighter sneutrinos than the LEP2 mass bound of 103 GeV, would not significantly change the mass limit we obtain.

VI. CONSPIRACIES?

Going beyond the generic features described in Section V, there might be a way of avoiding the LEP limits on charginos and sleptons: if the LSP is only very few GeV lighter than the particle produced then the additional final state leptons become soft and the LSP becomes slow. We briefly comment on the effect of two possible mass degeneracies on our lower limit for the neutralino LSP mass:

First, the lighter chargino mass can be almost mass degenerate with the lightest neutralino. This leads to additional neutralino–chargino co-annihilation as a way to circumvent the impact of the slepton mass limits. One way to achieve this degeneracy is to have $|\mu|$ define both the lightest neutralino mass and the light chargino mass. However, in Section V we learned that we violate the invisible Z decay width measurement in the case of a light Higgsino LSP. Another way this same mass degeneracy occurs is for $M_2 \ll M_1, |\mu|$, *i.e.* for a dominantly wino light chargino and lightest neutralino. Moreover, it can once

more arise from a diagonal parameter choice $M_2 = M_1 \ll |\mu|$. The effects on the spectrum are identical: the light wino-type chargino decays into slowly moving leptons or quarks and the neutralino LSP.

If a Z boson decays into two charginos which are mass degenerate with the LSP, all decay products escape the detector unobserved and the process contributes to the invisible Z decay width. In the limit $m_{\tilde{\chi}_1^\pm} \ll m_Z$ and for a pure wino-type chargino we can link the partial decay width of the Z boson to the decay width to one generation of neutrinos $\Gamma(\tilde{\chi}_1^+ \tilde{\chi}_1^-) \sim 4.7 \Gamma_{\nu\nu}$. The crucial observation is that while the Z boson does not couple to the gaugino fraction in a pair of neutralinos, it does couple to the gaugino fraction in a chargino pair roughly with the same strength as it couples to the Higgsino fraction. The experimental limit on the invisible decay of a Z boson translates into $\Gamma_{\text{inv}} \lesssim \Gamma_{\nu\nu}/40$. The typical finite mass correction for a 18 GeV decay product is $\sqrt{1 - 4m^2/m_Z^2} \sim 0.9$ and will not yield the required suppression by a factor of 1/200. We can, therefore, safely assume that mass degenerate neutralinos and charginos can indeed escape detection for continuum production but not for Z decays. Their masses have to be above half of the Z boson mass and are not in the very light LSP regime which we are exploring.

The second type of mass degeneracy occurs between the neutralino LSP and the lighter stau. This allows a very efficient annihilation of LSPs and prevents the universe from over-closing, even for a very light gaugino LSP. Moreover, it allows neutralino–stau co-annihilation to reduce the relic density further [40]. As for the charginos it is not trivial to avoid the Z decay data, since the normalization of events is known, *i.e.* there is a limit on invisible decays. The typical slepton partial width in the light slepton approximation is $2(T_3 - Q_s^2)^2 \Gamma_{\nu\nu}$ for a left handed and $2(-Q_s^2)^2 \Gamma_{\nu\nu}$ for a right handed slepton. This is, again, too large to be hidden in the error on the invisible Z decay width. However, the stau is the lightest slepton just because it mixes the weak eigenstates into mass eigenstates and yields a light mass eigenstate $\tilde{\tau}_1$. This mixing can be used to decouple the $\tilde{\tau}_1$ from the Z boson, the same way that a light sbottom can avoid the Z decay limits [37]. The tree level coupling to the Z boson vanishes for a choice of the scalar mixing angle $\cos^2 \theta = Q/T_3 s_w^2$ which, in case of the stau, is $\theta_\tau \sim \pi/4$. This decoupling condition does not affect the LSP annihilation cross section and, therefore, it would be possible to have a very light neutralino and tau slepton and get the correct amount of gaugino dark matter. The only worry is how to get one very light tau slepton with a mass of less than 18 GeV and keep the second stau heavy. Mixed pairs $\tilde{\tau}_1 \tilde{\tau}_2$ can in that case be produced at LEP2 even if the heavier stau has a mass of up to ~ 180 GeV. This mixed production cross section is proportional to $\sin 2\theta_\tau$ and will not be suppressed around the decoupling point for the light stau $\theta_\tau \sim \pi/4$. At this point it is obvious that this kind of scenario is ruled out assuming any scalar mass unification, involving different flavor slepton masses, Higgs masses and squark masses. Moreover, it will have to be carefully checked that the large stau mass splitting does not violate the experimental limits on the rho parameter.

Going back to the starting point of this section, we want to stress that the statement that an almost mass degenerate stau-neutralino combination can escape the LEP2 trigger has to be carefully examined. Indeed the decay products, *i.e.* the leptons and the neutralino LSP, will not gain any momentum from the stau or chargino decay. However, the decaying particles, *i.e.* the stau or the chargino, are very light compared to the beam energy. They themselves will move through the central detector rapidly and in turn boost their decay products. While we are not aware of a detailed study of this part of supersymmetric parameter space and while we did, therefore, point out possible complications in this section we very much doubt that mass degeneracies could hide a light stau or chargino from the LEP2 experiments. To finally close this (non-existing) loop hole should be a simple exercise for these experiments.

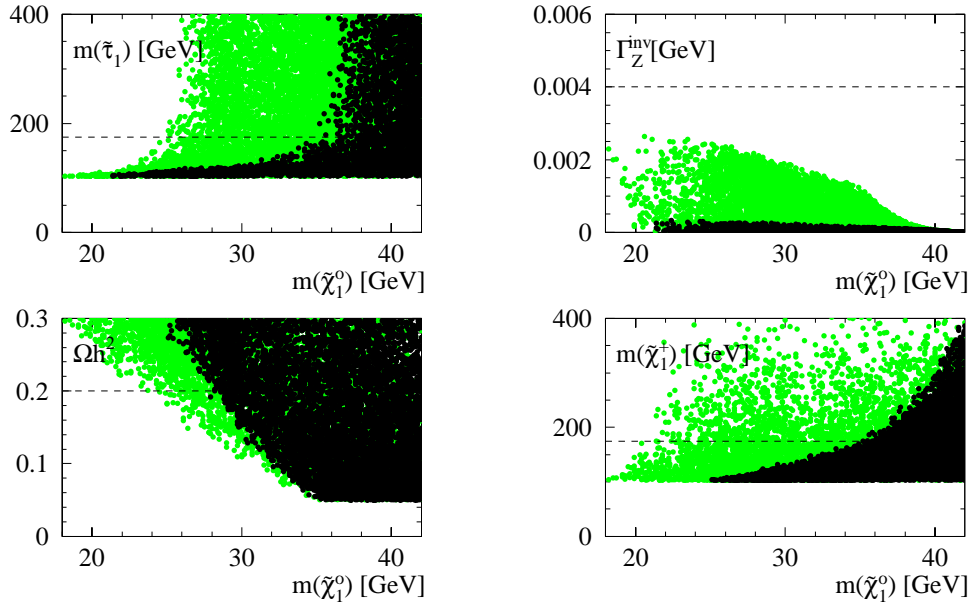


Figure 3. The MSSM data points with the neutralino LSP mass on one axis. All black and green (grey) parameter points respect the 103 GeV LEP limits as well as all other limits we impose. Upper row: versus the lightest slepton mass and versus the Z invisible decay width, like in Fig. 1. Here the color coding corresponds to the lightest chargino mass with the black points indicating $m_{\tilde{\chi}_1^+} > 175$ GeV. Lower row: versus the LSP relic density and versus the light chargino mass, like in Fig. 2. The color now coding corresponds to the lightest slepton mass with the black points indicating $m_{\tilde{\tau}_1} > 175$ GeV.

VII. OUTLOOK

Following the detailed discussion above, we emphasize that the neutralino LSP mass limit $m_{\tilde{\chi}_1^0} \gtrsim 18$ GeV is only possible because we have mass limits on charginos and all sleptons simultaneously. One of the two alone will not constrain the general MSSM parameter space. The kind of collider which seems to be designed to fulfill this task of multiple searches for new particles are e^+e^- colliders. The lead in this field has by now been changed from LEP2 to a linear collider [41]. The latter in a first stage could for example collect data at the top threshold. Assuming that this initial stage might not be sufficient to exploit the $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production channel and discover the lightest neutralino we estimate what a 175 GeV limit on charginos and sleptons would mean for the neutralino LSP mass. The results are depicted in Fig. 3. The upper row of plots is color coded the same way as Fig. 1: only the black points respect the mass limit for the lightest chargino $m_{\tilde{\chi}_1^+} > 175$ GeV. As expected the minimal possible neutralino LSP mass decreases once we enforce the stau mass limit $m_{\tilde{\tau}_1} > 175$ GeV, yielding a lower limit of $m_{\tilde{\chi}_1^0} > 35$ GeV. For this figure, we implicitly assume that the light stau be the lightest slepton. A minimum mass of 175 GeV, therefore, means that all other sleptons respect this mass limit as well. The invisible Z decay width does not have any impact on this result. The lower row of plots in Fig. 3 is color coded just like Fig. 2: only the black points respect the projected TESLA limit on the lightest slepton $m_{\tilde{\tau}_1} > 175$ GeV.

In the left panel of the lower row in Fig. 3 we also see the change of the allowed neutralino LSP mass e.g. if we require the relic density to be the central measured value $\Omega_{\text{CDM}}h^2 = 0.12 \pm 0.04$ [29]: no LSP masses below ~ 30 GeV are consistent with this central value and the 103 GeV LEP2 bounds. An upper limit of $\Omega_\chi h^2 < 0.2$ will automatically increase the lower LSP mass limit to $m_{\tilde{\chi}_1^0} > 25$ GeV.

In Summary we investigate how the LEP2 limits narrow the allowed range of the mass of a neutralino LSP in a general R parity conserving MSSM. These LEP2 mass limits have to be respected by all scalar leptons including all sneutrinos and by the charginos. The only assumption we use is that the LSP be responsible for the observed dark matter density. Under these assumptions the absolute lower limit on the neutralino LSP mass is $m_{\tilde{\chi}_1^0} > 18$ GeV. The lowest values for the LSP mass require all sleptons and the chargino to be just above the LEP2 limit of 103 GeV and yield an allowed relic density at the upper boundary of $\Omega_\chi h^2 \sim 0.3$.

Note added: after this paper had appeared as a preprint a similar analysis was published, which pointed out that small neutralino LSP masses are allowed for strongly mixed gaugino–Higgsino neutralinos [42]. The annihilation of these LSPs has to mainly proceed through a light pseudoscalar Higgs boson A in the s channel. To not over-close the universe the pseudoscalar Higgs boson mass has to be light, sitting in an allowed corner of the MSSM parameter space with $m_A \sim 90$ GeV and $m_h \sim 90$ GeV for the light scalar Higgs boson mass [43]. The main constraint on this kind of models then becomes the invisible Z decay width and even more importantly the $b \rightarrow s\gamma$. We point out that after including all constraints we do find smaller LSP masses when fixing $m_A = 90$ GeV and scanning over the MSSM parameter space. For a fixed value $m_A = 110$ GeV there still remain a few parameter points with an allowed LSP mass between 16 and 17 GeV, while for $m_A \gtrsim 130$ GeV the LSP annihilation through the s channel pseudoscalar is not efficient enough to impact the results described in this letter.

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