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Limits on the masses of Supersymmetric Particles at $\sqrt{s}$ =189 GeV

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Abstract

Searches for charginos, neutralinos and sleptons at LEP2 centre-of-mass energies from 130 GeV to 189 GeV have been used to set lower limits on the mass of the Lightest Supersymmetric Particle and other supersymmetric particles within the MSSM framework. R-parity conservation has been assumed. The lightest neutralino was found to be heavier than 32.3 GeV/c^2 independent of the m_0 value. The lightest chargino, the second-to-lightest neutralino, the sneutrino and the right-handed selectron were found to be heavier than 62.4 GeV/c^2, 62.4 GeV/c^2, 61.0 GeV/c^2, and 87.0 GeV/c^2, respectively. These limits do not depend on m_0 or M_2 and are valid for $1 \leq \tan\beta \leq 40$, in the μ region where the lightest neutralino is the LSP. If the sneutrino is heavier than the chargino the lightest neutralino has to be heavier than 32.4 GeV/c^2. The effects of mixings in the third family of sfermions on these limits are discussed. The confidence level of all limits given is 95%.

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1 Introduction

In 1998 the LEP centre-of-mass energy reached 188.7 GeV, and the DELPHI experiment collected an integrated luminosity of 158 pb^{-1}. These data have been analysed to search for the particles predicted by supersymmetric (SUSY) models [1]: sfermions, charginos and neutralinos.

In this paper we interpret results of the searches presented in Refs. [2, 3, 4, 5, 6, 7, 8, 9, 10, 11] to constrain the masses of the supersymmetric particles: the lightest neutralino ($\tilde{\chi}^0_1$), the lightest chargino ($\tilde{\chi}^\pm_1$), the next-to-lightest neutralino ($\tilde{\chi}^0_2$), the sneutrino ($\tilde{\nu}$), the selectron ($\tilde{\mathrm{e}}$), and the stau ($\tilde{\tau}$). The lightest neutralino is assumed to be the Lightest Supersymmetric Particle (LSP). The conservation of R-parity, implying a stable LSP, is assumed. The stable neutralino is a good dark matter candidate and its mass is of importance in cosmology.

The Minimal Supersymmetric Standard Model (MSSM) scheme with gravity mediated supersymmetry breaking and with universal parameters at the high mass scale typical of Grand Unified Theories (GUT's) is assumed [1]. The parameters of this model relevant to the present analysis are the masses M_1 and M_2 of the gaugino sector (which are assumed to satisfy the GUT relation $M_1 = \frac{5}{3}\tan^2\theta_W M_2 \approx 0.5 M_2$ at the electroweak scale), the universal mass m_0 of the scalar fermion sector, the trilinear couplings A_τ, A_b, A_t determining the mass mixing in the third family of sfermions, the Higgs mass parameter μ and the ratio $\tan\beta$ of vacuum expectation values of the two Higgs doublets. The model assumed here is slightly more general than the minimal Super Gravity (mSUGRA) motivated scenario: no general unification of scalar masses was assumed and, as a consequence the Electroweak Symmetry breaking condition was not used to determine the absolute value of μ. No assumption about unification of trilinear couplings at the GUT scale was made either. The mass spectrum of the Higgs sector depends on one more parameter, which is taken to be the pseudoscalar Higgs mass, M_{A^0}.

The mass spectrum of charginos and neutralinos and the LSP mass in particular depend on M_2 (which is traditionally taken as a free parameter), μ and $\tan\beta$. If the sfermions are heavy, the decays of the $\tilde{\chi}^\pm_1$ and the $\tilde{\chi}^0_2$ proceed predominantly via W and Z respectively. This leads to $q\bar{q}\tilde{\chi}^0_1$ or $l\nu\tilde{\chi}^0_1$ final states in the case of chargino decay and to $q\bar{q}\tilde{\chi}^0_1$ or $l^+l^-\tilde{\chi}^0_1$ states for $\tilde{\chi}^0_2$ decays.

If the sfermions are light, the decay branching ratios depend on the sfermion masses, which depend on m_0 in addition to M_2 and $\tan\beta$. In the third sfermion family, mixing between left and right sfermions may occur. This can give light stau and sbottom states for large $\tan\beta$ and $|\mu|$.

If the sfermions are heavy, chargino production is the most important SUSY detection channel for large regions in the parameter space. However, the chargino production cross-section at a given energy can be greatly reduced by destructive interference between the s-channel and t-channel contributions if the sneutrino mass is below 300 GeV/c^2 and the SUSY parameters take particular values [12]. On the other hand, if the selectron is light, the neutralino production cross-section is enhanced due to t-channel selectron exchange ($\tilde{\mathrm{e}}_L, \tilde{\mathrm{e}}_R$) [13].

The sensitivity of searches for sparticle production depends on the visible energy released in the decay process, which in turn depends primarily on the mass difference between the decaying sparticle and a non-detectable sparticle emitted in the process. With heavy sfermions, a particular situation arises at a very large M_2, when both $M_{\tilde{\chi}^\pm_1}$-$M_{\tilde{\chi}^0_1}$ and

$M_{\tilde{\chi}^0_2}$-$M_{\tilde{\chi}^0_1}$ tend to be small, causing a decrease in the search sensitivity. For light sleptons the chargino decay modes $\tilde{\chi}^\pm_1 \rightarrow \tilde{\nu} l$ or $\tilde{\chi}^\pm_1 \rightarrow \tilde{\tau}\nu$ with $\tilde{\tau} \rightarrow \tilde{\chi}^0_1 \tau$ could be present. In such cases the chargino pair production could be hard to detect if $M_{\tilde{\chi}^\pm_1} - M_{\tilde{\nu}}$ or $M_{\tilde{\tau}} - M_{\tilde{\chi}^0_1}$ were small.

No general unification of scalar masses was assumed. As a consequence the mass spectrum of the Higgs sector, and thus the decay branching ratios of heavier neutralinos ($\tilde{\chi}^0_2$,$\tilde{\chi}^0_3$,$\tilde{\chi}^0_4$), depend on one more parameter, which is taken to be the pseudoscalar Higgs mass, M_{A^0}. This mass was assumed to be 300 GeV/c^2 in this paper, but the results depend only weakly on this assumption.

2 The method

The method employed to set a lower limit on the LSP mass and on the masses of other supersymmetric particles is to convert the negative results of searches for charginos, neutralinos and sleptons into exclusion regions in the (μ, M_2) plane for different $\tan\beta$ values, and then to find the minimal allowed sparticle masses as a function of $\tan\beta$. The limits presented in this letter are valid for any M_2 and for the μ region in which the lightest neutralino is the LSP. The μ region depends on the value of $\tan\beta$ and on the mixing parameters in the third family (A_τ, A_t, A_b). It is typically between -1000 and 1000 GeV/c^2.

In the following we summarize briefly the methods employed and the results achieved in the searches for charginos, neutralinos and sleptons (subsection 2.1), and we present the method of combining different searches (subsection 2.2).

2.1 Searches for sleptons, neutralinos and charginos

Searches for Sleptons

The results [9] of the DELPHI slepton search at 189 GeV were used. For smuon and selectron production, in addition to the typical decay mode $\tilde{\ell} \rightarrow \tilde{\chi}^0_1 \ell$, the cascade decay $\tilde{\ell} \rightarrow \tilde{\chi}^0_2 \ell$ with $\tilde{\chi}^0_2 \rightarrow \gamma\tilde{\chi}^0_1$ was searched for. This decay is important for low $|\mu|$. These searches exclude slepton production with cross-section greater than (0.05-0.2)pb, assuming 100% branching fraction to the above decay modes and depending on the neutralino mass and on the slepton mass.

Searches for Neutralinos

The searches for neutralino production are described in Refs.[5, 6, 8, 11]. They cover $\tilde{\chi}^0_k\tilde{\chi}^0_j$ final states with cascade and direct decays of heavier neutralinos: $\tilde{\chi}^0_{k,j} \rightarrow \tilde{\chi}^0_i + \mathrm{f}\bar{\mathrm{f}}$ or $\tilde{\chi}^0_{k,j} \rightarrow \tilde{\chi}^0_i + \gamma$ ($k = 2,3,4 : j,i = 1,2,3$). The latter decay channel is enhanced in the region of small M_2 and $\mu < 0$ for $\tan\beta$=1, and, even at high m_0, extends the exclusion beyond the kinematic limit for chargino production [8]. The cross-section limits are typically around (0.2-0.4)pb.

The search for neutralinos covers a variety of final state topologies which are important for setting the limit on the LSP mass. The topologies with two acoplanar jets, leptons or photons, multilepton, multijet, multijet with photons, single photon topologies, and single tau topologies have been searched for.

The search for neutralino production is sensitive in the particular kinematic configurations when neutralino decay proceeds via light stau states and $M_{\tilde{\tau}}$ is close to $M_{\tilde{\chi}^0_1}$.

The production of $\tilde{\chi}^0_1\tilde{\chi}^0_2$ [8] with $\tilde{\chi}^0_2 \to \tilde{\tau}\tau$ and $\tilde{\tau} \to \tilde{\chi}^0_1\tau$ leads to only one τ visible in the detector in this case. The cross-section limits are of the order of 0.25 pb.

Searches for Charginos

The results of the search for charginos in DELPHI were described in Refs.[3, 5, 6, 7, 10]. With the high luminosity collected in 1998, chargino pair production with cross-section larger than 0.13 pb can be excluded, if $\Delta M > 20$ GeV/c^2 [7].

The chargino search is optimized to search for chargino pair-production with the following subsequent chargino decays: $\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 W^*$ and $\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_2 W^* \to \tilde{\chi}^0_1\gamma W^*$.

The search presented in [7] is sensitive down to ΔM=3 GeV/c^2, where $\Delta M = M_{\tilde{\chi}^\pm_1}$-$M_{\tilde{\chi}^0_1}$. The region of lower ΔM is covered by the search for $\tilde{\chi}^+_1\tilde{\chi}^+_1\gamma$ production (3 GeV/c^2> ΔM > 0.170 GeV/c^2), with the γ arising from the initial state radiation, and by the search for stable heavy particles and long lived heavy particles (0.170 GeV/c^2 > ΔM) [10].

2.2 Combination of different searches

In the scan of the SUSY parameter space two approaches were adopted. In the first the efficiencies of the different searches, as obtained in Refs. [2, 3, 4, 5, 6, 11, 7, 8, 9, 10, 11] by DELPHI, were parametrized for the dominant channels, and used together with the information about the number of selected events in the data and expected numbers of background events. The 95 % confidence level exclusion regions obtained with the different searches were then simply superimposed.

In a parallel approach, these searches were combined using a very fast detector simulation program (SGV) [14], together with SUSYGEN [15], to simulate simultaneously all channels of chargino, neutralino, sleptons and squark production and decay. This was done for about 500000 SUSY points, for which the selection criteria of the neutralino search could then be directly applied [8]. The results obtained with different neutralino topologies were combined using the multichannel Bayesian approach [16]. The search for neutralinos covers many topologies typical of SUSY particle production, and the efficiences obtained with the very fast simulation agree well with full simulation results [8].

Good agreement was found between the two approaches. Because the efficiencies were parametrized only for the dominating channels, the results obtained using parametrised efficiencies were found to be conservative. The results of the fast simulation scan were used in the regions of the parameter space where decay channels different from the ones the various searches were originally designed for were found to be important [1] or where there were several SUSY production processes contributing (eg. the selectron and the neutralino production) which otherwise would not be efficiently combined. Combined exclusion in each MSSM point is in this case obtained by directly applying the selection criteria to all processes which are expected to occur in this particular point.

The typical scan step size in μ and M_2 was 1 GeV/c^2 except in the region of the LSP limit, where the step size was decreased to 0.05 GeV/c^2. The step size in m_0 was varying, with the density of steps increasing in regions of potentially difficult mass configurations.

[1]For example, topologies used in the search for the neutralino production are efficient in the search for the selectron production as well. In particular, when the cascade decays of the selectron are important namely $\tilde{e} \to \tilde{\chi}^0_2\, e$ with $\tilde{\chi}^0_2 \to q\bar{q}\tilde{\chi}^0_1$ or $\tilde{\chi}^0_2 \to \ell\bar{\ell}\tilde{\chi}^0_1$ the standard search for selectron production is not efficient.

Special care was taken to set up the scan logic in such a way that no such configuration was overlooked. Whenever two nearby scan points were excluded by different searches, the scan was performed with smaller steps between these points to check the continuity of the exclusion.

3 Results

The unification of sfermion masses to a common m_0 at the GUT scale allows the sfermion masses at the Electroweak Scale to be calculated as functions of $\tan\beta$, M_2 and m_0. In particular the sneutrino ($\tilde{\nu}$), the left-handed selectron and smuon ($\tilde{e}_L$,$\tilde{\mu}_L$) and the right-handed selectron and smuon ($\tilde{e}_R$, $\tilde{\mu}_R$) masses [2] can be expressed as:

1) ${M_{\tilde{\nu}}}^2 = m_0^2 + 0.77M_2^2 + 0.5{M_Z}^2\cos 2\beta$
2) $M_L^2 = m_0^2 + 0.77M_2^2 - 0.23{M_Z}^2\cos 2\beta$
3) $M_R^2 = m_0^2 + 0.22M_2^2 - 0.23{M_Z}^2\cos 2\beta$

In the high m_0 scenario, $m_0 = 1000$ GeV/c^2 was assumed, which implied the sfermion masses of the same order. Limits arise in this case from a combination of chargino and neutralino searches described in [7] and [8].

For high m_0, the chargino pair-production cross-section is large and the chargino is excluded nearly up to the kinematic limit, provided $M_2 < 200$ GeV/c^2. A particular situation arises for very high values of M_2, where ΔM=$M_{\tilde{\chi}_1^{\pm}}$-$M_{\tilde{\chi}_1^0}$ can be small. However the search presented in [7] is sensitive down to ΔM=3 GeV/c^2 which occurs for $M_2 \simeq 1400$ GeV/$c^2$and the region of $M_2 > 1400$ GeV/c^2 is covered by the chargino searches described in [10]. The limits presented here are thus valid for any M_2.

It may also be remarked that at low M_2, the chargino tends to decay to the next-to-lightest neutralino $\tilde{\chi}_2^0$, with $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_2^0 W^*$ followed by $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma$ or $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$. The ΔM=$M_{\tilde{\chi}_1^{\pm}}$-$M_{\tilde{\chi}_1^0}$ is large, resulting in increased background from W^+W^- production. For setting the limit on the LSP mass, it is therefore important that the chargino search includes topologies with photons stemming from the decays $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_2^0 W^* \rightarrow \tilde{\chi}_1^0\gamma W^*$. The search for topologies with γ's does not suffer from W^+W^- background and is effective for large ΔM (close to M_W).

Of the detectable channels of neutralino production (*i.e.* excluding $\tilde{\chi}_1^0\tilde{\chi}_1^0$), $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0\tilde{\chi}_3^0$ are important for large regions in the parameter space, but in order to cover as much as possible one must also consider channels like $\tilde{\chi}_2^0\tilde{\chi}_3^0$ and $\tilde{\chi}_2^0\tilde{\chi}_4^0$, giving cascade decays with multiple jets or leptons in the final state. At high m_0 the production cross-section for all these neutralino production channels drops to very low values for $|\mu|$ above $\simeq$ 75 GeV/c^2. This is because the two lightest neutralinos then have large photino ($\tilde{\chi}_1^0$) and zino ($\tilde{\chi}_2^0$) components: their pair-production is therefore suppressed by the low coupling to the Z, while pair-production of heavier neutralinos is not kinematically accessible. Nevertheless for $\tan\beta < 1.2$ GeV/c^2 and $M_2 > 60$ GeV/c^2 the neutralino exclusion reaches beyond the kinematic limit for chargino production at negative μ (see figure 1 and [8]). This region is important for setting the limit on the LSP mass.

For medium m_0, 100 GeV/$c^2 \lesssim m_0 \lesssim$ 1000 GeV/c^2 the $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production cross-section grows quickly in the gaugino-region ($|\mu| \gtrsim$ 75 GeV/c^2) with the decrease of

[2] It is worth noting that for $\tan\beta \geq 1$ we have $\cos 2\beta \leq 0$, so the $\tilde{\nu}$ is never heavier than the $\tilde{e}_L$.

m_0, due to appearing contribution from the selectron t-channel exchange. The chargino production cross-section in the gaugino region drops slowly, but it remains high enough to allow for chargino exclusion nearly up to the kinematical limit for $m_0 \gtrsim 200$ GeV/c^2. For lower $m_0 \sim 100$ GeV/c^2 the chargino production cross-section reaches its minimum in the gaugino region, while the neutralino production cross-section is very much enhanced. Consequently the region of the (μ, M_2) parameter space excluded by searches for neutralino production at low m_0 is larger than the one excluded by search for chargino production at high m_0 (see figure 1 and [8]).

For the low m_0, $m_0 \lesssim 100$ GeV/c^2 and low M_2, $M_2 \lesssim 200$ GeV/c^2, the situation is much more complicated because light sfermions affect not only production cross-sections but also decay patterns of charginos and neutralinos. They can also be searched for in direct pair-production. Exclusion regions at low m_0 arise from the combination of searches for chargino, neutralino and slepton production.

For low m_0 and M_2 the sneutrino is light, the chargino decay mode $\tilde{\chi}_1^\pm \rightarrow \tilde{\nu}\ell$ is dominant, and it leads to an experimentally undetectable final state if $M_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\nu}}$. For every value of M_2 and μ, an m_0 can be found such that $M_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\nu}}$. The search for charginos therefore cannot be used to exclude regions in the $(,\mu,M_2)$ plane if very low m_0 values are allowed. The search for selectron production is used instead to put a limit on the sneutrino mass (and thus on the chargino mass), the selectron and the sneutrino masses being related. The selectron pair production cross-section is typically larger than the smuon pair production cross-section, due to the contribution of t-channel neutralino exchange. However at $|\mu| \lesssim 200$ GeV/c^2 the selectron production cross-section tends to be small and the exclusion arises mainly from the search for neutralino pair-production.

Mixing between the left-handed and right-handed sfermion states can be important for the third family sfermions and lead to light $\tilde{\tau}_1$, $\tilde{\mathrm{b}}_1$ and $\tilde{\mathrm{t}}_1$. In this paper mass splitting terms at the Electroweak Scale proportional to $m_\tau(A_\tau\text{-}\mu\tan\beta)$, $m_b(A_b\text{-}\mu\tan\beta)$ and $m_t(A_t\text{-}\mu/\tan\beta)$ were considered, for $\tilde{\tau}$, $\tilde{\mathrm{b}}$, and $\tilde{\mathrm{t}}$ respectively. These terms lead to $\tilde{\tau}_1$, $\tilde{\mathrm{b}}_1$ or $\tilde{\mathrm{t}}_1$ being the LSP for large values of $|\mu|$. The results presented in this paper are limited to the range of the μ parameter where the lightest neutralino is the LSP.

At $\tan\beta \geq 8$, sufficiently high values of $|\mu|$ are allowed for $\tilde{\tau}_1$ to be degenerate in mass with $\tilde{\chi}_1^0$ while m_0 is high enough for the selectron and the sneutrino pair-production to be kinematically not allowed. Chargino decay $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu$ with $\tilde{\tau} \rightarrow \tilde{\chi}_1^0\tau$ is hard to detect, leaving the $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and the $\tilde{\chi}_2^0\tilde{\chi}_2^0$ production with $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau$ as the only detectable channels of sparticle production.

3.1 Results for high m_0

Figure 2 gives the lower limit on $M_{\tilde{\chi}_1^0}$ as a function of $\tan\beta$. The lightest neutralino is constrained to have a mass:

$$M_{\tilde{\chi}_1^0} > 32.4 \text{ GeV}/c^2$$

for $m_0 = 1000$ GeV/c^2 and any value of M_2. The limit occurs at $\tan\beta$=1. Figure 1 (upper part) shows the region in the (μ,M_2) plane for $\tan\beta$=1 excluded by the chargino and neutralino searches, relevant for the LSP mass limit at $m_0 = 1000$ GeV/c^2. This result improves on the high m_0 one presented in [7] due to the constraint from the search for neutralino production. However, at $\tan\beta \gtrsim 1.2$ the LSP limit is given exclusively by the chargino search and it reaches half of the limit on the chargino mass at high $\tan\beta$, where the contours of constant $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ are parallel. The raise of the LSP limit for small $\tan\beta$ can be explained by the change of the shape of these contour with $\tan\beta$.

The lowest non-excluded $M_{\tilde{\chi}_1^0}$ occurs for $\tan\beta$=1, μ = -68.7 GeV/c^2 and M_2 = 54.8 GeV/c^2. For these parameters, $\tilde{\chi}_4^0\tilde{\chi}_2^0$ production is kinematically allowed at $\sqrt{s}$ = 189 GeV ($M_{\tilde{\chi}_4^0}$= 118.9 GeV/c^2, $M_{\tilde{\chi}_2^0}$= 68.7 GeV/c^2) and has the cross-section of 0.12 pb. The chargino pair-production cross-section is 0.11 pb. The cross-sections for the production of other gauginos are much smaller, and the limit arises from a combination of searches for $\tilde{\chi}_4^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ production. The dominant decays of $\tilde{\chi}_2^0$ and $\tilde{\chi}_4^0$ are ; $\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0$ (31 %), $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ (31 %), $\tilde{\chi}_2^0 \to \nu\bar{\nu}\tilde{\chi}_1^0$ (15 %) and $\tilde{\chi}_4^0 \to q\bar{q}\tilde{\chi}_2^0$ (56 %), $\tilde{\chi}_4^0 \to \nu\bar{\nu}\tilde{\chi}_2^0$ (17 %), $\tilde{\chi}_4^0 \to h_0\tilde{\chi}_1^0$ (15.0 %).

Figure 3 shows the lower limit on $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ as a function of M_2 for $\tan\beta$=1. The upper part of the figure presents the limit on $M_{\tilde{\chi}_1^\pm}$ for $\mu < 0$. $M_{\tilde{\chi}_1^\pm}$ above the kinematic limit for chargino pair-production is excluded for 100 GeV/c^2 < M_2 < 400 GeV/c^2 due to the constraint from the search for the neutralino production. The lower part of the figure shows the limit on $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ for -1000 GeV/c^2 $\leq \mu \leq$ 1000 GeV/c^2 and for M_2 up to 30 000 GeV/c^2. For $M_2 >$ 1400 GeV/c^2 the limits are given by the results presented in [10]. The limit on the chargino mass is:

$$M_{\tilde{\chi}_1^\pm} > 62.4 \text{ GeV}/c^2.$$

The limit does not depend on $\tan\beta$ and is valid for any M_2. It occurs at a very high M_2 value, were $M_{\tilde{\chi}_1^\pm}$, $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\chi}_2^0}$ are degenerate and ΔM= $M_{\tilde{\chi}_1^\pm}$-$M_{\tilde{\chi}_1^0}$ $\simeq$ 0.170 GeV/c^2.

3.2 The LSP mass limit for any m_0

Figure 2 gives the lower limit on $M_{\tilde{\chi}_1^0}$ a function of $\tan\beta$ for any m_0. The "any m_0" limit follows the high m_0 limit up to $\tan\beta$=1.2 and then drops to its lowest value at $\tan\beta$=4.

The lightest neutralino is constrained to have a mass:

$$M_{\tilde{\chi}_1^0} > 32.3 \text{ GeV}/c^2$$

independent of m_0 and $M_{\tilde{\chi}_1^0}$ > 32.4 GeV/c^2 if the sneutrino is heavier than the chargino. The limit for "any m_0" is reached for $\tan\beta \simeq 4$, where both $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are degenerate with the sneutrino (m_0 = 71.2 GeV/c^2, μ=-277 GeV/c^2, and M_2= 60.9 GeV/c^2, $M_{\tilde{\chi}_2^0}$ = 66.8 GeV/c^2, $M_{\tilde{\chi}_1^\pm}$ = 66.7 GeV/c^2, $M_{\tilde{\nu}}$= 66 GeV/c^2, $M_{\tilde{e}_R}$ = 87.2 GeV/c^2 and $M_{\tilde{\tau}_1}$= 80.3 GeV/c^2). If the sneutrino is heavier than the chargino the lowest non-excluded neutralino mass occurs at $\tan\beta$ =1.

The $\tan\beta$ dependence of the LSP limit can be understood as follows:
For $\tan\beta < 1.2$, the (μ, M_2) region excluded by neutralino and slepton searches at low m_0 is larger than the region excluded by chargino and neutralino searches for large m_0 (see figure 1). Thus for $\tan\beta < 1.2$ the limit on the neutralino mass for "any m_0" is given by the high m_0 limit of 32.4 GeV/c^2.

The region in the (μ, M_2) plane excluded by neutralino searches at a given m_0 becomes smaller with the increase of $\tan\beta$ and the LSP mass limit is reached at a lower m_0

value. At $\tan\beta \gtrsim 1.4$ the minimal sneutrino mass allowed by the neutralino and slepton searches drops below 94 GeV/c^2. This implies that for $M_{\tilde{\chi}_1^\pm} < 94$ GeV/c^2 an m_0 value can be found such that $M_{\tilde{\chi}_1^\pm} = m_{\tilde{\nu}}$ and the chargino decays "invisibly" (see figure 4). For $\tan\beta \gtrsim 1.4$ the limits are given by the combination of searches for neutralino and slepton production.

Figure 5 illustrates the exclusion regions in the (μ,M_2) plane for $\tan\beta$ =4 and $m_0 = 71$ GeV/c^2. The lower limit of $M_{\tilde{\chi}_1^0} > 32.3$ GeV/c^2 occurs close to these particular values of $\tan\beta$ and m_0. The $M_{\tilde{\chi}_1^0}$=32.3 GeV/c^2 isomass curve is indicated. The exclusion regions derived from searches for neutralino production, for slepton production and from the combined search for neutralino and slepton production are shown. The edge of the combined slepton and neutralino exclusion at $M_2 = 60.6$ GeV/c^2 corresponds to the $M_{\tilde{e}_R}$=87.2 GeV/c^2 isomass curve. This edge imposes a limit on the sneutrino mass $M_{\tilde{\nu}}$=66 GeV/c^2, and determines the upper reach of the exclusion obtained from the search for the chargino production. As the various final state topologies which were used to search for neutralinos [8] (see subsection 2.1) were employed here also to search for slepton production, the slepton exclusion does not deteriorate significantly for small negative values of μ where the $\tilde{\ell} \to \tilde{\chi}_2^0\ell$ and $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ decay channels dominate, giving multilepton final states. This region is also covered by the neutralino searches. For M_2 >30 GeV/c^2 and $\mu < -130$ GeV/c^2 the invisible $\tilde{\chi}_2^0 \to \nu\bar{\nu}$ branching fraction is above 90% . Because only $\tilde{\chi}_2^0\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0\tilde{\chi}_2^0$ are produced in this region the neutralino exclusion disappears.
For $4 \lesssim \tan\beta \lesssim 8$ the limit improves slightly due to the increase of the $\tilde{\tau}_1$ production cross-section, as $\tilde{\tau}_1$ gets lighter as the mass spliting term (A_τ - $\mu\tan\beta$) increases. At $\tan\beta \gtrsim 8$ the limit degrades somewhat again due to the possibility of $M_{\tilde{\tau}_1}$ being close to $M_{\tilde{\chi}_1^0}$, making the $\tilde{\tau}_1$ undetectable. In this region the LSP limit is given by the neutralino exclusion and reaches $M_{\tilde{\chi}_1^0} > 33.2$ GeV/c^2 for $\tan\beta = 40$. The limit is reached for $m_0 = 122$ GeV/c^2, $\mu = -252.5$ GeV/c^2 with $M_{\tilde{\tau}_1} = 35.4$ GeV/c^2 and all other sleptons heavier than the kinematic limit for the slepton pair-production.

The dependence of the LSP limit on the mixing in the stau sector was studied. For A_τ large and positive, $\simeq 1000$ GeV/c^2, the limit at $\tan\beta = 4$ improves slightly due to larger stau production cross-section. The limit for $\tan\beta \gtrsim 8$ decreases because with the larger splitting in the stau sector, the stau-neutralino mass degeneracy occurs for higher m_0, where the neutralino production cross-section is lower. To summarise, the dependence of the neutralino mass limit on the mixing in the stau sector is weak, the limit changes by $\lesssim 2$ GeV/c^2 for a change of A_τ between -1000 GeV/c^2 and 1000 GeV/c^2. It should be noted that the range of A_τ values studied here is much larger than $|A_\tau| \simeq 50$ GeV/c^2 at the Electroweak Scale given by the assumption of a common trilinear coupling at the GUT scale, $A_0 = 0$. Values of $|A_\tau| \simeq 50$ GeV/c^2 do not influence the limit at all, as they are much smaller than the $\mu\tan\beta$ values in the limit region.

3.3 $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\nu}$ and $\tilde{e}_R$ mass limits for any m_0

Figure 4 shows the chargino mass limit as a function of $\tan\beta$ for $M_2 < 200$ GeV/c^2. The lowest non-excluded chargino mass is found in the MSSM points very close to these giving the LSP mass limit, and the above arguments hold to explain the dependence of the chargino mass limit on $\tan\beta$. For $\tan\beta \lesssim 1.2$ the limit occurs at high m_0

values. For $1.4 \lesssim \tan\beta \lesssim 4$ and $M_2 < 200$ GeV$/c^2$, the limit occurs at low m_0 in the chargino-sneutrino degeneracy region. It rises slightly at $\tan\beta \gtrsim 4$, and then falls back for $\tan\beta \gtrsim 10$ because of the small $\Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}^0_1}$.

The lightest chargino is constrained to have a mass:

$$M_{\tilde{\chi}^{\pm}_1} > 62.4 \text{ GeV}/c^2.$$

This limit is valid for any m_0, $M_2 < 200$ GeV$/c^2$and $1 \leq \tan\beta \leq 40$, and it occurs in the region of the neutralino-stau degeneracy for $\tan\beta$= 40. It coincides with the one obtained at very high M_2 (see subsection 3.1) in the chargino-neutralino degeneracy region. Thus the chargino is bound to be heavier than $M_{\tilde{\chi}^{\pm}_1} > 62.4$ GeV$/c^2$ for any m_0 and M_2 values and $1 \leq \tan\beta \leq 40$.

The mass of the next-to-lightest neutralino has to satisfy (see figure 6):

$$M_{\tilde{\chi}^0_2} > 62.4 \text{ GeV}/c^2.$$

The limit occurs in the same MSSM point as the chargino mass limit and it is valid for any m_0 and M_2 values and $1 \leq \tan\beta \leq 40$.

The sneutrino and the $\tilde{e}_R$ have to be heavier than:

$$M_{\tilde{\nu}} > 61 \text{ GeV}/c^2 \text{ and } M_{\tilde{e}_R} > 87 \text{ GeV}/c^2.$$

These limits result from the combination of slepton and neutralino search. The selectron mass limit is valid for -1000 GeV$/c^2 \leq \mu \leq$ 1000 GeV$/c^2$ and $1 \leq \tan\beta \leq 40$ provided that $M_{\tilde{e}_R}$ - $M_{\tilde{\chi}^0_1} > 10$ GeV$/c^2$ (see figure 4, dotted curve), and it allows a limit to be set on the sneutrino mass as shown in figure 4 (dashed curve). If $M_{\tilde{e}_R}$ - $M_{\tilde{\chi}^0_1} < 10$ GeV$/c^2$, the most unfavourable situation appears when $\tilde{\chi}^+_1\tilde{\chi}^-_1$ and $\tilde{\chi}^0_2\,\tilde{\chi}^0_1$ production is kinematically inaccessible and the splitting between $M_{\tilde{e}_R}$ and $M_{\tilde{e}_L}$ is sufficiently large to make $\tilde{e}_R\tilde{e}_L$ production inaccessible as well. In this case the lower limit on $M_{\tilde{e}_R}$ is about 70 GeV$/c^2$ but the limit on the sneutrino mass does not deteriorate, as $M_{\tilde{\nu}}$ is high in the above region. The selectron mass limit for $\tan\beta = 1.5$ and $\mu = -200$ GeV$/c^2$ was presented in [9]. Limits on $M_{\tilde{e}_R}$ and $M_{\tilde{\nu}}$ were obtained with the assumption of no mass splitting in the third sfermion family ($A_\tau - \mu\tan\beta$=0), implying $M_{\tilde{e}_R} = M_{\tilde{\tau}_R} = M_{\tilde{\tau}_1} = M_{\tilde{\mu}_R}$. If mass splitting in the stau sector is present (in the form $A_\tau - \mu\tan\beta$) and $A_\tau = 0$, the sneutrino mass limit rises to $M_{\tilde{\nu}}$ >64 GeV$/c^2$, as low m_0 values are not allowed at high $\tan\beta$ if the lightest neutralino is the LSP.

4 Summary

Searches for sleptons, charginos and neutralinos at centre-of-mass energies up to $\sqrt{s}$ = 188.7 GeV set lower limits on the masses of the supersymmetric particles.

Within the Minimal Supersymmetric Standard Model with gauge mass unification and sfermion mass unification at the GUT scale, the lightest neutralino has been constrained to have a mass $M_{\tilde{\chi}^0_1} > 32.3$ GeV$/c^2$.

The lightest chargino, the second-to-lightest neutralino, the sneutrino and the $\tilde{e}_R$ were found to be heavier than 62.4 GeV$/c^2$, 62.4 GeV$/c^2$, 61.0 GeV$/c^2$, and 87 GeV$/c^2$, respectively. These limits do not depend on m_0 or M_2, and are valid for $1 \leq \tan\beta \leq 40$, in the μ range where the lightest neutralino is the LSP. If the sneutrino is heavier than the chargino, the lightest neutralino has to be heavier than 32.4 GeV/c^2. The effects of mixing in the third family of sfermions on these limits have been discussed. The search for $\tilde{\chi}^0_1\tilde{\chi}^0_2$ and $\tilde{\chi}^0_2\tilde{\chi}^0_2$ production with $\tilde{\chi}^0_2 \to \tilde{\tau}\tau$ was exploited in setting the limits. No significant dependence of the above mass limits on the mixing in the stau sector was found.

The branching fractions of the decays of heavier neutralinos depend on the mass of the lightest Higgs boson (h_0), which in turn depends on the mass of the pseudoscalar boson M_{A^0} within the model used. For example, close to the LSP limit point at high m_0 the branching ratio $\tilde{\chi}^0_4 \to \tilde{\chi}^0_1\ h_0$ decreases from 15 % to 12 %, if M_{A^0} rises from 300 GeV/c^2 to 1000 GeV/c^2. There is no change in the efficiency of the search for the neutralino production. No significant dependence of the limits on the mass of the pseudoscalar Higgs boson was found.

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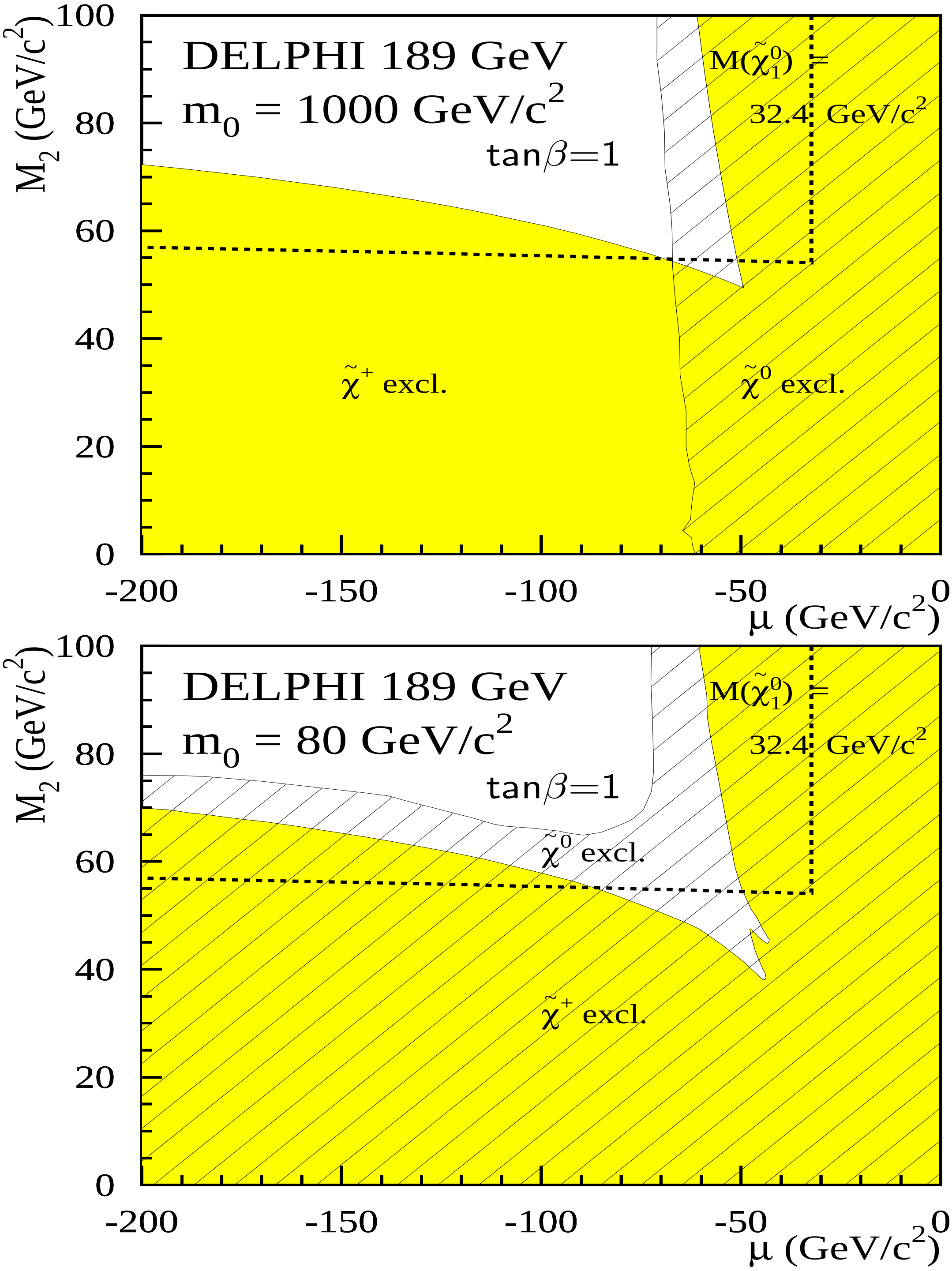

Figure 1: Excluded regions in the (μ, M_2) plane for $m_0 = 1000$ GeV/c^2 and $\tan\beta = 1$ (the upper plot) and for $m_0 = 80$ GeV/c^2 and $\tan\beta = 1$ (the lower plot). The shaded areas show regions excluded by searches for charginos and the hatches areas show regions excluded by searches for neutralinos. The thick dashed curve shows the isomass contour for $M_{\tilde{\chi}_1^0} = 32.4$ GeV/c^2, the lower limit on the LSP mass obtained at $\tan\beta$=1. Chargino exclusion at the upper plot is close to the isomass contour for $M_{\tilde{\chi}_1^\pm}$ at the kinematic limit.

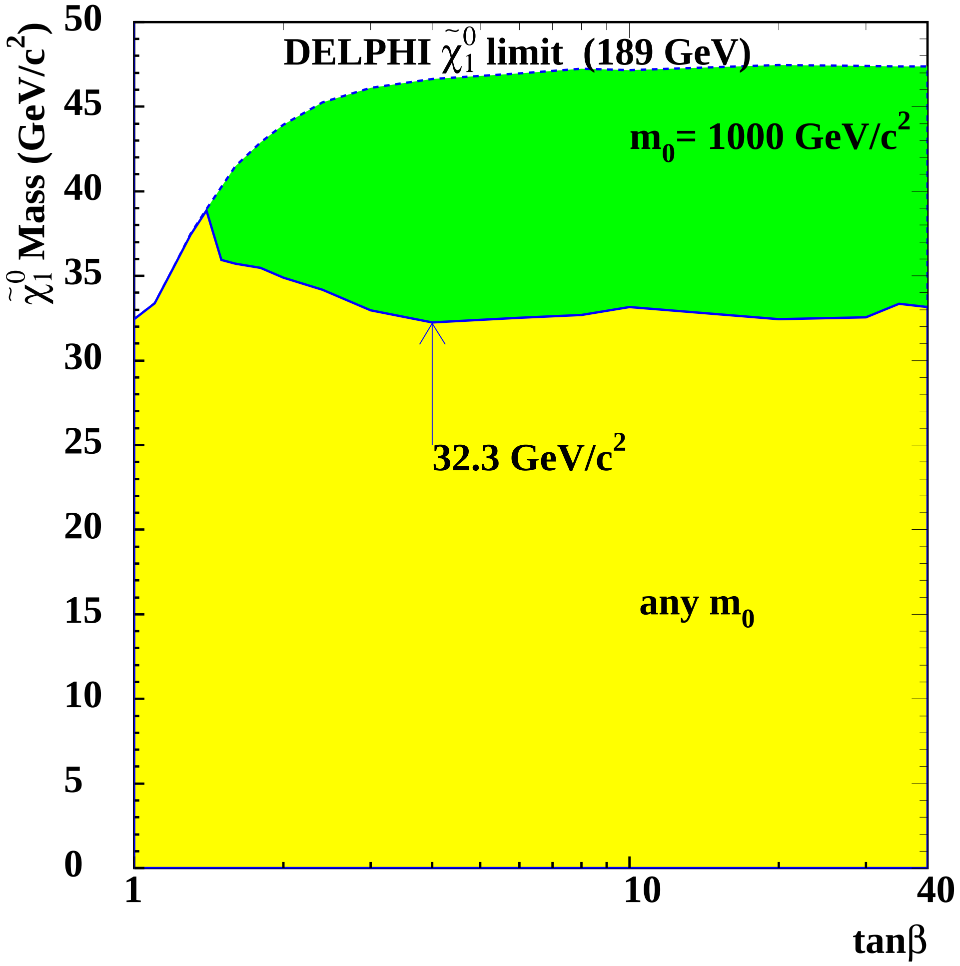

Figure 2: The figure shows the lower limit at 95% confidence level on the mass of the lightest neutralino, $\tilde{\chi}_1^0$, as a function of $\tan\beta$ assuming a stable $\tilde{\chi}_1^0$. The dashed curve shows the limit obtained with the assumption of m_0 =1000 GeV$/c^2$, the solid curve shows the limit obtained allowing for light sfermions.

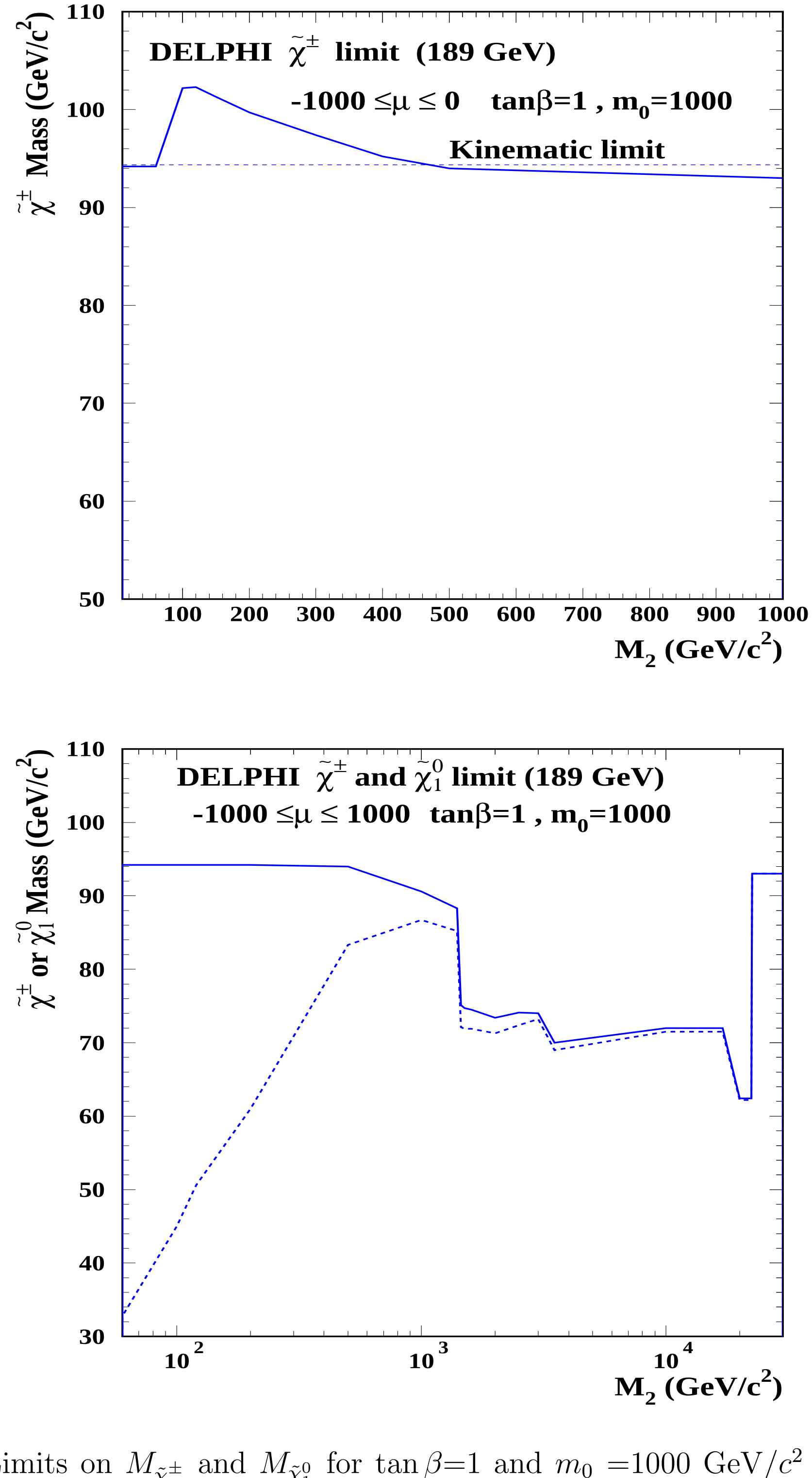

Figure 3: Limits on $M_{\tilde{\chi}_1^{\pm}}$ and $M_{\tilde{\chi}_1^0}$ for $\tan\beta$=1 and m_0 =1000 GeV/c^2 are shown as a function of M_2. The upper figure shows the lower limit on $M_{\tilde{\chi}_1^{\pm}}$ for $\mu < 0$ resulting from searches for neutralinos and charginos. The lower part of the figure shows the limit on $M_{\tilde{\chi}_1^{\pm}}$ (solid curve) and $M_{\tilde{\chi}_1^0}$ (dashed curve) for -1000 GeV/c^2 $\leq \mu \leq$ 1000 GeV/c^2. The region of $M_2 < 55$ GeV/c^2 is excluded (see figure 1).

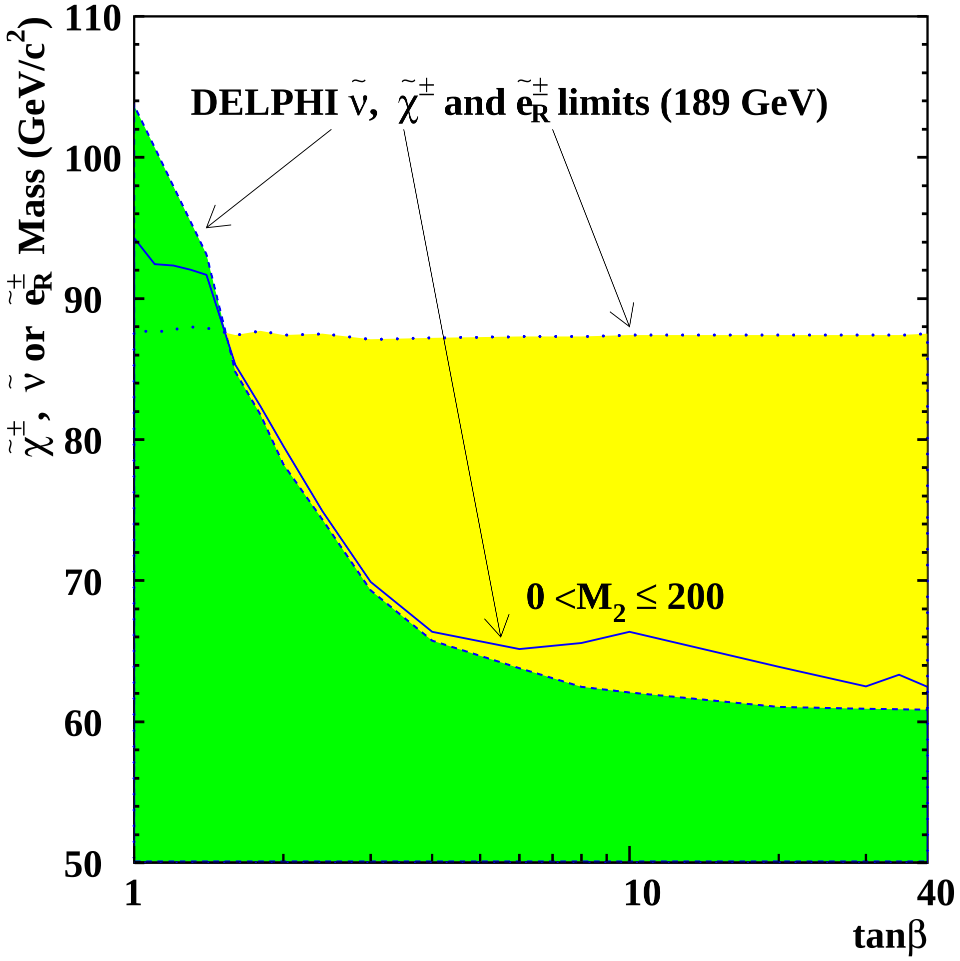

Figure 4: The minimal sneutrino mass allowed by the slepton and neutralino searches is shown by dark shading and the dashed curve, as a function of $\tan\beta$, together with the limit on the chargino mass (the solid curve) and the limit on $\tilde{\mathrm{e}}_R$ mass (dotted curve and the light shading). The sneutrino and selectron mass limits were obtained with the assumption that there is no mass splitting in the third sfermion family. The selectron mass limit is valid for $M_{\tilde{\mathrm{e}}_R} - M_{\tilde{\chi}^0_1} > 10$ GeV/c^2.

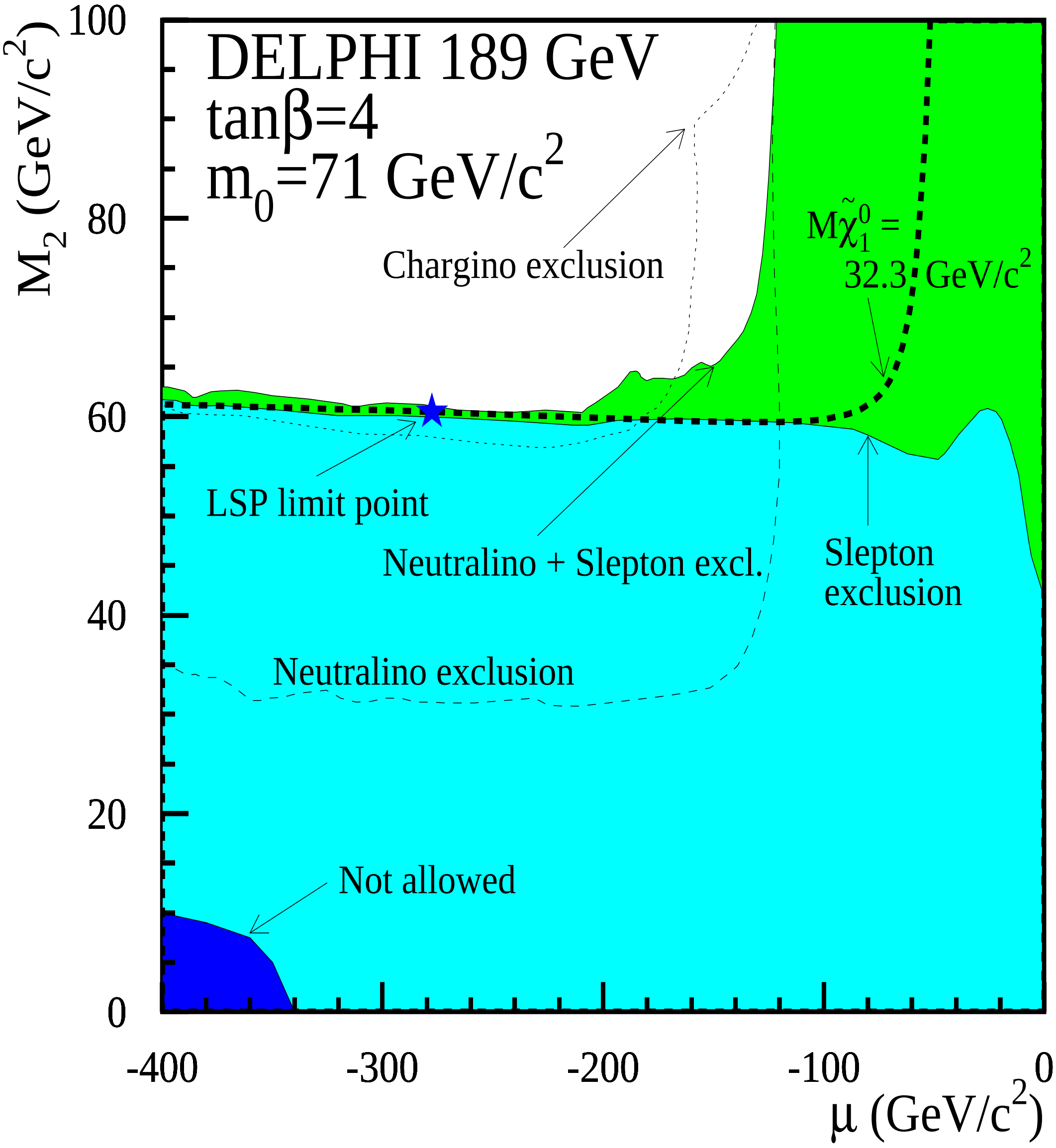

Figure 5: Excluded regions in the (μ,M_2)-plane for $m_0 = 71$ GeV/c^2 and $\tan\beta = 4$. The thin curves show the regions excluded by searches for charginos (dashed) and neutralinos (dash-dotted). The region excluded by the slepton search is shown in darker shading and the thin solid curve. The combined neutralino-slepton exclusion is shown by the lighter shading and the thin dashed curve. The upper edge of the chargino exclusion for $\mu < 200$ GeV/c^2 is determined by the upper edge of the combined neutralino-slepton exclusion. Also shown is the relevant isomass curve for $\tilde{\chi}^0_1$. The dark shaded region is not allowed due to the stop being the LSP.

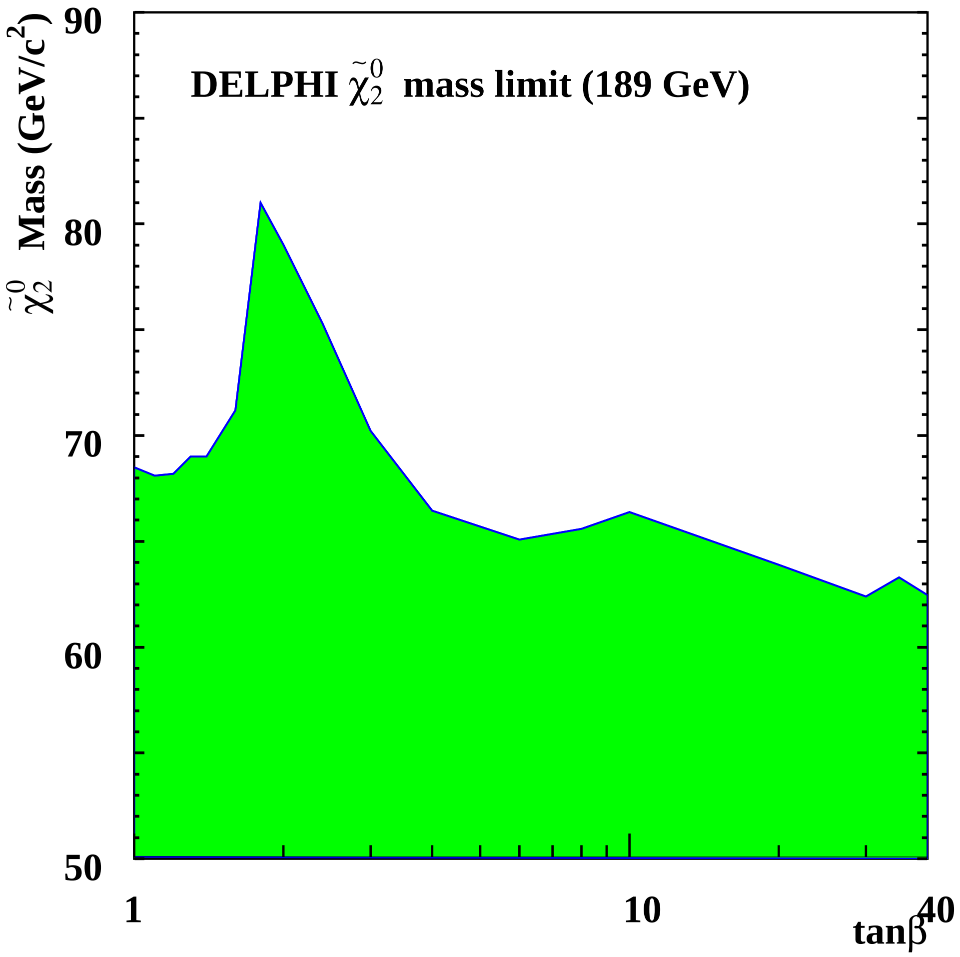

Figure 6: The limit on the next-to-lightest neutralino mass resulting from slepton, neutralino and chargino searches is shown, as a function of $\tan\beta$.