

# Mass Limit for the Lightest Neutralino

The ALEPH Collaboration

**Abstract:** Indirect limits on the mass of the lightest neutralino are derived from the results of searches for charginos, neutralinos, and sleptons performed with data taken by the ALEPH Collaboration at centre-of-mass energies near the Z peak and at 130 and 136 GeV. Within the context of the Minimal Supersymmetric Standard Model and when  $M_{\tilde{\nu}} \geq 200 \text{ GeV}/c^2$ , the bound  $M_{\tilde{\chi}} > 12.8 \text{ GeV}/c^2$  at the 95% confidence level applies for any  $\tan\beta$ . The impact of lighter sneutrinos is presented in the framework of SUSY grand unified theories; a massless neutralino is allowed only for a narrow range of  $\tan\beta$ ,  $\mu$ , and the scalar mass parameter  $m_0$ . Finally, by including Higgs mass constraints and requiring that radiative electroweak symmetry breaking occur, more stringent bounds on  $M_{\tilde{\chi}}$  as a function of  $\tan\beta$  are derived.

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# The ALEPH Collaboration

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# 1 Introduction

The lightest supersymmetric particle (LSP) commonly is assumed to be the lightest neutralino,  $\chi$ . This assumption follows naturally if R-parity, which distinguishes supersymmetric and ordinary particles, is conserved, in which case the LSP must be stable [1]. Cosmological considerations [2] rule out an LSP with charge or color, leaving only the lightest neutralino and the sneutrinos as possible LSP's. While a lower limit on the sneutrino mass of  $43 \text{ GeV}/c^2$  can be derived from the invisible  $Z$  width, previous analyses have not excluded a massless neutralino, hence the current focus on neutralinos. However, the improved limits on  $M_\chi$  presented here do not require sneutrinos to be heavier than neutralinos. Since the lightest neutralino, if stable, could constitute a significant fraction of the dark matter of the universe [3], bounds on its mass from high energy physics experiments are quite relevant [4, 5].

Searches for charginos, neutralinos and sleptons have been carried out using data taken with the ALEPH detector [6] at LEP 1 ( $\sqrt{s} \sim M_Z$ ) and more recently at LEP 1.5 ( $\sqrt{s} = 130 - 136 \text{ GeV}$ ). The negative results of those searches are reported in Refs. [7, 8], where details of the search techniques and definitions of terms can be found. It was assumed that the lightest neutralino is stable and escapes detection, causing an apparent missing energy in the event.

The results of LEP 1 and LEP 1.5 chargino and neutralino searches together place significant bounds on the mass of the lightest neutralino, as described in this article. While in each case open regions in parameter space exist which allow a very light, even massless, neutralino, it turns out that these regions are not in common. For large sneutrino masses, a massless neutralino allowed by the LEP 1 analysis is excluded by LEP 1.5, and vice-versa.

The combination of LEP 1 and LEP 1.5 results is fruitful in the scalar lepton sector also. The limit on the sneutrino mass coming from the  $Z$  width and the limits from the direct search for sleptons taken together exclude a significant region in parameter space when their masses are linked according to the ideas of SUSY-based grand unified theories. This exclusion can be used to constrain the mass of the neutralino in a way which complements the limits from the charginos and neutralinos.

The non-observation of Higgs bosons at LEP 1 can also be used to restrict neutralino masses in a highly constrained SUSY GUT called "minimal supergravity." In this theory, the derivation of electroweak symmetry breaking through radiative corrections induced by the top quark Yukawa coupling allows a reduction in the number of SUSY parameters, leading ultimately to a stronger limit on  $M_\chi$ .

## 2 Analysis

In the Minimal Supersymmetric Standard Model (MSSM), chargino ( $\chi^\pm$ ) and neutralino ( $\chi, \chi', \chi'', \chi'''$ ) masses depend on the parameters  $M_1, M_2, \mu$ , and  $\tan\beta$ . The gauge fermion masses at the electroweak scale are denoted by  $M_1$  and  $M_2$ . If they are equal at the GUT scale, then  $M_1 = \frac{5}{3} \tan^2 \theta_W M_2$ , which is assumed here. The independent

parameter  $\mu$  represents the Higgsino mass, and  $\tan\beta$  is the ratio of Higgs doublet expectation values. Since the top quark is much heavier than the bottom quark, one expects  $\tan\beta > 1$ . Furthermore, if the top quark Yukawa coupling remains perturbative up to the GUT scale, then  $\tan\beta > 1.2$  [9]. The restriction  $\tan\beta \geq 1$  is imposed in this analysis, but it is worth noting that the chargino and neutralino masses and couplings are symmetric under the transformation  $\tan\beta \rightarrow \cot\beta$ . Tree-level relations for all masses are used, as radiative corrections for these particles are small [10].

The functional dependence of the chargino and neutralino masses on the SUSY parameters is different. Consequently, for any given chargino mass, there is a smallest neutralino mass, possibly zero. In this analysis, bounds in the  $(\mu, M_2)$  plane for a series of  $\tan\beta$  and sneutrino mass values are derived using the ALEPH analyses to obtain experimental efficiencies and to investigate special cases. The SUSYGEN program [11] was used to generate chargino, neutralino, and slepton events in relevant regions of the SUSY parameter space. For each  $\tan\beta$  and sneutrino mass, the point in parameter space outside all regions excluded at 95% CL giving the lowest neutralino mass is found. Fig. 1 allows a comparison of the lines of constant  $M_\chi$  mass with these experimental bounds in the  $(\mu, M_2)$  plane.

The slepton and sneutrino masses play a key role in the production and decay of charginos and neutralinos. The destructive interference between  $s$ -channel and  $t$ -channel diagrams reduces the chargino cross section when the electron-sneutrino is lighter than  $70 \text{ GeV}/c^2$ . Constructive interference increases associated neutralino production when the selectron is light. The three-body decay of charginos and neutralinos proceeds mainly through intermediate W and Z exchange when all sneutrinos and sleptons are heavy. When they are light enough, however, two-body decays dominate, with radical consequences. In particular, the final state  $\chi^+ \rightarrow \ell^+ \tilde{\nu}$  will not be selected if the mass difference  $M_{\chi^+} - M_{\tilde{\nu}}$  is smaller than about  $3 \text{ GeV}/c^2$ , leaving an experimental ‘blind spot’ in the exclusion of charginos heavier than  $45 \text{ GeV}/c^2$ , the limit inferred from the Z width. Similarly, the dominance of the decay  $\chi' \rightarrow \nu \tilde{\nu}$  when  $M_{\tilde{\nu}} < M_{\chi'}$  leads to a complete loss of experimental acceptance for the  $\chi\chi'$  final state. The cases of heavy and light sneutrinos and sleptons are discussed in detail in the following sections.

## 2.1 Heavy Sneutrinos and Sleptons

Large sneutrino and slepton masses were assumed when deriving the excluded regions in the  $(\mu, M_2)$  plane depicted in Fig. 5 of Ref. [8], a detail of which is shown in Fig. 1. In this case the influence of the  $t$ -channel diagram in the production cross section is small, and the decay branching fractions of charginos and neutralinos are approximately the same as those of W and Z bosons.

The chargino search at LEP 1.5 provides the most stringent bound on  $M_\chi$  as a function of  $\mu$  for  $\tan\beta \gtrsim 2$ . When  $\tan\beta \gtrsim 10$ , the lowest value of  $M_\chi$  is found deep in the gaugino region ( $\mu \approx -4 \text{ TeV}/c^2$ ). Although such regions are not favoured theoretically, the difference in the  $M_\chi$  bound between  $\mu = -4 \text{ TeV}/c^2$  and  $-500 \text{ GeV}/c^2$  is less than  $0.2 \text{ GeV}/c^2$ , so theoretical

prejudice on the range of  $\mu$  need not be taken into account. As  $\tan\beta$  approaches 2, the minimum neutralino mass is found for  $\mu$  near  $-70 \text{ GeV}/c^2$ .

When  $\tan\beta$  falls below 2, the neutralino search at LEP 1.5 excludes additional regions of parameter space, as can be seen clearly for  $\tan\beta = \sqrt{2}$  in Fig. 2. R marks the point at which the chargino bound places a lower limit on  $M_\chi$ ; this limit is improved at point Q by the LEP 1.5 neutralino bound. The improvement is significant for  $1.1 < \tan\beta < 1.5$ . For example, when  $\tan\beta = 1.35$ , the chargino limits alone do not exclude a massless neutralino, but the neutralino results place the bound at  $M_\chi > 10 \text{ GeV}/c^2$ .

The reach of the LEP 1.5 neutralino bounds is limited to the higgsino region (typically  $|\mu| \lesssim 55 \text{ GeV}/c^2$ ), and does not suffice to exclude massless neutralinos for  $\tan\beta < 1.1$ . Fortunately, the direct search for neutralinos at LEP 1 covers the region not covered by LEP 1.5. The production of  $\chi\chi'$  and  $\chi'\chi'$  in Z decays would be large, so this region is excluded by the direct search for neutralinos at LEP 1 [7], as shown in Fig. 2, where the point P marks the limit obtained from the LEP 1.5 and LEP 1 excluded regions taken together. The results from LEP 1 start to play a role for  $\tan\beta \lesssim 2$ , and, taken together with the chargino and neutralino results from LEP 1.5, exclude for any  $\tan\beta$  a lightest neutralino with mass less than  $12.8 \text{ GeV}/c^2$  at 95% CL. This bound is shown in Fig. 3, along with the previous bound from LEP 1, and the intermediate results from the LEP 1.5 chargino and neutralino searches. It does not depend on any specific relations among sneutrino and slepton masses provided they are all greater than approximately  $100 \text{ GeV}/c^2$ .

A minor exception to this bound on  $M_\chi$  deserves some comment. A close-up view of the relevant excluded regions in the  $(\mu, M_2)$  plane is shown in Fig. 4, for  $\tan\beta = 1.01$ . A small hole not covered by any of these analyses is indicated near  $\mu = -30 \text{ GeV}/c^2$  and  $M_2 = 3 \text{ GeV}/c^2$ . At centre-of-mass energies reached by LEP so far, chargino production in this region is not possible. Furthermore, only the couplings of  $\chi'\chi''$  and  $\chi'\chi'''$  to the Z are non-vanishing. The latter, however, is kinematically forbidden, leaving  $\chi'\chi''$  alone as a possible signal channel. The cross section is about 0.7 pb, allowing exclusion for roughly twice the luminosity recorded by ALEPH. One might expect, therefore, that a combination of the neutralino searches performed by the LEP Collaborations would show that hole to be covered. The analysis of Ref. [7] was performed using fewer than  $2 \times 10^5$  Z decays. An update using the full data sample would reduce the size of this hole but not eliminate it completely. It exists only for  $\tan\beta < 1.02$  and  $M_{\tilde{\nu}} > 80 \text{ GeV}/c^2$ , and hereafter will be ignored. The bound  $M_\chi > 12.8 \text{ GeV}/c^2$  is given by the point P in Fig. 4.

The LEP 1 results alone cannot rule out a massless neutralino for low  $\tan\beta$  because the chargino mass limit does not overlap the limit from the neutralino search sufficiently. The improved bounds presented in Fig. 3 do not result simply from the higher centre-of-mass energies at LEP 1.5, but rather from a particular juxtaposition of excluded regions. In this light it is worth noting that  $\chi\chi'$  production excluded by the LEP 1.5 neutralino search covers a narrow strip along  $M_2 \approx -2|\mu|$  not ruled out by LEP 1 searches (Fig. 2) due to a vanishing coupling of the Z to  $\chi\chi'$ .

The importance of the neutralino searches in the small  $|\mu|$ , small  $M_2$  regime is evident. For part of this region the final state can contain one or two  $\chi'$ 's, which decay to  $\chi\gamma$  with a

large branching fraction [12]. Even though the  $\chi'$  and  $\chi$  can be very light, they are boosted and the photon is energetic. The results presented here were made insensitive to the details of these radiative decays by augmenting the selection of Ref. [8] with one which requires an energetic, isolated photon, and with the search for acoplanar photon pairs reported in Ref. [13]. Details are given in the Appendix.

## 2.2 Light Sneutrinos and Sleptons

The impact of light sneutrinos and sleptons in the production and decay of charginos and neutralinos can be investigated taking into account experimental bounds. The most general case is too complicated to be useful, however, so the available information is best organized by making some additional, theoretically well-motivated assumptions.

In supergravity-inspired GUTs all SUSY scalar particles have a common mass  $m_0$  and all SUSY fermions have a common mass  $m_{1/2}$  at the GUT scale [14]. After evolution from the GUT to the electroweak scale according to the renormalization group equations [15], the following formulae for slepton and sneutrino masses apply:

$$\begin{aligned} m_{\tilde{l}_R}^2 &= m_0^2 + 0.15 m_{1/2}^2 - \sin^2 \theta_W M_Z^2 \cos 2\beta \\ m_{\tilde{l}_L}^2 &= m_0^2 + 0.52 m_{1/2}^2 - \frac{1}{2}(1 - 2 \sin^2 \theta_W) M_Z^2 \cos 2\beta \\ m_{\tilde{\nu}}^2 &= m_0^2 + 0.52 m_{1/2}^2 + \frac{1}{2} M_Z^2 \cos 2\beta. \end{aligned} \tag{1}$$

According to these assumptions, all charged left-sleptons have the same mass, and all right-sleptons have the same mass, always smaller than that of the left-sleptons. The theoretical parameters  $m_{1/2}$  and  $M_2$  are interchangeable:

$$M_2 = 0.82 m_{1/2} \tag{2}$$

at the electroweak scale. Consequently, the gaugino and the slepton masses are linked.

The sensitivity of the  $M_\chi$  limit (Fig. 3) to light sneutrino and selectron masses can be investigated coherently by use of these relations. The results of the previous subsection correspond to  $m_0 = 200 \text{ GeV}/c^2$ . For smaller values of  $m_0$ , the changes in the production and decay of charginos and neutralinos follow a pattern which can be illustrated by the following example.

Relevant excluded regions in a limited portion of the  $(\mu, M_2)$  plane are shown in Figs. 2, 5, and 6, for  $\tan \beta = \sqrt{2}$  and decreasing values of  $m_0$ . As discussed previously, the sneutrinos and sleptons have little influence for  $m_0 = 200 \text{ GeV}/c^2$  (Fig. 2), and the lowest allowed value for  $M_\chi$  is given by the intersection point P of the LEP 1.5 chargino curve and the LEP 1 direct search for neutralinos. For  $m_0 = 68 \text{ GeV}/c^2$  however (Fig. 5), the limit is weaker due to the effects described in the following. If the electron-sneutrino and selectron had no influence on the production or decay of charginos and neutralinos, then point P would mark the limit on  $M_\chi$ . Taking into account the decrease of the chargino cross section due to the low electron-sneutrino mass ( $M_{\tilde{\nu}} \approx 62 \text{ GeV}/c^2$ ), the limit falls to point P'. At that point, however, the two-body decays  $\chi^\pm \rightarrow \ell^\pm \tilde{\nu}$  and  $\chi' \rightarrow \nu \tilde{\nu}$  dominate, and since



the sneutrino mass is close to the chargino and neutralino masses ( $M_{\chi^\pm} \approx 64 \text{ GeV}/c^2$  and  $M_{\chi^0} \approx 65 \text{ GeV}/c^2$ ), the point is not excluded. The actual experimental limit is given by point P'', at which  $M_\chi = 9.2 \text{ GeV}/c^2$ . This erosion of the excluded region from P' to P'' is a direct consequence of the sharp transition from three-body to two-body decays mentioned above. The actual 'blind spot' in the exclusion of charginos at LEP 1.5 is shown in Fig. 7. Although a substantial region of two-body decays is excluded, it does not strengthen the lower limit on  $M_\chi$ .

Given the importance of sneutrinos and sleptons on the  $M_\chi$  limit, it is worth examining the bounds on their masses. The analysis of Ref. [8] is employed to derive bounds on the production of charged sleptons. Masses are calculated as a function of  $m_0$ ,  $M_2$ , and  $\tan\beta$  according to Eqs. (1) and (2). Production cross sections for selectrons and decay branching ratios for left-sleptons depend on couplings to and masses of the gauginos, so  $\mu$  plays an implicit role. Fixing  $\tan\beta$ , limits in the  $(M_2, m_0)$  plane can be derived, taking the values for  $\mu$  which give the most conservative limit. Only those ranges of  $\mu$  not already excluded by chargino and neutralino bounds are considered. In practice, the weakest limit on  $M_2$  for a given  $m_0$  is obtained for  $-300 \lesssim \mu \lesssim -50 \text{ GeV}/c^2$ .

Significant mixing between  $\tilde{\tau}_R$  and  $\tilde{\tau}_L$  can occur for large  $\tan\beta$ , resulting in a light mass eigenstate  $\tilde{\tau}_1$ . Although the production rate for the light  $\tilde{\tau}_1$  would be larger than for the flavour eigenstate  $\tilde{\tau}_R$ , this mixing between left and right-sleptons has been ignored.

Recent precise measurements of the Z line shape [16] imply a bound on the sneutrino mass:  $M_{\tilde{\nu}} > 43 \text{ GeV}/c^2$  at 95% CL. Generally speaking, the sleptons exclude a larger region in the  $(M_2, m_0)$  plane than the sneutrino mass bound when  $\tan\beta \lesssim 2$ . However, due to the different sign in the coefficients of the  $\cos 2\beta$  terms (Eq. 1), the latter bound is stronger for  $\tan\beta > 2$ .

Fig. 8 shows the regions excluded in the  $(M_2, m_0)$  plane, for  $\tan\beta = 1, \sqrt{2}, 2,$  and  $35$ , computed for  $\mu < 0$ . For  $\tan\beta = 35$  the exclusion comes solely from the sneutrino mass, while for  $\tan\beta = 2$ , both sneutrinos and sleptons play a role (the transition occurs at  $M_2 = 62 \text{ GeV}/c^2$ ). Sleptons dominate the limit for  $\tan\beta = 1$  and  $\sqrt{2}$ . The unusual shape for  $M_2 > 60 \text{ GeV}/c^2$  results from a production cross section which increases as  $m_0$  approaches zero, and an experimental acceptance which decreases due to small differences between slepton and neutralino masses. For  $\tan\beta = 1$ , in fact, a significant region is disallowed theoretically by the requirement that the neutralino be lighter than the charged sleptons, as indicated by the dashed line. Slightly above this theoretical limit the experimental acceptance is zero because the lepton momenta are too low. At  $M_2 \sim 44 \text{ GeV}/c^2$ , however, the sneutrino limit coming from the Z width applies, as shown.

In the large  $M_2$  region the mass difference  $M_{\tilde{\ell}_L} - M_{\tilde{\ell}_R}$  is large, and light selectrons, smuons, and staus all contribute to the limit. The associated production of  $\tilde{e}_L\tilde{e}_R$  contributes also, with both left- and right-sleptons decaying purely to  $\ell\chi$ . In contrast, the bound for small  $M_2$  comes mainly from  $\tilde{e}_L$  and  $\tilde{e}_R$  pairs which are nearly mass degenerate, and the contribution from  $\tilde{e}_L\tilde{e}_R$  is negligible. Although the left-sleptons develop a large branching fraction ( $\gtrsim 60\%$ ) to  $\chi^\pm\nu$  for large negative  $\mu$ , the acceptance is only a few percent lower than for the single-prong  $\ell\chi$  final state, because the event selection includes topologies with leptons and hadrons as well as acoplanar pairs [8].

The slepton and sneutrino bounds on  $M_2$  as a function of  $m_0$  supplement the limits on  $M_\chi$  derived above. An example of the impact of slepton bounds in the  $(\mu, M_2)$  plane is shown in Fig. 6 for  $m_0 = 56 \text{ GeV}/c^2$  and  $\tan\beta = \sqrt{2}$ . A massless neutralino is excluded by the chargino, neutralino, and slepton bounds taken together.

The cases  $\tan\beta = 1, \sqrt{2}, 2,$  and  $35$  have been analyzed fully, as illustrated by the examples shown in Figs. 2, 5, and 6. The case  $\tan\beta = 35$  is simpler than the others because the chargino contours vary less dramatically with  $\mu$ . The limit on  $M_\chi$  is obtained by calculating the chargino limit as a function of  $\mu$  assuming zero efficiency when  $M_{\chi^\pm} > M_{\tilde{\nu}}$  in accordance with the ‘blind spot’ shown in Fig. 7. The limit on  $M_{\chi^\pm}$  coming from the Z line shape is independent of the chargino decay mode, however, and contributes for  $m_0$  in a narrow range around  $67 \text{ GeV}/c^2$ .

Fig. 9 displays the lower bound on  $M_\chi$  as a function of  $m_0$  for fixed values of  $\tan\beta$  and  $\mu < 0$ . The limits for  $m_0 > 70 \text{ GeV}/c^2$  come from the charginos and neutralinos, and are nearly independent of  $m_0$ . Below some point  $m_0 \approx 70 \text{ GeV}/c^2$  the effects of a light sneutrino cause a precipitous drop in the limit; this drop is more a consequence of effectively invisible two-body decays than of reduced chargino production. For  $40 < m_0 < 60 \text{ GeV}/c^2$ , the limits follow from the bounds on  $M_2$  from sneutrinos and sleptons, within the  $\mu$  range allowed by the charginos and neutralinos, similar to those depicted in Fig. 8. In particular, the region of small  $M_2$  and large  $m_0$  is important as it generally overlaps with the bounds from charginos. The value of  $\mu$  giving the lowest  $M_\chi$  is used, which generally differs from that which gives the lowest  $M_2$ , due to the dependence of  $M_\chi$  on  $\mu$ . Sneutrinos dominate for  $\tan\beta = 2$  and  $35$ , and sleptons dominate for  $\tan\beta = \sqrt{2}$  and  $1$ , hence the slight difference in shape.

For  $\tan\beta = 1, 2,$  and  $35$  the chargino/neutralino and the slepton/sneutrino bounds overlap, precluding massless neutralinos. For  $\tan\beta$  in the neighbourhood of  $\sqrt{2}$ , however, a massless  $\chi$  is possible, provided  $m_0 \approx 60 \text{ GeV}/c^2$ , *i.e.*,  $M_{\tilde{\nu}} \approx 47 \text{ GeV}/c^2$ ,  $M_{\tilde{e}_L} \approx M_{\tilde{e}_R} \approx 65 \text{ GeV}/c^2$ , and  $\mu \approx -60 \text{ GeV}/c^2$ . The full extent of this massless neutralino window in the  $(\mu, m_0)$  plane is displayed in Fig. 10. The larger triangular opening is obtained allowing  $\tan\beta$  to be free, while the dashed contour is obtained fixing  $\tan\beta = \sqrt{2}$ . There is no opening for  $\tan\beta < 1.2$  or  $\tan\beta > 1.8$ . This window is caused by the impact of light sneutrinos on the experimental efficiency for selecting charginos and neutralinos, not by kinematic limits or a lack of luminosity.

Although the four limits shown in Fig. 9 behave similarly, the limit on  $M_\chi$  for a given  $m_0$  plainly varies with  $\tan\beta$ . Four values of  $m_0$  have been chosen to illustrate this dependence:  $m_0 = 200 \text{ GeV}/c^2$ , (Fig. 3), exemplifies the case in which sneutrinos and selectrons play a negligible role, while for  $m_0 = 70 \text{ GeV}/c^2$  their effect is pronounced but not disastrous. For  $m_0 = 50 \text{ GeV}/c^2$ , the limit comes entirely from the slepton and sneutrino bounds evaluated for the  $\mu$  ranges allowed by chargino and neutralino bounds. The value  $m_0 = 62 \text{ GeV}/c^2$ , giving a relatively weak bound on  $M_\chi$ , is included also. The limits on  $M_\chi$  for these four fixed values of  $m_0$  are shown in Fig. 11 for  $\mu < 0$ .

Indirect limits on  $M_\chi$  from the chargino, neutralino, slepton, and sneutrino bounds have been derived for  $\mu > 0$ , also, and are shown in Fig. 12 for the same values of  $m_0$ . The limits for  $m_0 = 70 \text{ GeV}/c^2$  and  $200 \text{ GeV}/c^2$  are stronger for positive  $\mu$  than negative  $\mu$  because

they come mainly from gauginos. They also show little or no dependence on  $\tan\beta$ . For  $m_0 = 50 \text{ GeV}/c^2$ , however, a light sneutrino erodes the chargino limits for large positive  $\mu$  and  $\tan\beta \gtrsim 1.5$ . The strong  $\mu$  dependence of  $M_\chi$  in this case leads to a limit weaker than the one obtained for negative  $\mu$ .

### 2.3 Minimal Supergravity Scenario

The large number of parameters of the MSSM can be reduced by additional hypotheses, most of which are natural within the framework of supergravity [1]. Here the following further assumptions are made: The scalar mass parameter  $m_0$  is universal, applying for Higgs bosons and squarks as well as for sleptons and sneutrinos. The trilinear coupling  $A$  is universal for all scalars. Electroweak symmetry breaking proceeds from radiative corrections induced by the large top quark Yukawa coupling, a calculation which relates the  $\mu$  parameter to the others, up to a sign. The remaining parameters are therefore  $m_{1/2}$ ,  $m_0$ ,  $A$ ,  $\tan\beta$  and the sign of  $\mu$ . The possible sets of values for these parameters are restricted by the requirements that the top Yukawa coupling should remain perturbative up to the GUT scale, that none of the scalar particle squared masses should be negative, and that the LSP should be the lightest neutralino. This set of assumptions is commonly referred to as “minimal supergravity.”

In the following, all calculations were performed using the ISASUSY package [17]. The top quark mass was set to  $175 \text{ GeV}/c^2$ , except for values of  $\tan\beta$  too small to be consistent with such a mass, in which case the largest possible top mass was chosen (*e.g.*  $165 \text{ GeV}/c^2$  for  $\tan\beta = \sqrt{2}$ ). The  $A$  parameter was set to zero (at the GUT scale).

Exclusion domains in the  $(m_0, m_{1/2})$  plane are shown in Fig. 13 for  $\tan\beta = 2$  and 10, and for both signs of  $\mu$ . The dark areas are forbidden by the requirement that a correct electroweak symmetry breaking be achieved, or by one of the other theoretical constraints mentioned above. Substantial domains are excluded by the Z width measurement ( $M_{\tilde{\nu}} > 43 \text{ GeV}/c^2$  and  $M_{\chi^\pm} > 45 \text{ GeV}/c^2$ ). Large regions are excluded by the Higgs boson searches at LEP 1 [18] (*e.g.*  $m_h > 61 \text{ GeV}/c^2$  for  $\tan\beta = 2$  and  $m_h > 45 \text{ GeV}/c^2$  for  $\tan\beta = 10$ ), particularly for low values of  $\tan\beta$  and for negative  $\mu$ . These excluded domains are considerably extended by the chargino searches at LEP 1.5. It turns out that the constraints from neutralino searches at LEP 1 and LEP 1.5 and the slepton searches at LEP 1.5 do not exclude any additional region of parameter space.

The lower bound on  $M_\chi$  as a function of  $\tan\beta$  is displayed in Fig. 14. Large portions of the  $(m_0, m_{1/2})$  plane are excluded on theoretical grounds when  $\tan\beta < 1.2$ , resulting in a rapid rise for the  $M_\chi$  bound as  $\tan\beta \rightarrow 1$ . The LEP 1.5 chargino bound is effective for  $\tan\beta$  up to 2.8, supplemented for negative  $\mu$  by the Higgs bound, which decreases slowly as  $\tan\beta$  increases. At  $\tan\beta \approx 2.9$ , however, the sneutrino and chargino are almost mass degenerate, and for positive  $\mu$ , the lower limit on  $M_\chi$  drops precipitously. The Higgs bound prevents such a drop for negative  $\mu$ , and for larger  $\tan\beta$ , the neutralino bounds come into play, slowly eroding as  $\tan\beta \gtrsim 5$ . The curve for  $\mu > 0$  follows the LEP 1 chargino bound for  $\tan\beta > 2.9$ .

For  $\tan\beta = 2$ , the lowest allowed neutralino mass is 28.5 and 35  $\text{GeV}/c^2$  for  $\mu < 0$  and  $\mu > 0$ , respectively; for  $\tan\beta = 10$ , the limits are 28 and 25  $\text{GeV}/c^2$ . The absolute lower bound on  $M_\chi$  under these theoretical assumptions is 22  $\text{GeV}/c^2$ .

### 3 Additional Implications

The less theoretically constrained analyses of subsections 2.1 and 2.2 have further implications which are elaborated here.

It has been pointed out recently [19] that the LEP 1 results and the LEP 1.5 chargino results do not rule out the so-called “supersymmetric limit,” for which  $M_1, M_2, \mu \rightarrow 0$  and  $\tan\beta \rightarrow 1$ . In this region of the  $(\mu, M_2)$  plane, the Z does not couple to  $\chi$  and  $\chi'$ , and associated production of  $\chi'\chi''$  and  $\chi'\chi'''$  is kinematically suppressed for  $\sqrt{s} \sim 91$  GeV. At the higher centre-of-mass energies of LEP 1.5, however, these channels are open, and the neutralino search of Ref. [8] and the additional selections detailed in the Appendix exclude these states, as shown in Fig. 4. The experimental upper limit on the cross section near the limit point is 3.0 pb, at 95% CL, to be compared to 3.5 pb expected in the MSSM. The range excluded in  $\mu$  survives for small  $m_0$ , owing to the dependence of  $M_{\tilde{\nu}}$  on  $M_2$ .

The possibility that a light gluino might exist has remained experimentally open, and has attracted theoretical interest [20]. Unification of gauge couplings at the GUT scale implies that the gluino mass is proportional to  $M_2$  (neglecting radiative corrections), so the limits on  $M_2$  presented here imply bounds on the gluino mass. In particular, within the theoretical framework assumed in this analysis, a massless gluino is allowed by the ALEPH data only in the region depicted in Fig. 10. However, a new limit on the selectron mass was published recently by the AMY Collaboration [21], which extends the region excluded by ALEPH for very light neutralinos, and closes the hole in Fig. 10.

Bounds on massive gluinos have been obtained from proton collider experiments [22]. Assuming gauge unification, this limit translates into  $M_2 > 49$  GeV/ $c^2$ . Imposing this constraint in the analysis, the limit  $M_\chi > 27$  GeV/ $c^2$  is obtained for large  $m_0$ , independent of  $\tan\beta$ . The reported gluino limits, however, were obtained for specific values of  $\mu$  and  $\tan\beta$ , and it is not known how robust they are against variations of these parameters.

In the slepton sector, the variation of the sneutrino mass with  $\tan\beta$  complements that of the charged sleptons (Eq. 1). Fixing  $M_2$ , the sneutrino bound on  $m_0$  becomes stronger as  $\tan\beta$  increases, while the slepton bound becomes weaker. The combined limit turns out to vary little with  $\tan\beta$ , making a  $\tan\beta$ -independent bound in the  $(M_2, m_0)$  plane possible: For each value of  $M_2$  and within the ranges of  $\mu$  allowed by the chargino and neutralino searches, the limit in  $m_0$  is calculated as a function of  $\tan\beta$ . The lowest value is taken, which occurs for  $1 < \tan\beta < 3$ , giving the result shown in Fig. 15.

### 4 Conclusion

The combination of chargino and neutralino search limits obtained by the ALEPH Collaboration using data acquired at LEP 1 and LEP 1.5 excludes a lightest neutralino with mass less than 12.8 GeV/ $c^2$ , when the sneutrino mass is greater than 200 GeV/ $c^2$ . For large values of  $\tan\beta$ , the lower limit climbs to 34.1 GeV/ $c^2$ . The dependence on sneutrino and slepton masses has been investigated in the context of a SUSY GUT scenario. Although the

limits are weakened when the scalar mass parameter  $m_0$  falls below  $80 \text{ GeV}/c^2$ , a massless neutralino is allowed only for restricted ranges of  $\tan\beta$ ,  $m_0$ , and  $\mu$ . Further theoretical assumptions based on minimal supergravity allow the absolute lower limit  $M_\chi > 22 \text{ GeV}/c^2$ . Finally, an excluded region in the  $(M_2, m_0)$  plane independent of  $\mu$  and  $\tan\beta$  has been delineated. All of these combined limits are far more constraining than those obtained by considering either LEP 1 or LEP 1.5 data alone.

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## Appendix

The analysis of Ref. [8] has been augmented by two sets of selection criteria which require energetic, isolated photons, in order to make the results independent of the rate of radiative decay  $\chi' \rightarrow \chi\gamma$ . This is especially important in the small  $|\mu|$ , small  $M_2$  regime, where the production of  $\chi'\chi''$  and  $\chi'\chi'''$  final states is possible at LEP 1.5. Definitions of the quantities used and motivations for the selection criteria are given in Ref. [8].

The first set of selection criteria is similar to the search for hadronic events with missing energy, optimized for large mass differences ( $M_{\chi^\pm} - M_\chi$ ). It is orthogonal to that analysis, however, in that one photon is required with at least 10 GeV in energy and isolated in so far as the sum of energies of all energy flow objects inside a cone of  $30^\circ$  (and outside a cone of  $5^\circ$ ) around the photon should be less than 3 GeV.

The other requirements were adjusted to give an optimal efficiency for neutralino events in the small  $|\mu|$ , small  $M_2$  region. The number of charged particle tracks should be at least seven. The visible mass of the event, photon included, should be at least 10% of  $\sqrt{s}$  and no more than 90% of  $\sqrt{s}$ , in order to suppress radiative returns to the Z. The total transverse momentum of the event should be at least 10% of the visible energy. The missing momentum vector should point at least  $25.8^\circ$  from the beam axis, and the energy in a  $30^\circ$  “wedge” around this vector should be no more than 5% of  $\sqrt{s}$ . The acoplanarity angle, calculated from the vector sums of all energy flow objects in each hemisphere, should be less than  $160^\circ$ . Finally, the direction of a hypothetical neutrino, calculated using energy and momentum conservation and allowing for initial state radiation along the beam line, must point at least  $25.8^\circ$  from the beam axis. The expected number of background events is 0.2, coming mainly from radiative returns to the Z.

The second set of selection criteria is based on the two-photon analysis of Ref. [13]. Some selection criteria were tightened in order to reduce background expectations, and no attempt was made to incorporate converted photons. The event is required to have no charged particle tracks and a minimum of two photons. Taking the two most energetic ones, one photon must have energy greater than 10 GeV and the other energy greater than 5% of  $\sqrt{s}$ . The angle of the first photon with the beam should be at least  $18.2^\circ$ , and the angle of the second,  $25.8^\circ$ . The acoplanarity angle of the two photons should be less than  $170^\circ$ . Finally, the total energy within  $12^\circ$  of the beam axis should be zero. The background expectation is half an event from  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ .

The efficacy of these selections can be judged from two test cases. The first one ( $\mu = -1 \text{ GeV}/c^2$ ,  $M_2 = 1 \text{ GeV}/c^2$ ,  $\tan\beta = 1.01$ ) is near the supersymmetric limit, and the first two neutralinos are nearly massless. The analysis of Ref. [8] accepts a signal cross section of 0.32 pb, to which the two selections described above add 0.23 and 0.11 pb, respectively; the total number of events expected would be 3.5. The second point in parameter space ( $\mu = -25 \text{ GeV}/c^2$ ,  $M_2 = 1 \text{ GeV}/c^2$ ,  $\tan\beta = 1.01$ ) is close to the boundary in Fig. 4. The new selections add 0.32 and 0.18 pb to the 0.10 pb accepted by the old analysis, giving an expected signal of 3.1 events. These yields are estimated taking  $m_0$  to be large; they would increase for smaller  $m_0$ .

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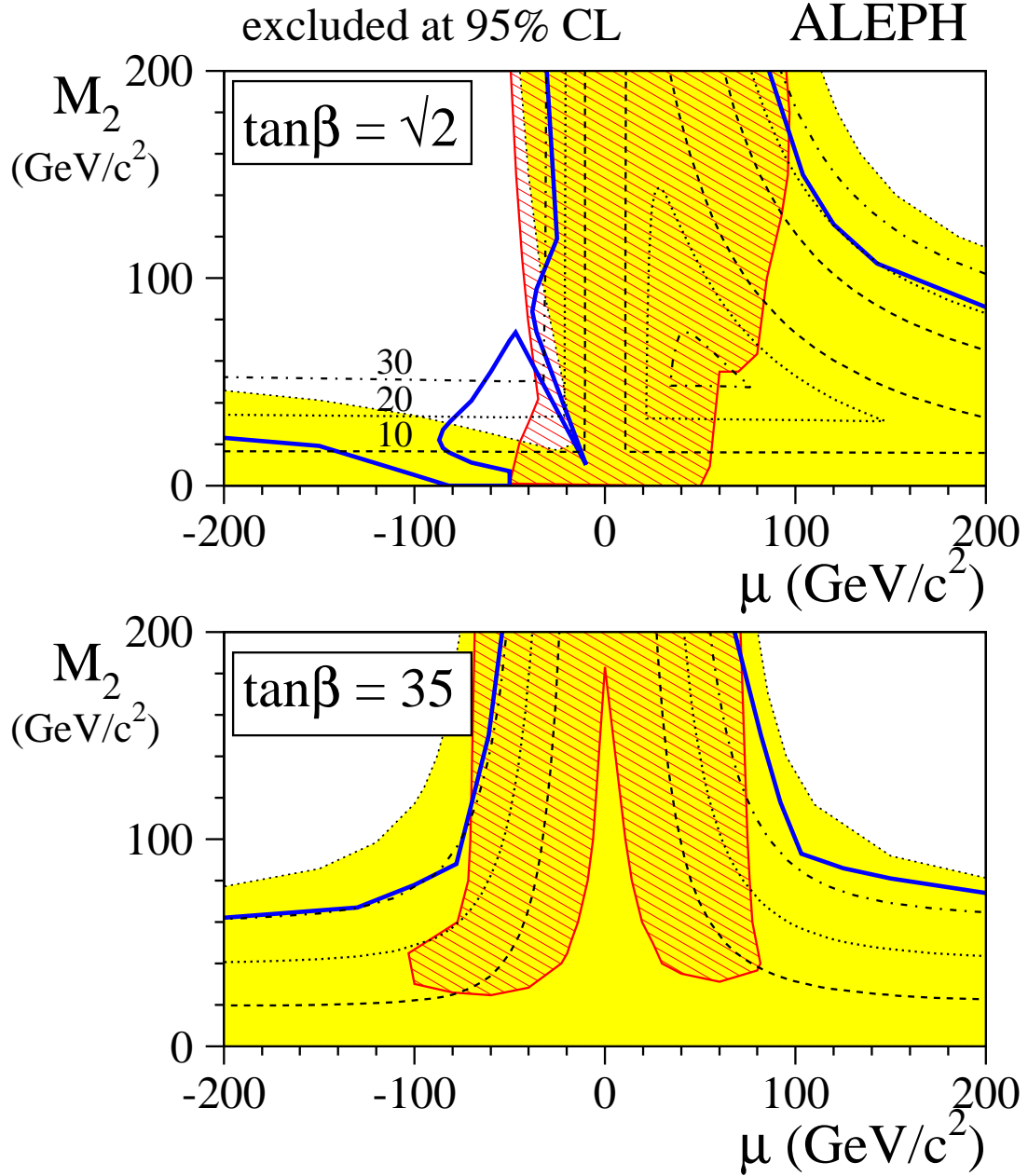


Figure 1: Excluded regions in the  $(\mu, M_2)$  plane, for  $\tan\beta = \sqrt{2}$  and 35, computed for  $M_{\tilde{\nu}} = 500$  GeV/c<sup>2</sup>. The shaded (hatched) region is excluded by the chargino (neutralino) search at LEP 1.5. The heavy black curve shows the region excluded at LEP 1. Finally, curves of constant neutralino mass ( $M_{\chi} = 10, 20,$  and  $30$  GeV/c<sup>2</sup>) are shown.



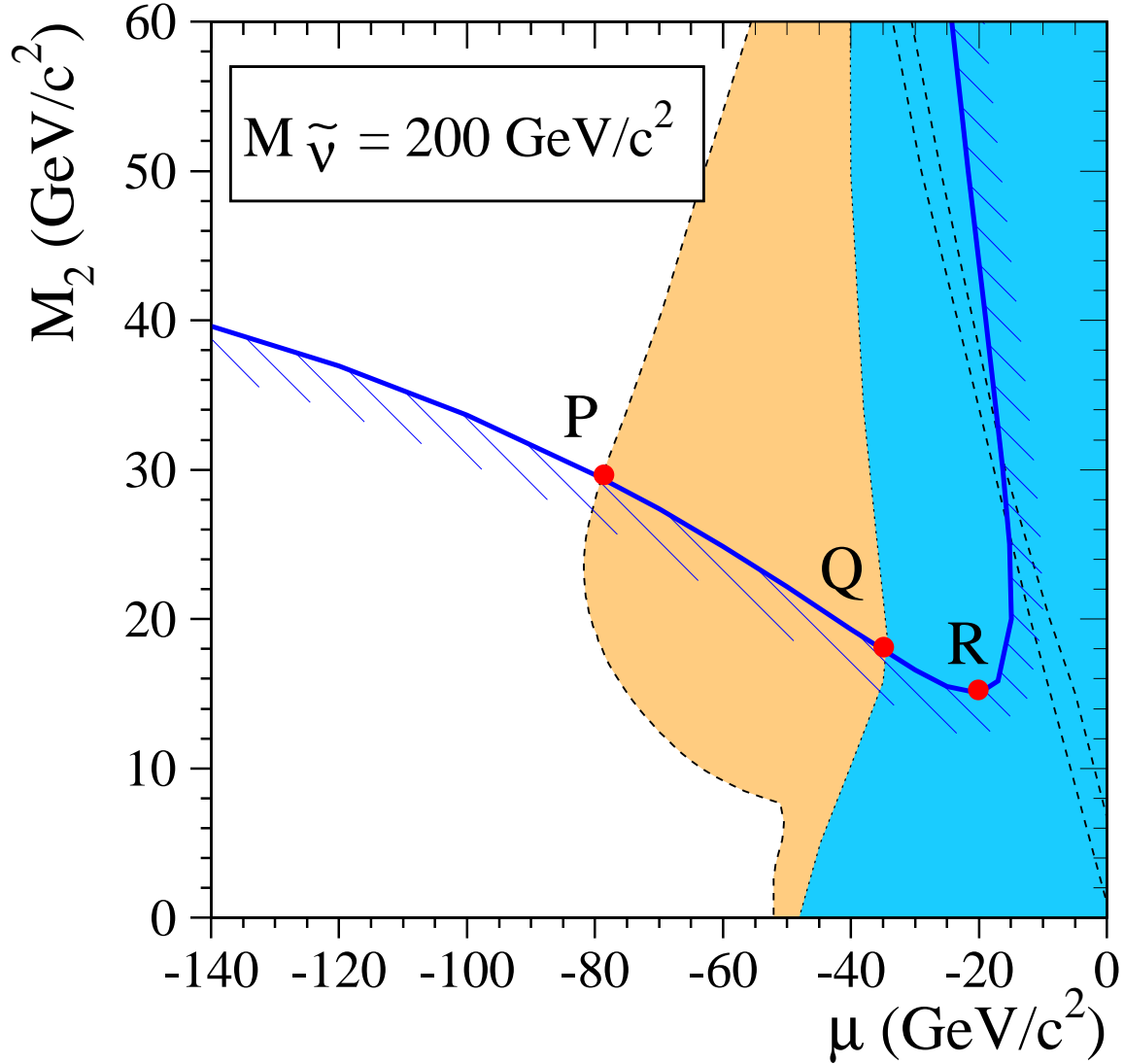


Figure 2: Close-up view of the limit contours coming from the chargino search at LEP 1.5 (heavy solid curve), from the neutralino search at LEP 1.5 (dark shaded region), and the direct search for neutralinos at LEP 1 (light shaded region), for  $\tan\beta = \sqrt{2}$  and  $M_{\tilde{\nu}} = 200 \text{ GeV}/c^2$ . (Additional exclusion contours from the  $Z$  width are not shown as they do not play any role in the bound on  $M_{\tilde{\chi}}$  for this value of  $\tan\beta$ .) Point Q is the intersection of the chargino and neutralino searches from LEP 1.5 which gives a slightly better limit on  $M_{\tilde{\chi}}$  than the chargino limit alone (point R). Point P is the intersection of the chargino and LEP 1 neutralino searches, which sets the best limit on  $M_{\tilde{\chi}}$ . The thin strip not excluded by LEP 1 is indicated by the dashed curves; it is excluded by neutralino searches at LEP 1.5.

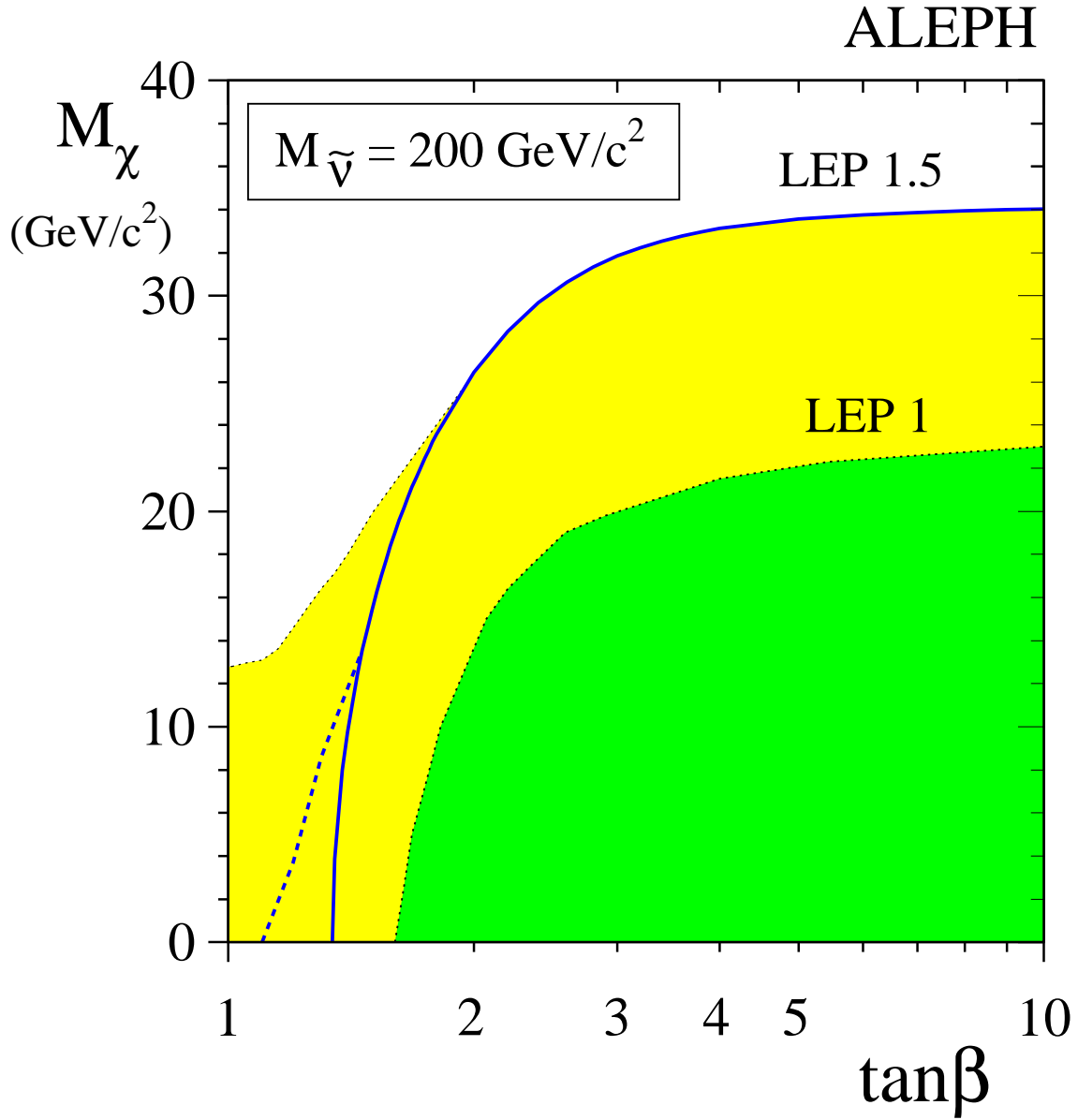


Figure 3: Lower limit on the mass of the lightest neutralino as a function of  $\tan\beta$ , for  $M_{\tilde{\nu}} = 200 \text{ GeV}/c^2$ . The previous limit from LEP 1 is shown as the dark area. The solid curve shows the limit obtained by the LEP 1.5 chargino search alone, with the small extension coming from the LEP 1.5 neutralino search shown as a dashed curve. The combined result is given by the light shaded area.

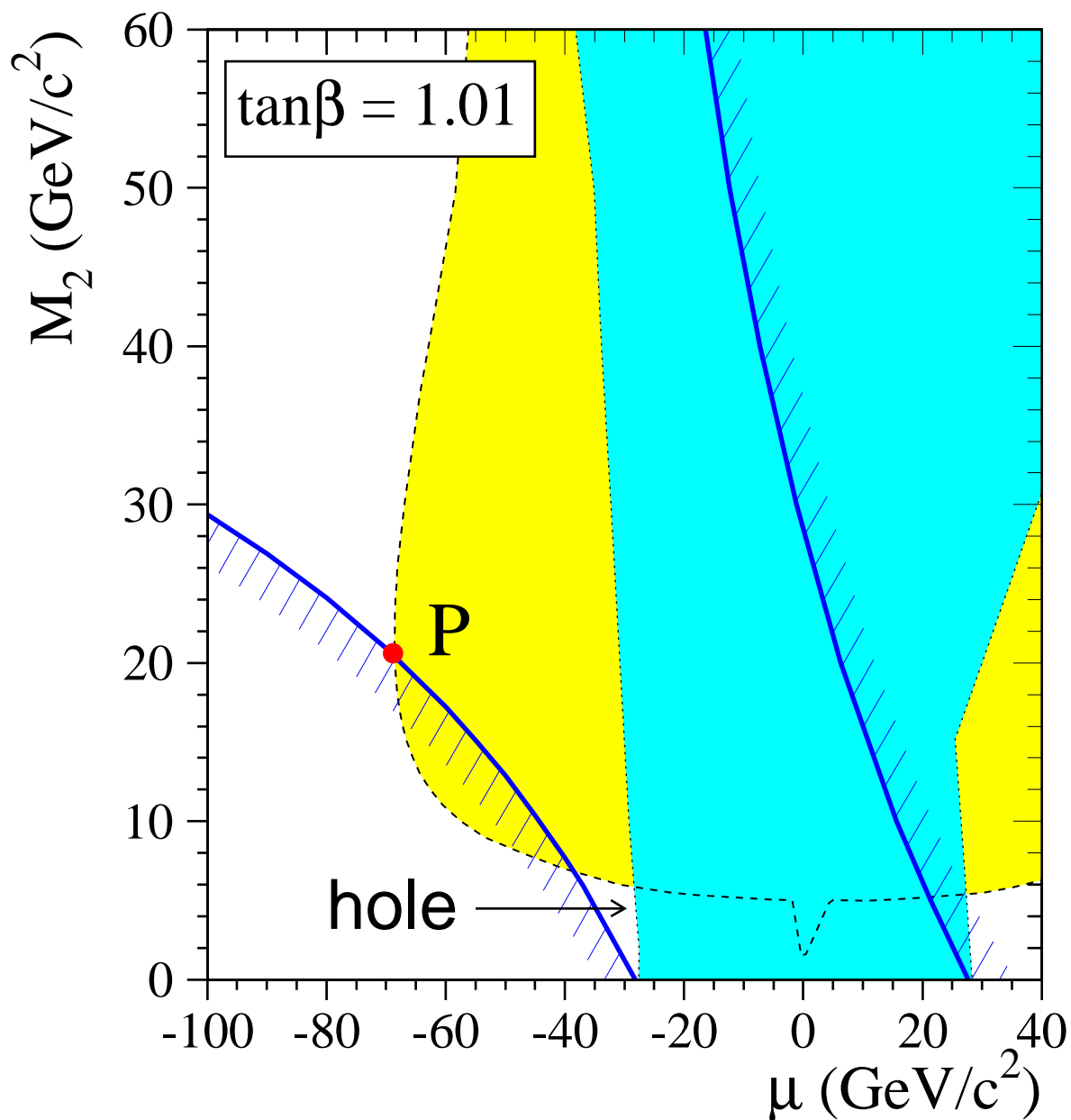


Figure 4: Close-up view of the limit contours coming from the chargino search at LEP 1.5 (heavy solid curve), from the neutralino search at LEP 1.5 (dark shaded region), and the direct search for neutralinos at LEP 1 (light shaded region), for  $\tan\beta = 1.01$  and  $M_{\tilde{\nu}} = 200 \text{ GeV}/c^2$ . A small triangular hole near  $\mu = -30 \text{ GeV}/c^2$  is evident.

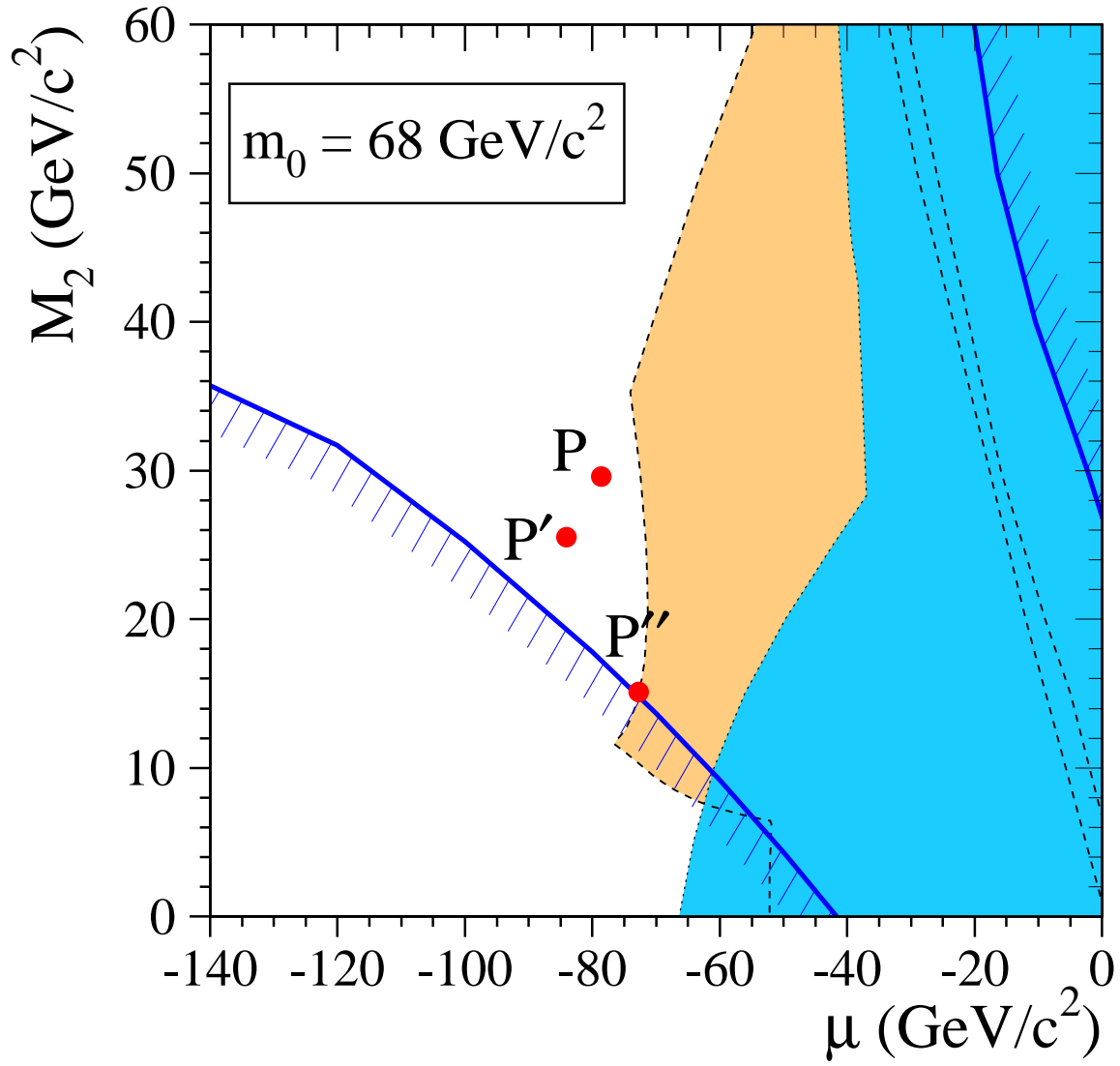


Figure 5: Close-up view of limit contours for  $\tan \beta = \sqrt{2}$  and  $m_0 = 68 \text{ GeV}/c^2$ . Contours have the same meaning as in Fig. 2. See the text for an explanation of the points P, P', and P''.

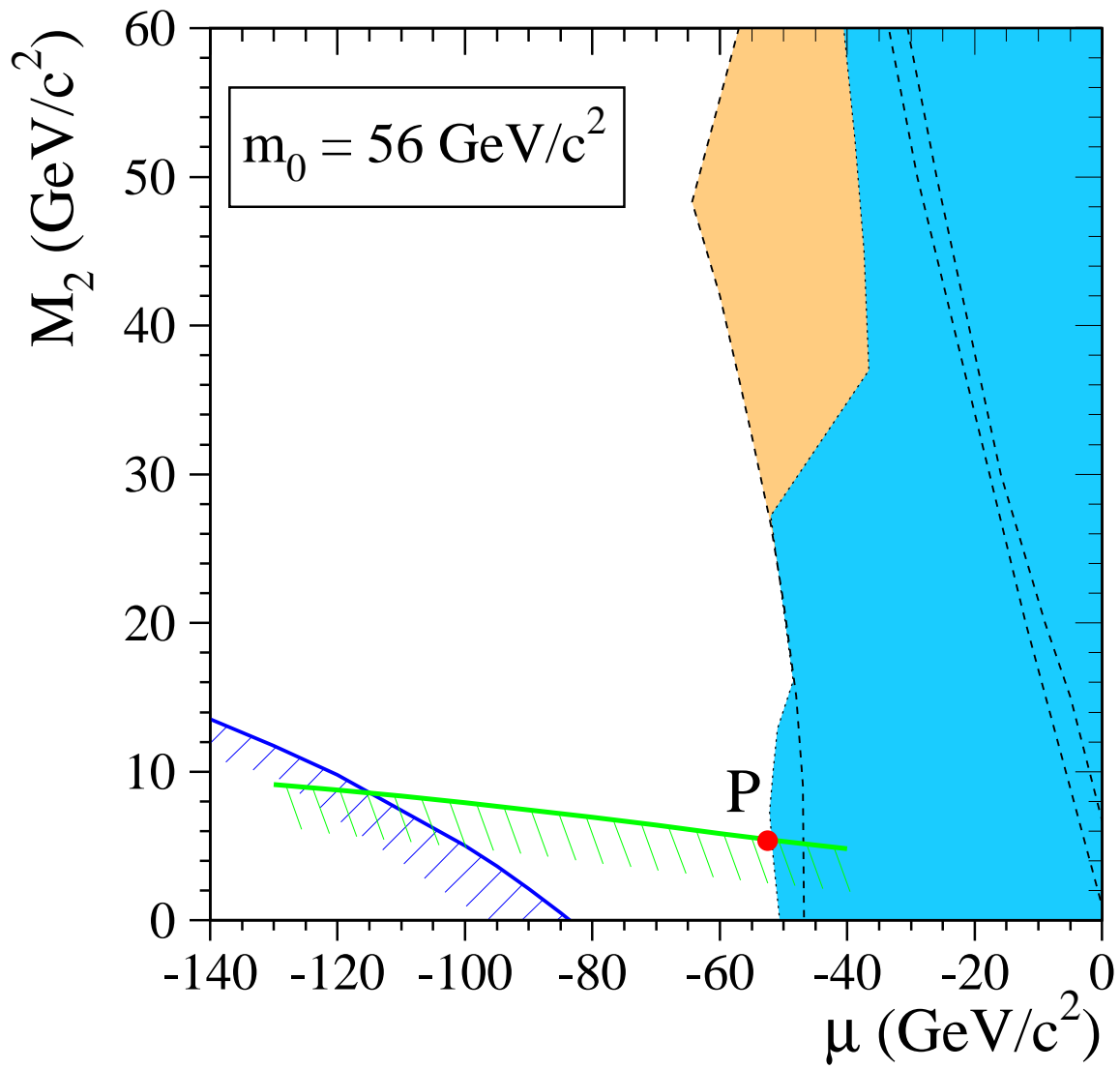


Figure 6: Close-up view of limit contours for  $\tan \beta = \sqrt{2}$ , for  $m_0 = 56 \text{ GeV}/c^2$ . They have the same meaning as in Fig. 2. The nearly horizontal solid line passing through point P is the bound derived from the slepton search.

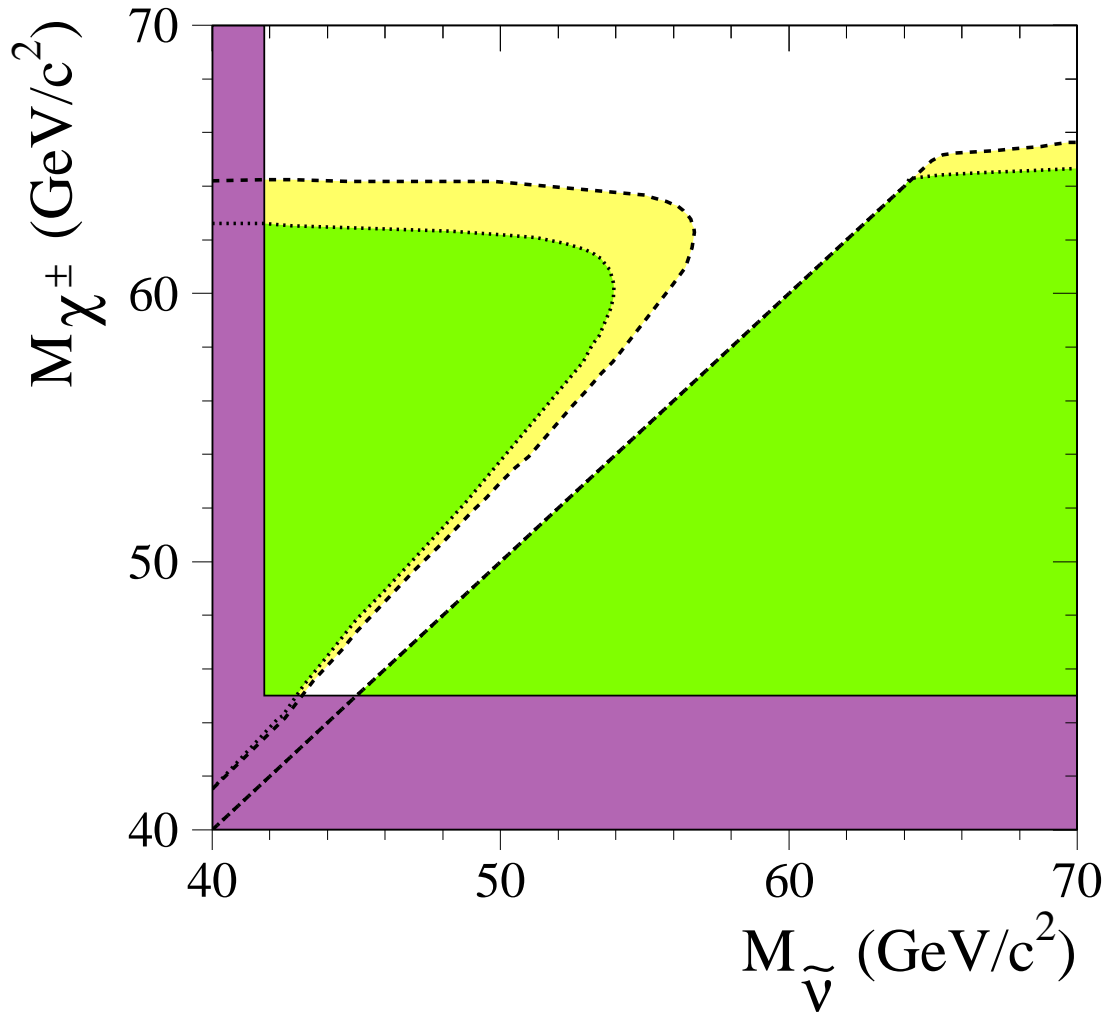


Figure 7: *Exclusion contour for charginos as a function of  $M_{\tilde{\nu}}$ . The case of the near gaugino region ( $\mu = -100 \text{ GeV}/c^2$ ) is represented by the medium dark region, which is extended to the light region for the far gaugino region ( $\mu = -500 \text{ GeV}/c^2$ ). The limits from LEP 1 are indicated by the darkest region.*

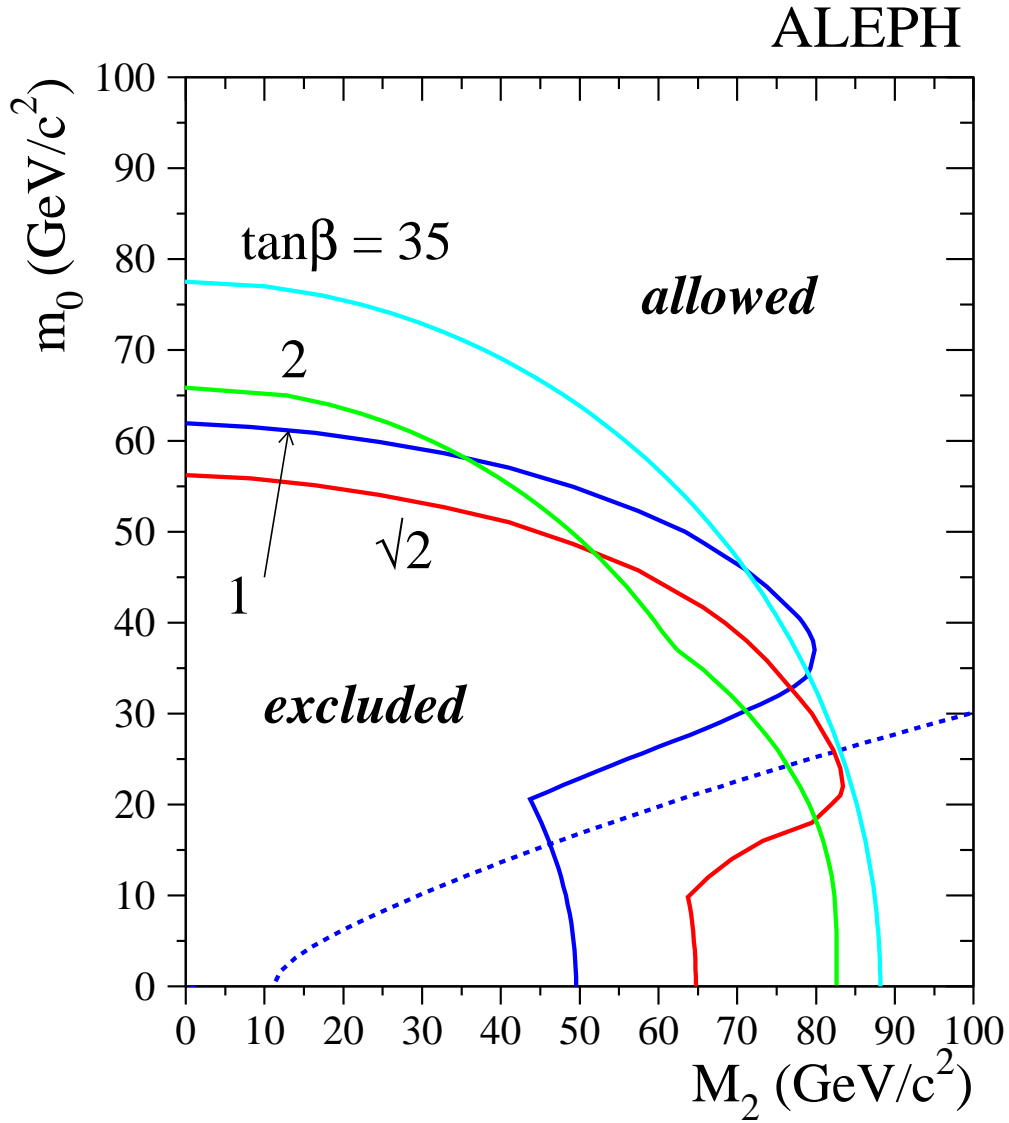


Figure 8: The solid curves show the region in the  $(M_2, m_0)$  plane excluded by the combined slepton and sneutrino limits for fixed values of  $\tan\beta = 1, \sqrt{2}, 2,$  and  $35$ , computed for  $\mu < 0$ . The dashed curve shows the theoretical limit  $M_{\tilde{l}_R} > M_\chi$  for  $\tan\beta = 1$ .

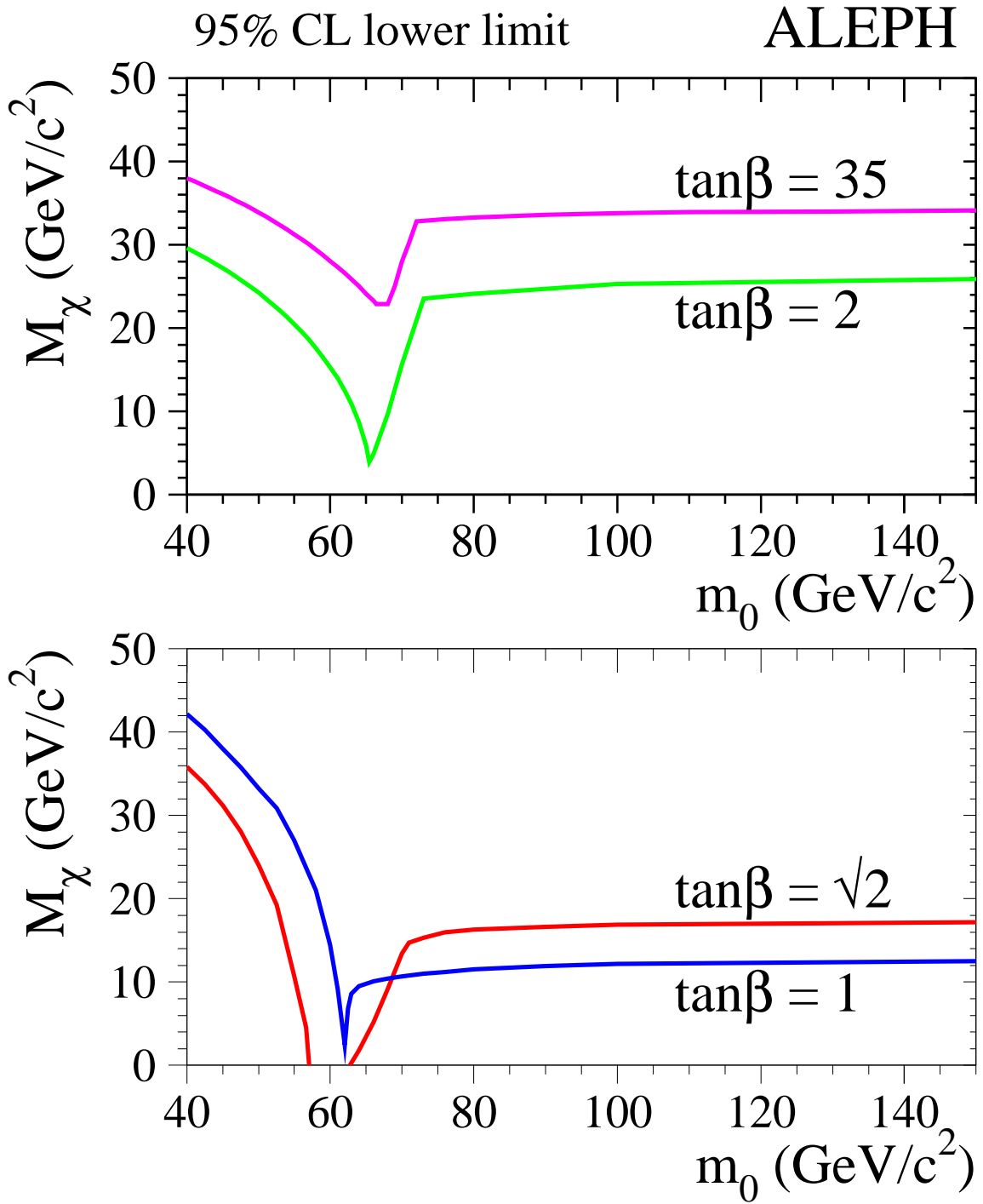


Figure 9: Limit on  $M_\chi$  as a function of  $m_0$  for  $\tan\beta = 35, 2, \sqrt{2},$  and  $1$ , restricting  $\mu < 0$ . For  $m_0 \gtrsim 65$  GeV/c<sup>2</sup>, the limit comes from the chargino and neutralino searches, while for  $m_0 \lesssim 65$  GeV/c<sup>2</sup>, it comes from the slepton and sneutrino constraints.



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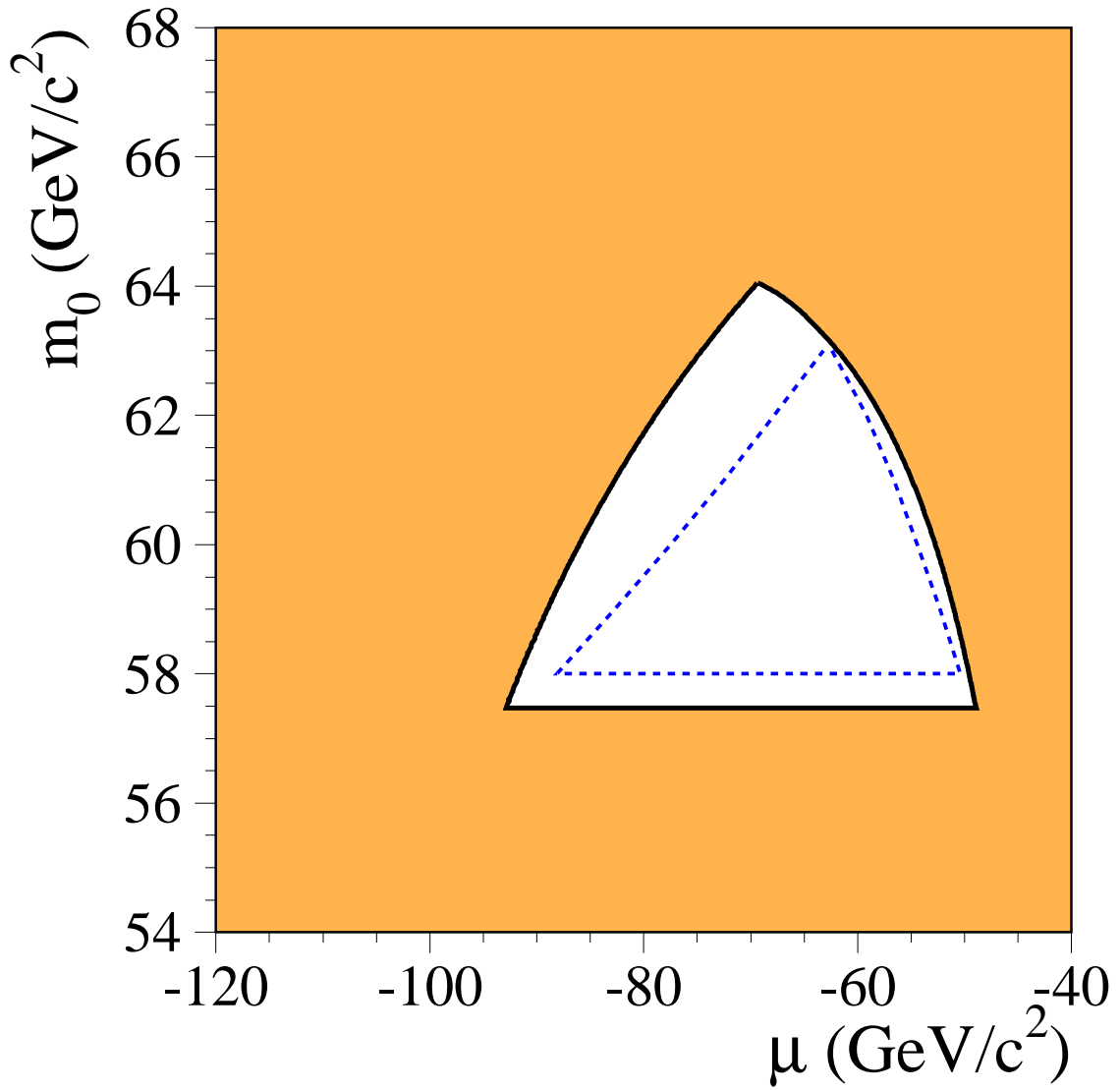


Figure 10: *Opening in the  $(\mu, m_0)$  plane in which  $M_2 = 0$ , hence a massless neutralino, is allowed. The larger triangular window is obtained allowing  $\tan\beta$  to be free; the dashed curve shows the window for  $\tan\beta = \sqrt{2}$ .*

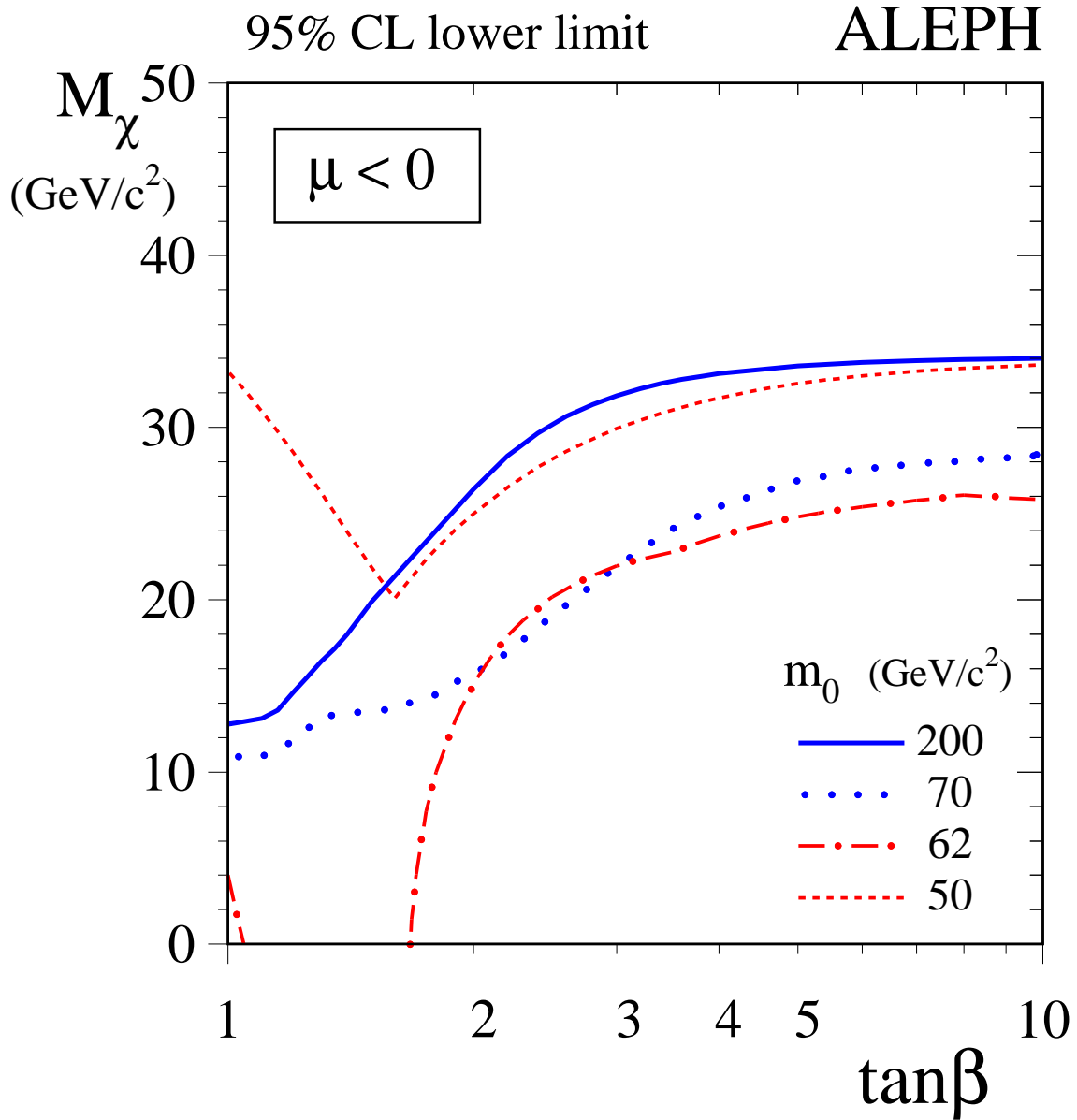


Figure 11: For  $\mu < 0$ , the lower limit on the mass of the lightest neutralino as a function of  $\tan\beta$ , for  $m_0 = 200, 70, 62,$  and  $50$  GeV/c<sup>2</sup>.

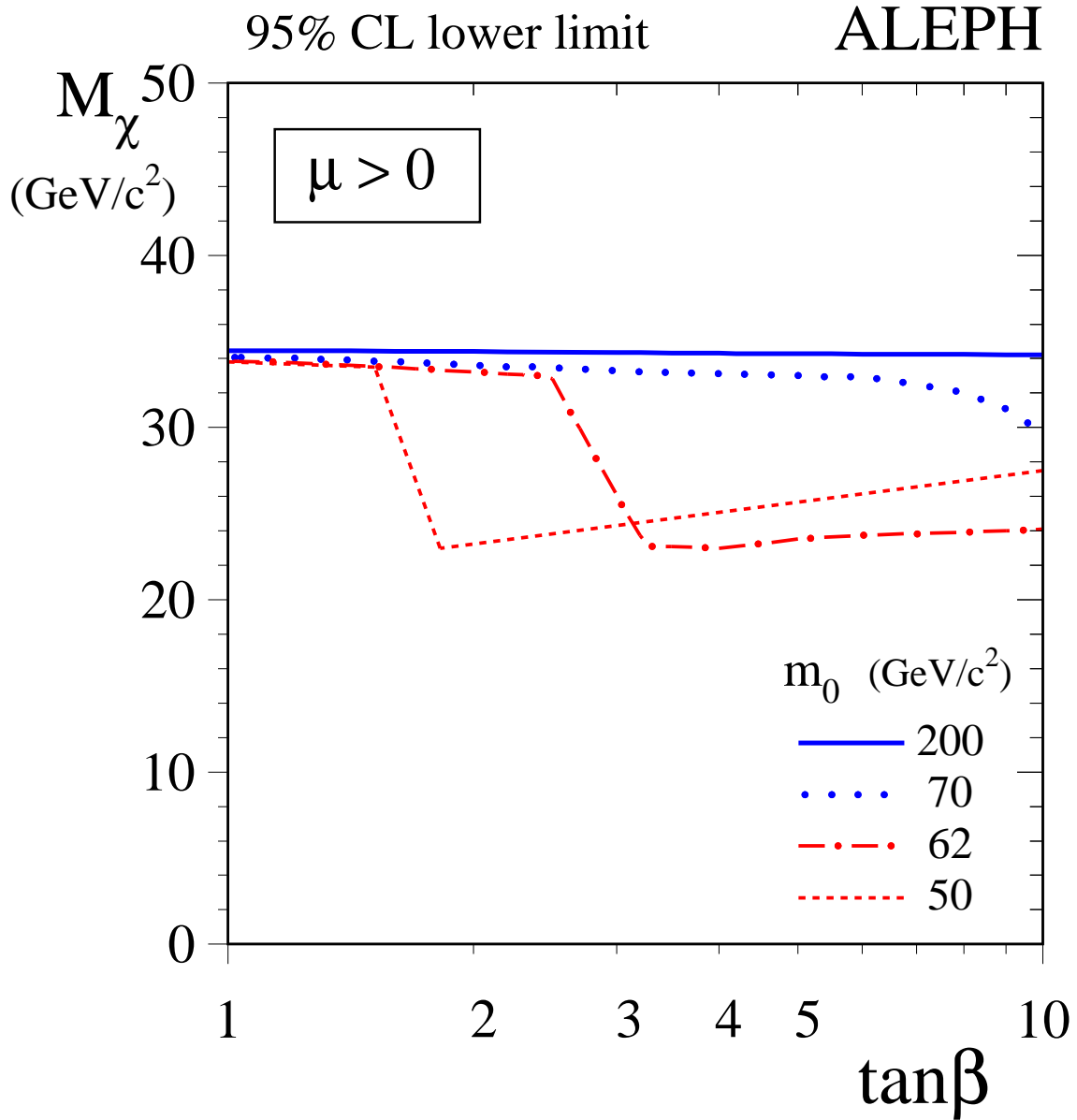


Figure 12: For  $\mu > 0$ , the lower limit on the mass of the lightest neutralino as a function of  $\tan\beta$ , for  $m_0 = 200, 70, 62,$  and  $50$  GeV/c<sup>2</sup>.

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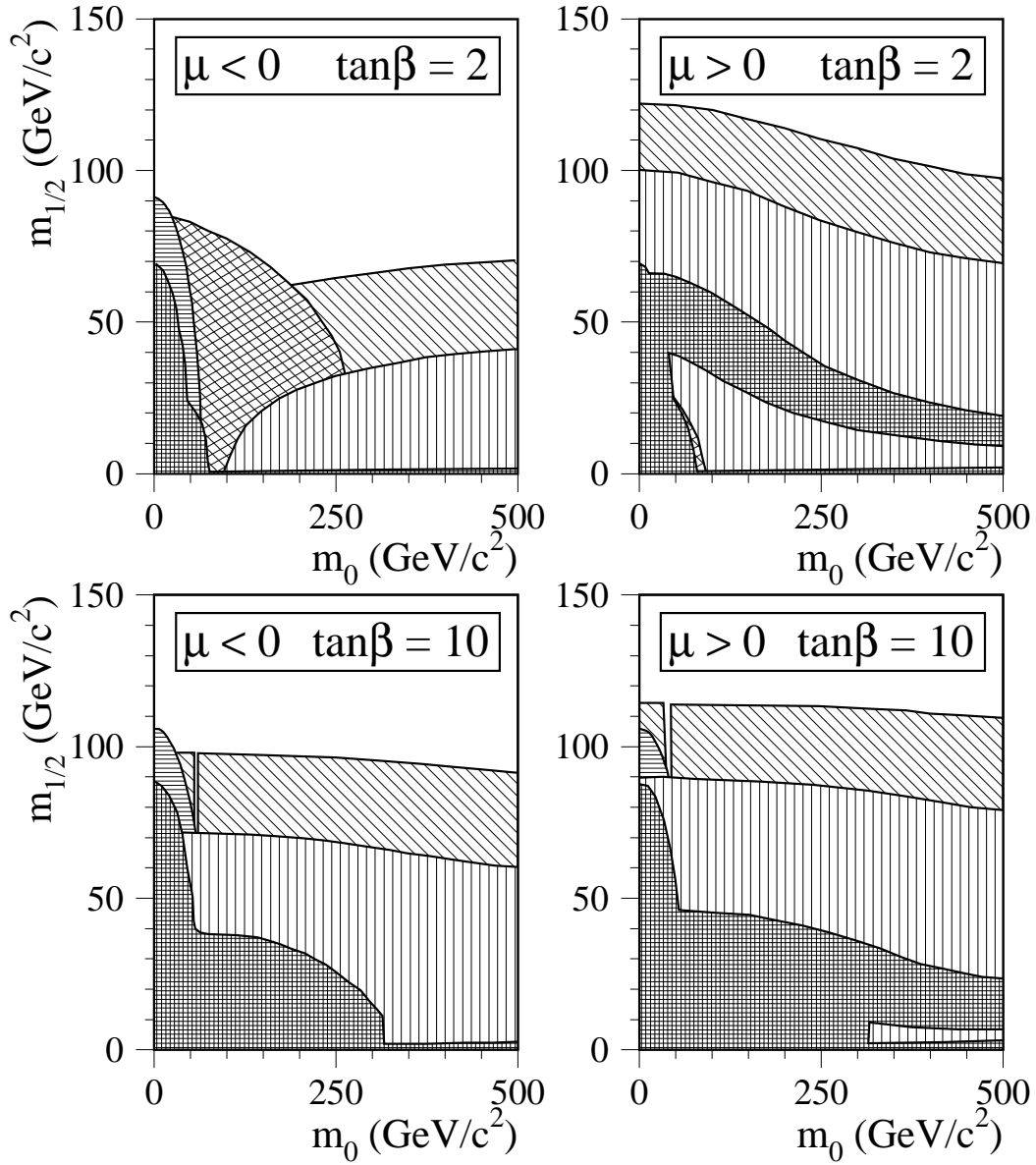


Figure 13: *Excluded domains in the  $(m_0, m_{1/2})$  plane for  $\tan\beta = 2$  (top) and 10 (bottom), and for  $\mu < 0$  (left) and  $\mu > 0$  (right). The dark shaded regions are theoretically excluded. The vertical, horizontal, crossed and slanted hatched regions are excluded by charginos at LEP 1, by sneutrinos at LEP 1, by Higgs bosons at LEP 1 and by charginos at LEP 1.5, respectively.*

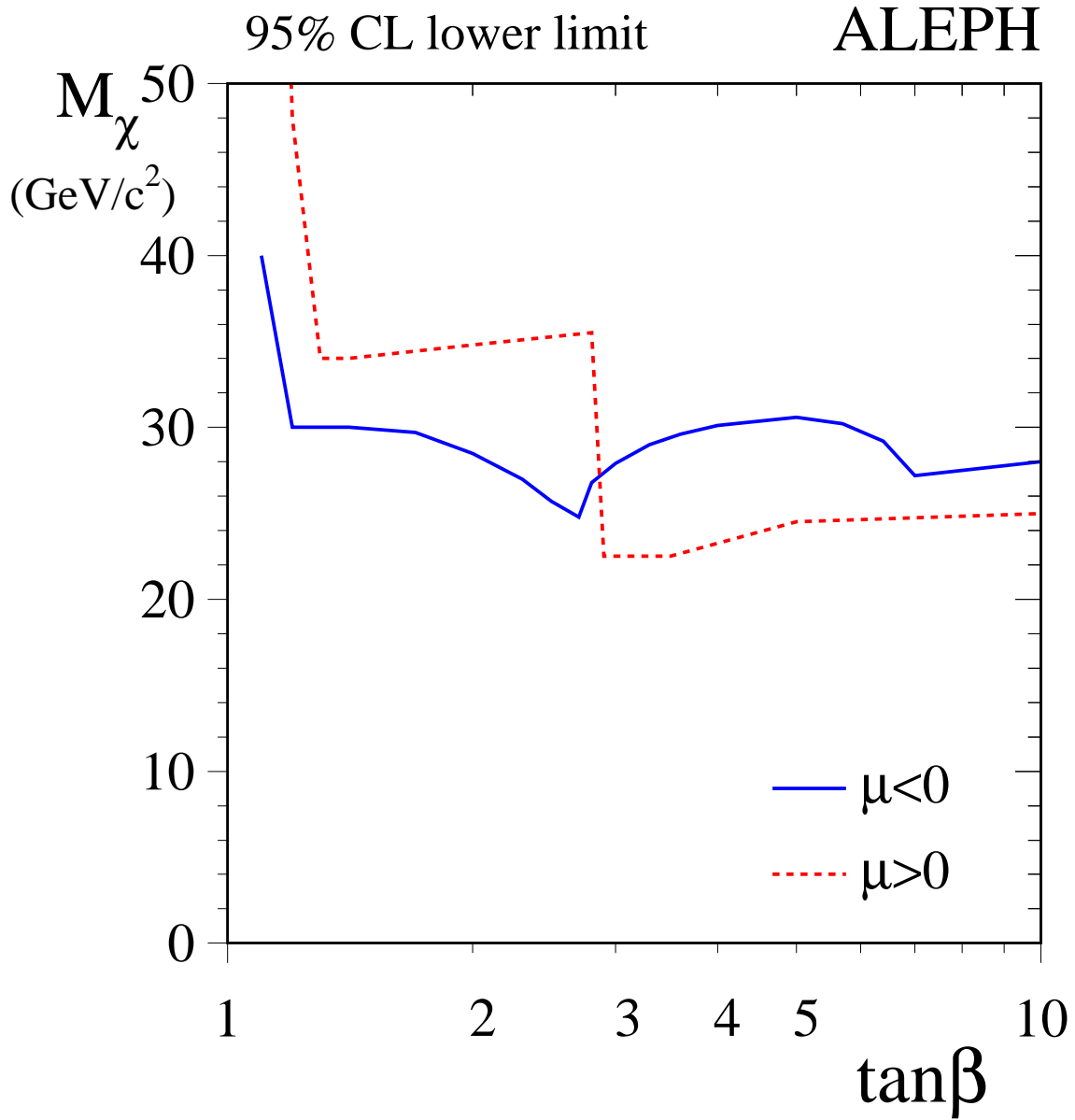


Figure 14: Lower limit on the mass of the lightest neutralino as a function of  $\tan\beta$ , obtained in the context of minimal supergravity.

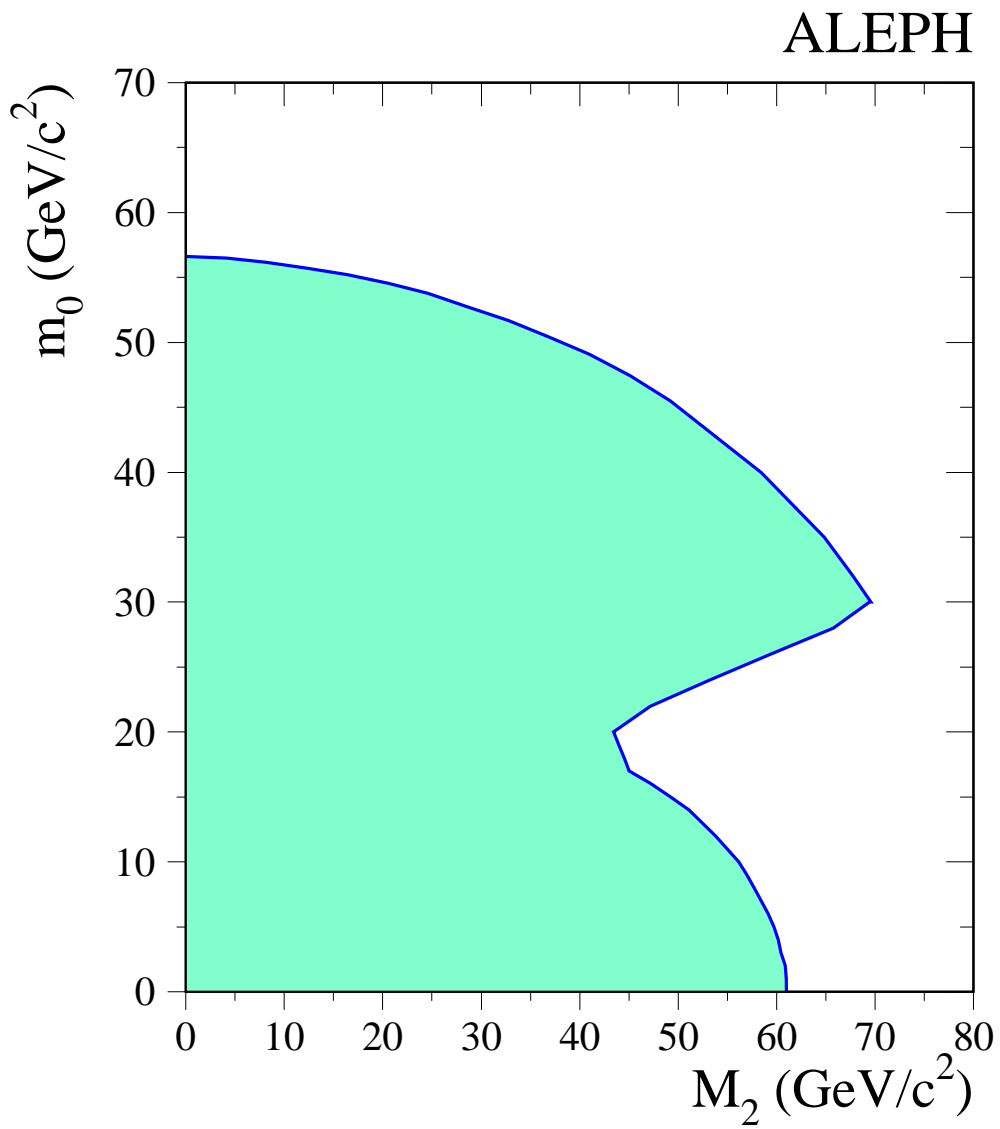


Figure 15: *Region in the  $(M_2, m_0)$  plane excluded by charginos, neutralinos, sneutrinos, and sleptons, valid for all  $\mu$  and  $\tan \beta$ .*