

Understanding SUSY limits from LEP

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Abstract. LEP results have constrained heavily the Minimal Supersymmetric Standard Model, while providing hints for light Higgs boson and for “SUSY-assisted” gauge coupling unification. In this paper the results obtained at LEP within two scenarios, the gravity-mediated MSSM framework and the minimal SUGRA scenario are presented. Model-dependence and coverage of LEP results is discussed.

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1. Introduction

Supersymmetry (SUSY) is believed to be one of the most attractive scenarios for physics beyond the Standard Model. In the last few years around 150 papers on experimental searches for SUSY were published, out of which around 100 were related to the LEP results. This large number of papers reflects perhaps as well the large number of free parameters relevant to SUSY models at the presently explored energy scale. LEP is well suited to explore corners of SUSY models in a relatively assumption independent way.

In this paper the results obtained by LEP experiments within the gravity-mediated constrained MSSM framework and the minimal SUGRA scenario are presented, emphasis is put on the model dependence of the exclusion. See [1] for a recent general review.

In the Minimal Supersymmetric extension of the Standard Model (MSSM) [2], each Standard Model particle has a supersymmetric partner with the same couplings and with spin differing by $\hbar/2$. Large corrections to the Higgs mass from interactions involving virtual particles (heavy quarks in particular) are partially cancelled due to their superpartners. If they are lighter than $1-10 \text{ TeV}/c^2$ this solves the so called hierarchy problem [3]. Moreover, supersymmetric particles modify the energy dependence of the electromagnetic, weak and strong coupling constants, and help them to unify at the scale of around 10^{15} GeV [4].

The Higgs sector of the MSSM has to be extended to two complex Higgs doublets H_1, H_2 responsible for giving masses to the up and down-type fermions. Five physical Higgs boson mass states remain after the Electroweak Symmetry breaking. The lightest scalar neutral Higgs boson h^0 and the heavier pseudoscalar neutral Higgs boson A are of interest for this paper. On the tree level, masses of the Higgs bosons depend on just two parameters, which can be chosen as $\tan\beta$, the ratio of vacuum expectation values of the two Higgs doublets, and m_A . In particular $m_h < m_Z * |\cos 2\beta|$ ‡, however due to radiative corrections mentioned above (which depend on the top quark mass, and on the mass terms of the superpartners of heavy quarks), the upper limit on the mass of the lightest Higgs boson grows to $m_h \lesssim 135 \text{ GeV}/c^2$ [5, 6].

‡ For $m_A \gg m_Z$, $m_{h^0(\text{tree})} \sim m_Z * |\cos 2\beta| / (1 + m_Z^2/m_A^2)$, and for $\tan\beta \gtrsim 10$, $m_{h^0(\text{tree})} \sim m_Z * |\cos 2\beta|$

If $m_A \gtrsim 150 \text{ GeV}/c^2$ the lightest supersymmetric Higgs boson resembles very much the one of the Standard Model. Precise electroweak measurements [7] suggest that the Higgs boson is relatively light §, $m_h = 88_{-36}^{+53} \text{ GeV}/c^2$, well in the range of the MSSM prediction. Searches for the Standard Model like Higgs boson at LEP [8, 9] set a lower limit for m_h , $m_h > 114.4 \text{ GeV}/c^2$ (if $\tan\beta < 6$, or $m_A > 120 \text{ GeV}/c^2$), constraining heavily the MSSM. The 1.7σ “excess” observed at LEP [10] of events compatible with production of the Standard Model Higgs boson with $m_h \sim 114 - 117 \text{ GeV}/c^2$, together with the EW constraints, makes low m_h , just above the reach of LEP, quite probable.

The MSSM provides a phenomenologically interesting wealth of superpartners of the Standard Model particles. Supersymmetric partners of gauge and Higgs bosons (gauginos and higgsinos) mix to realize four neutral mass states, neutralinos, $\tilde{\chi}_i^0$: $i=1,4$, and four charged mass states, charginos, $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$. Superpartners of left-handed and right-handed fermions, “right-handed” and “left-handed” scalar quarks (squarks) and scalar leptons (sleptons) can mix. This leads to the off-diagonal “left-right” terms in their mass matrices and induces an additional mass splitting between the lighter and the heavier state.

While the Higgs sector is well constrained in the MSSM, very little can be said about the superpartners mass spectrum unless one makes some additional assumptions. As no superpartners were found so far the Supersymmetry has to be broken. The pattern of the sparticle mass spectrum depends primarily on the mechanism of its breaking.

In the models with gravity mediated supersymmetry breaking which will be discussed in this paper, the lightest neutralino ($\tilde{\chi}_1^0$) is usually the Lightest Supersymmetric Particle (LSP). If R-parity || is conserved the LSP does not decay, and it is an ideal cold dark matter candidate [11]. Constraints on models with broken R-parity were discussed in [12] and are thus not discussed in this paper.

Experimental searches motivated by the MSSM with R-parity conservation and gravity-mediated supersymmetry breaking exploit features of the model independent of further assumptions, like the strength of superpartner couplings to the gauge bosons, pair-production of sparticles, and the missing energy and momentum signature due to escaping LSPs in the final state.

However, to cover “pathological” situations with final states which cannot be efficiently detected or situations where the production cross-sections are low, or finally to achieve more predictivity and set limits on masses of the sparticles which are not directly observable (e.g. the LSP in the R-parity conserving model), additional model assumptions have to be made. In this paper two “flavours” of such constraining assumptions are discussed (see section 2): the constrained MSSM with non-universal Higgs parameters (CMSSM with nUHP), which is often used to interpret LEP results, and an even more constrained minimal SUGRA scenario (mSUGRA) ¶, often used to interpret Tevatron results and for benchmark searches at future colliders [15]. It is shown in section 4 that in both models LEP results can be used to exclude sparticles much beyond the kinematic limit of LEP.

Perspectives to find sparticles at the Tevatrons Run II in view of limits from LEP are discussed in [18].

§ The central value moves to $\sim 110 \text{ GeV}/c^2$ if the top quark mass is assumed to be one standard deviation above its central value

|| R-parity is a multiplicative quantum number defined as $R = (-1)^{3(B-L)+2S}$ where B , L and S are the baryon number, the lepton number and the spin of the particle, respectively. SM particles have $R=+1$ while their SUSY partners have $R = -1$

¶ The definition of mSUGRA used in this paper corresponds to what is called CMSSM with universal Higgs masses in [14, 15, 16]

2. The models: CMSSM with nUHP and mSUGRA

To make the MSSM more predictive, the unification of some parameters at a high mass scale typical of Grand Unified Theories (GUT) can be assumed. In this section, approximate relations between the model parameters and the superpartners masses which are important to understand the experimental limits will be quoted without explanations. For a more complete information see e.g. [2].

2.1. CMSSM with nUHP

As well as the already mentioned $\tan\beta$ and m_A , the following parameters are relevant in the constrained MSSM with non-universal Higgs parameters:

- μ , the Higgs mass parameter,
- M_1, M_2, M_3 , the $U(1) \times SU(2) \times SU(3)$ gaugino masses at the electroweak (EW) scale. Gaugino mass unification at the GUT scale is assumed, with a common gaugino mass of $m_{1/2}$. The resulting relation between M_1 and M_2 is $M_1 = \frac{5}{3} \tan^2\theta_W M_2 \sim 0.5 M_2$,
- $m_{\tilde{f}}$, the sfermion masses. Under the assumption of sfermion mass unification, m_0 is the common sfermion mass at the GUT scale,
- the trilinear couplings A_f determining the mixing in the sfermion families. The third family trilinear couplings are the most relevant ones, A_τ, A_b, A_t .

Gaugino mass unification leads to $m_{1/2} \simeq 1.2 M_2$ and to the following approximate relations between $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$ and the gluino mass ($m_{\tilde{g}}$):

- in the region where $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ are *gauginos* ($|\mu| \gg M_1$), $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq 2 m_{\tilde{\chi}_1^0}$, $m_{\tilde{g}} \simeq 3.2 m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^\pm} \simeq M_2$,
- in the *higgsino* region ($|\mu| \ll M_1$), $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^0} \simeq |\mu|$.

The relations between chargino, neutralino and gluino masses and $|\mu|$ and M_2 are affected by radiative corrections of the order of 2%-20% [19]. However, *only the relative relations between chargino, neutralino and gluino masses are important from the experimental point of view*, and here the corrections are much smaller. For example, the relation $m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_1^0} \simeq 2$ in the gaugino region, which is usually exploited to set a limit on the LSP mass, receives the corrections only of the order of 2%; and the ratio $m_{\tilde{g}}/m_{\tilde{\chi}_1^\pm} \simeq 3.2$ receives corrections of the order of 6%. Thus, for example, the limit [29] on the chargino mass of $103.5 \text{ GeV}/c^2$ set by LEP (valid for $m_{\tilde{\nu}} > 300 \text{ GeV}/c^2$, $m_{\tilde{\tau}_1} > m_{\tilde{\chi}_1^\pm}$, and for $M_2 \lesssim 200 \text{ GeV}/c^2$) can be safely translated to $m_{\tilde{\chi}_1^0} \gtrsim 51 \text{ GeV}/c^2$ and $m_{\tilde{g}} \gtrsim 310 \text{ GeV}/c^2$.

If the sleptons are heavy the chargino mass limit excludes regions in $(M_2, |\mu|)$ plane (see e.g. [20]). For $\tan\beta \gtrsim 2$, $|\mu| \gtrsim 100 \text{ GeV}/c^2$ is excluded up to very high values of M_2 (of the order of $1000 \text{ GeV}/c^2$ or more) while $M_2 \lesssim 100 \text{ GeV}/c^2$ is excluded for $|\mu| \gtrsim 100 \text{ GeV}/c^2$.

Electroweak symmetry imposes the following relation between the masses of the superpartners of the left-handed electron (\tilde{e}_L) and of the neutrino ($\tilde{\nu}$),

$$1) m_{\tilde{e}_L}^2 = m_{\tilde{\nu}}^2 + m_W^2 |\cos 2\beta|.$$

The assumption of sfermion mass unification relates masses of the ‘‘left-handed’’ (m_L) and the ‘‘right-handed’’ (m_R) ‘‘light’’ sfermions, ‘‘light’’ squark masses, and the gaugino mass parameter M_2 . For example :

$$2) m_{\tilde{\nu}}^2 = m_0^2 + 0.77 M_2^2 - 0.5 m_Z^2 |\cos 2\beta|$$

$$3) m_L^2 = m_0^2 + 0.77 M_2^2 + (0.5 - \sin^2\theta_W) m_Z^2 |\cos 2\beta|$$

- 4) $m_R^2 = m_0^2 + 0.22M_2^2 + \sin^2\theta_W m_Z^2 |\cos 2\beta|$
 5) $m_{d_L} = m_0^2 + 9M_2^2 + (0.5 - 1/3\sin^2\theta_W)m_Z^2 |\cos 2\beta|$
 Thus, for example, $m_{d_L} \gtrsim 310 \text{ GeV}/c^2$, if $m_{\tilde{\chi}_1^\pm} \gtrsim 103.5 \text{ GeV}/c^2$.

Mixing between left and right states (present for superpartners of heavy fermions) gives rise to off-diagonal “left-right” mixing terms in their mass matrices, which lead to a mass splitting between the lighter and the heavier state. At the EW scale these terms are proportional to $m_\tau(A_\tau - \mu \tan \beta)$, $m_b(A_b - \mu \tan \beta)$ and $m_t(A_t - \mu/\tan \beta)$ for $\tilde{\tau}$, \tilde{b} and \tilde{t} , respectively, where A_τ, A_b, A_t are free parameters. Therefore, for large μ this can give light stau and sbottom states if $\tan \beta$ is large, or a light stop for small $\tan \beta$.

For large m_A , the lightest Higgs boson mass depends primarily on $\tan \beta$, m_{top} and the mixing in the stop sector X_t (expressed here as $X_t = A_t - \mu/\tan \beta$), and this dependence is maintained whether any additional constraints on the MSSM are imposed or not. The top quark mass is presently known with the uncertainty (1σ) of around $5 \text{ GeV}/c^2$ [21], and the resulting uncertainty of the lightest Higgs boson mass calculation is around $6.5 \text{ GeV}/c^2$, as $\Delta m_{h^0}/m_{h^0} \simeq 2\Delta m_{top}/m_{top}$. It was shown in [6] that for a given $\tan \beta$ and top mass, the maximal m_{h^0} occurs for $X_t/m_{SUSY} = \sqrt{6}$. Another, slightly lower maximum occurs for $X_t/m_{SUSY} = -\sqrt{6}$. m_{SUSY} is typically taken to be of the order of the gluino mass, or of the diagonal terms in the squark mass matrices, and m_{h^0} grows with m_{SUSY} .

It should be noted that the off-diagonal terms in mass matrices of the third family particles cannot be too big compared to the diagonal terms, in order for a real solution for sparticle masses to exist. As diagonal terms grow with m_0 and M_2 , for every given value of the off-diagonal term a lower limit is set on the corresponding combination of m_0 and M_2 ⁺.

2.2. *mSUGRA*

In the minimal SUGRA model not only the sfermion masses, but also the Higgs masses m_{H_1} and m_{H_2} , are assumed to unify to the common m_0 at the GUT scale. Then $m_{H_2}^2$ becomes negative at the EW scale in most of the parameter space, thus ensuring EW symmetry breaking.

The additional requirements of the unification of the trilinear couplings to a common A_0 and the correct reproduction of the EW symmetry scale, which fixes the absolute value of μ , defines the minimal gravity-broken MSSM (mSUGRA). The value of μ^2 can be determined minimising the Higgs potential and requiring the right value of m_Z . At tree level [2]:

- 6) $\mu^2 = -1/2m_Z^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2 \beta}{\tan^2 \beta - 1}$
 7) $m_{H_1}^2 \simeq m_0^2 + 0.5m_{1/2}^2$, $m_{H_2}^2 \simeq -(0.275m_0^2 + 3.3m_{1/2}^2)$

The parameter set is then reduced to $m_{1/2}$, m_0 , $\tan \beta$, A_0 and the sign of μ .

In addition to the mass relations listed in the previous subsection, m_A can be related to $m_{1/2}$ (M_2), m_0 and Yukawa coupling of the top quark. The stop mixing parameter can be expressed (approximately) as $A_t = 0.25A_0 - 2m_{1/2}$. For low $\tan \beta$, $m_A^2 \simeq m_0^2 + 3m_{1/2}^2 - m_Z^2$. As m_{h^0}

⁺ To avoid “tachyonic” mass solutions we must have:

$$m_{lr} + m_{rr} > \sqrt{(m_{ll} - m_{rr})^2 + 4 * m_{lr}^2}$$

where m_{lr} is the off-diagonal mixing term, and m_{ll} , m_{rr} are the diagonal mass terms. For example, for the stop we have $m_{lr} = m_{top}X_t$ and,

$$m_{ll} \simeq m_0^2 + 9M_2^2 + m_{top}^2 + m_Z^2 \cos 2\beta (0.5 - 2/3 \sin^2 \theta_W)$$

$$m_{rr} \simeq m_0^2 + 8.3M_2^2 + m_{top}^2 + 2/3 m_Z^2 \cos 2\beta \sin^2 \theta_W$$

For an example value of $X_t = \sqrt{6} \text{ TeV}/c^2$, the condition above sets a lower limit on a combination of m_0^2 and M_2^2 : $m_0^2 + 8.5M_2^2 > 0.39 \text{ TeV}/c^2$. Thus, if $m_0 < 300 \text{ GeV}/c^2$ we must have $M_2 > 190 \text{ GeV}/c^2$.

grows with m_A and A_t (see section 1), Higgs searches can be used to set a limit on $m_{1/2}$ (M_2) which depends on $\tan\beta$, A_0 , and m_{top} . The lightest Higgs mass can thus be related to $m_{1/2}$ (M_2), and the experimental limit on it can be used to set limits on the masses of (for example) the lightest chargino and the lightest neutralino dependent on $\tan\beta$, A_0 and m_{top} .

3. LEP results

In years 1995-2000, the Aleph, DELPHI, L3 and OPAL experiments at LEP collected an integrated luminosity of more than 2000 pb⁻¹ at centre-of-mass energies ranging from 130 GeV to 208 GeV. These data have been analysed to search for the sfermions, charginos, neutralinos and Higgs bosons predicted by supersymmetric models [8, 20, 22, 23, 24, 25, 26, 27].

3.1. Searches for charginos and neutralinos

After the Higgs [28], charginos were the most important SUSY discovery channel at LEP. Unless there is a light sneutrino (in the gaugino region the chargino production cross-section can be quite small due to the negative interference between the t-channel sneutrino exchange diagram and the s-channel Z/γ exchange diagram. Higgsino-type charginos do not couple to the sneutrino.), the chargino pair production cross-section is predicted to be large if $m_{\tilde{\chi}_1^\pm} < \sqrt{s}/2$. A lower limit on the chargino mass of 103.5 GeV/ c^2 was set [29], shown on figure 1 assuming 100% branching fraction to the decay mode $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$. Although this limit is ‘‘earmarked’’ to be set only in one MSSM point, it is valid as long as the chargino decays as above.

Cross-section limits for chargino pair-production were set (see figure 1). They depend primarily on the difference between the mass of the chargino and an undetectable sparticle it decays to (e.g. $\tilde{\chi}_1^0$ or $\tilde{\nu}$). Chargino pair production with cross-section larger than 0.1-0.2 pb (corresponding to $\sqrt{s} \sim 205$ GeV, the average energy of the year 2000 data) is excluded for $\Delta M > 20$ GeV/ c^2 [22, 30], where $\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ or $\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\nu}}$. If these limits are combined, a chargino production cross-section above 0.05 pb-0.1 pb can be excluded. The limit on the chargino mass of $m_{\tilde{\chi}_1^\pm} \gtrsim 100$ GeV/ c^2 can be set for the light sneutrino as well, as long as $\Delta M \gtrsim 10$ GeV/ c^2 . Alas, no official LEP combination exists for the chargino decaying to the sneutrino and a lepton.

If sfermion mass unification is assumed, searches for \tilde{e}_R can be used to set a lower limit on the sneutrino mass, and thus on the chargino mass in the case of a light sneutrino and $\Delta M < 10$ GeV/ c^2 . Moreover, if \tilde{e}_L and \tilde{e}_R are light, neutralino production in the gaugino region is enhanced (experimentally observable neutralino production (for example $\tilde{\chi}_1^0 \tilde{\chi}_2^0$) has quite large cross-section in the higgsino region as higgsinos couple directly to Z . However, in the gaugino region there is no tree-level coupling of $\tilde{\chi}_1^0$ to Z , and $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$ can only be mediated via t-channel selectron exchange), and neutralino searches set an indirect limit on the sneutrino mass in some regions of the parameter space.

Another ‘‘blind-spot’’ in chargino searches arises when the $\tilde{\tau}_1$ is light and close in mass to the $\tilde{\chi}_1^0$ [20, 29]. Chargino decays $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1 \nu$ with $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$ then dominate, and lead to an ‘‘invisible’’ final state; but the search for neutralino production can be used [20, 29] in this case. If neutralinos decay via light stau states and $m_{\tilde{\tau}}$ is close to $m_{\tilde{\chi}_1^0}$, $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production with $\tilde{\chi}_2^0 \rightarrow \tilde{\tau} \tau$ and $\tilde{\tau} \rightarrow \tilde{\chi}_1^0 \tau$ leads to only one τ visible in the detector; nevertheless limits on the cross-section times branching ratio are of the order of 0.1-0.4 pb [30]. The search for $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ in the same region reaches a sensitivity of 0.06 pb [20]. In the CMSSM with nUHP, the region in (M_2, μ, m_0) space where the stau is degenerate in mass with the LSP depends on

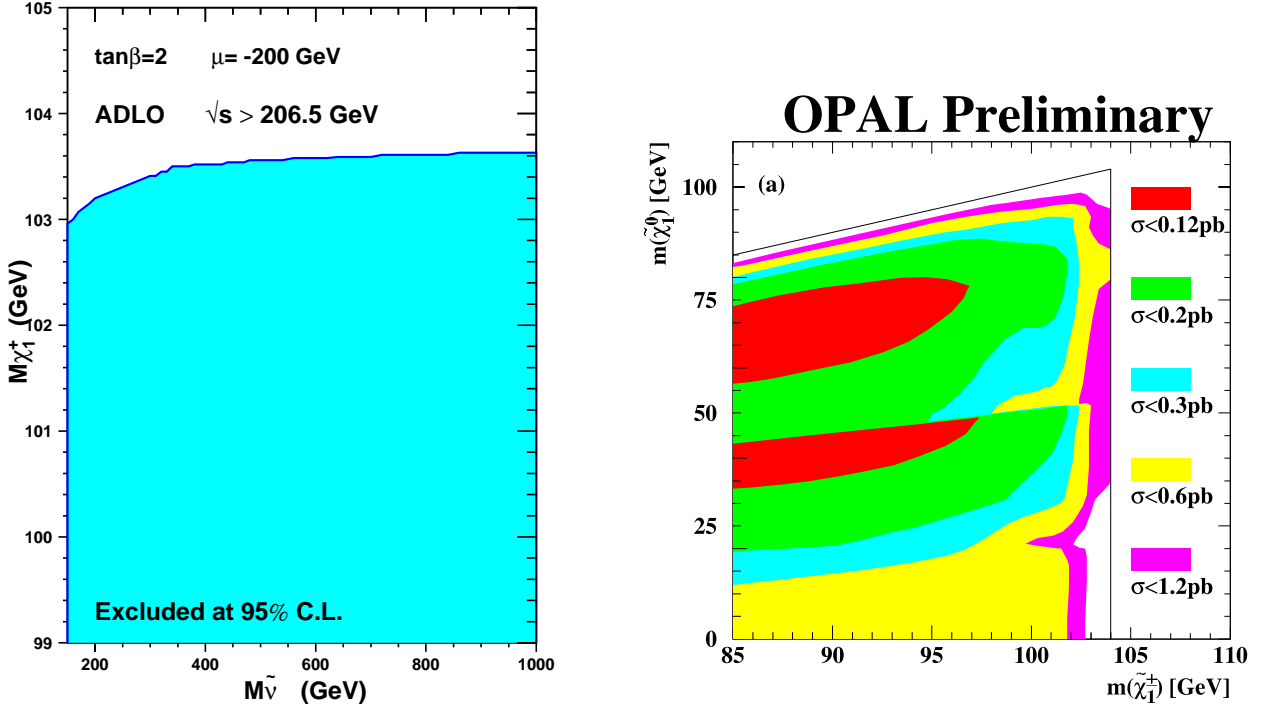


Figure 1. Left hand side: Limit on the chargino mass at 95 % confidence level, resulting obtained by the LEP SUSY working group (see text). The limit is valid for the decay channel $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$ Right hand side: Limits on the chargino production cross-section in the $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm})$ plane, at 95 % confidence level, resulting from Opal searches. The limits are valid for the decay channel $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$

mixing parameters: A_τ , and A_b, A_t . It is possible to find configurations of mixing parameters (typically with $|\mu|$ few times larger than M_2 and m_0) such that the stau is light and close in mass to $\tilde{\chi}_1^0$ while the selectrons are heavy, rendering the neutralino cross-section small. However, the chargino production cross-section is large in this case, and this region can be explored by the search for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \gamma$ production [20, 31, 32] where the photon arises from initial state radiation and is detected together with a few low energy tracks originating from $\tilde{\chi}_2^0 \rightarrow \tilde{\tau} \tau$ and $\tilde{\tau} \rightarrow \tilde{\chi}_1^0 \tau$ decay chain.

In mSUGRA, $|\mu|^2$ is in the range $3.3 m_{1/2}^2 - 0.5 m_Z^2 < \mu^2 < m_0^2 + 3.8 m_{1/2}^2$ for $\tan \beta > 2$ and and light stau cannot be degenerate with neutralino for large m_0 . Thus neutralino searches set a limit on the chargino mass for small $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ which is close to the one obtained for heavy sleptons (around $103 \text{ GeV}/c^2$).

It is perhaps worth mentioning that, because in the higgsino region ($M_1 \gg |\mu|$) the $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production cross-sections at LEP are large, $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production can be excluded nearly up to the kinematic limit as long as $m_{\tilde{\chi}_1^0}$ is not too close to $m_{\tilde{\chi}_2^0}$ ($M_2 \lesssim 1500 \text{ GeV}/c^2$ in the constrained MSSM). For $200 < M_2 < 1500 \text{ GeV}/c^2$ a lower limit on the LSP mass of $70 \text{ GeV}/c^2$ was set by DELPHI [33], using the data collected at $\sqrt{s} = 189 \text{ GeV}$. In the constrained MSSM the mass difference between the lightest chargino and the lightest neutralino is less than $3 \text{ GeV}/c^2$ for $M_2 \gtrsim 1500 \text{ GeV}/c^2$. A lower limit on the $m_{\tilde{\chi}_1^\pm}$ of around $92 \text{ GeV}/c^2$ was set in this region by LEP SUSY working group, [29], implying a similar lower limit on the mass of the lightest neutralino.

3.2. Searches for Sleptons and Squarks

Pair-produced selectrons and muons with the typical decay modes, $\tilde{\ell} \rightarrow \tilde{\chi}_1^0 \ell$, have been searched for by all LEP collaborations. These searches exclude slepton pair production with a cross-section above (0.02-0.1) pb depending on the neutralino mass and on the slepton mass, assuming 100% branching fraction to the above decay mode. With this assumptions, right-handed smuons (selectrons) lighter than around 96 (99) GeV/c^2 can be excluded, provided $m_{\tilde{\mu}_R}(m_{\tilde{e}_R}) - m_{\tilde{\chi}_1^0} \gtrsim 20 \text{ GeV}/c^2$ and that the selectron pair production cross-section is as for $\tan \beta=2, \mu=-200$.

For the minimal coupling to Z/γ and sufficiently large $\Delta M = m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} > 15 \text{ GeV}/c^2$, $m_{\tilde{\tau}_1} \lesssim 85 \text{ GeV}/c^2$ can be excluded, while the lower limit on the mass of the stable stau is close to $97 \text{ GeV}/c^2$.

It should be noted that while selectron production cross-section depends on the neutralino mass and composition, the smuon and stau production cross-section depends only on the sparticle handness and mass, thus the limit presented here is valid as long as smuons(staus) decay as above.

The results of the searches for sbottom (\tilde{b}) and stop (\tilde{t}) were combined by the LEP SUSY working group. The typical decay modes $\tilde{t} \rightarrow \tilde{\chi}_1^0 c$ and $\tilde{b} \rightarrow \tilde{\chi}_1^0 b$ have been searched for. These searches exclude squark pair production with a cross-section above (0.05-0.1) pb depending on the neutralino and on the squark masses, assuming 100% branching fraction to the above decay modes. For the minimal coupling to Z/γ and for $\Delta M = m_{\tilde{t}}(m_{\tilde{b}}) - m_{\tilde{\chi}_1^0} > 15 \text{ GeV}/c^2$, the $\tilde{t}(\tilde{b})$ with mass below 95 (93) GeV/c^2 is then excluded, as it can be seen on figure 2, [29].

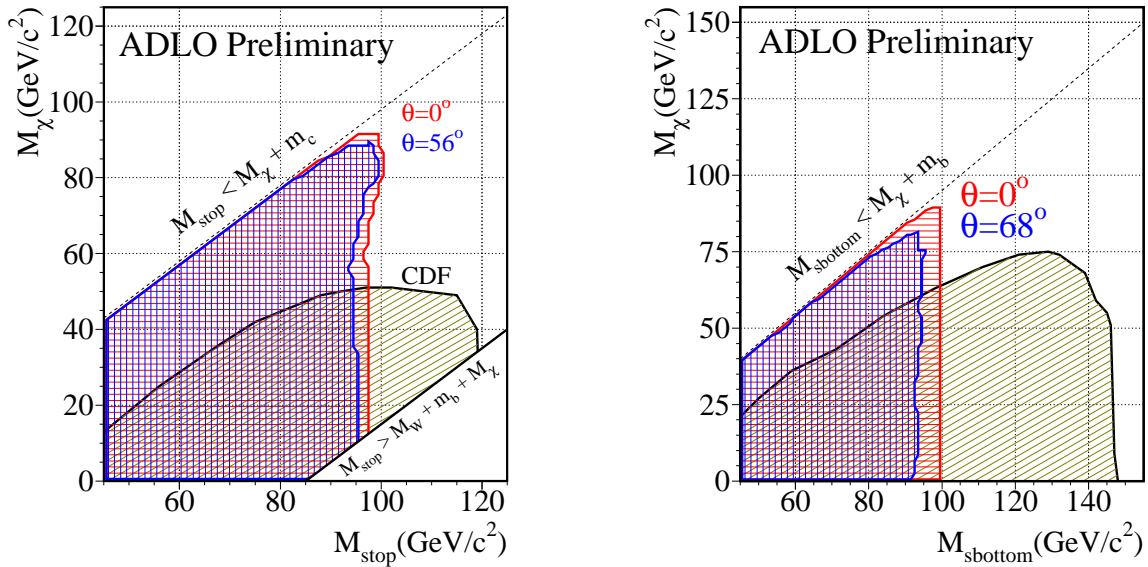


Figure 2. Excluded ranges in $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ and $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ planes, at 95 % confidence level, resulting from the combined Aleph, Delphi, Opal and L3 searches. The hatched shading is excluded by the CDF collaboration, assuming mass degeneracy between the lighter and the heavier stop (sbottom) states. (see text).

4. Limits in CMSSM and mSUGRA scenario

The searches described in the previous section were used to set limits on sparticles masses in the CMSSM with non universal Higgs parameters and in mSUGRA. *Limits presented in this section are valid in the R-parity conserving scenario and in all R-parity violating scenarios where a chargino limit of $103 \text{ GeV}/c^2$ or more can be set by LEP experiments.*

4.1. Limits in the CMSSM with nUHP

Higgs boson searches and chargino searches set limits in this scenario. "Holes" which arise in chargino searches in the R-parity conserving scenario are covered by selectron, neutralino, Higgs and squark searches. Limits presented in this section are for $m_A \leq 2000 \text{ GeV}/c^2$.

Limits on the mass of the lightest neutralino

Efforts of LEP collaborations went into covering various blind spots in the chargino searches, in order to set an "absolute" neutralino mass limit (within the CMSSM). As explained below, the limit is set in one of the two quite highly fine-tuned blind spots: chargino-sneutrino mass degeneracy with $\Delta M \lesssim 3 \text{ GeV}/c^2$ and stau-neutralino mass degeneracy with similar ΔM . As none of these situations is likely to occur it is probably worth asking, what would be the neutralino mass limit if both of these degeneracies are avoided. The answer will be given at the end of this subsection.

The effect of various searches is illustrated on figure 3 showing the LSP mass limit set by the Higgs and SUSY, as a function of $\tan \beta$.

The mixing in the stop sector was of the form, $A_t - \mu/\tan \beta$, while it was assumed that mixing in the sbottom and stau sector is negligible. Mixing in the stop sector was tuned to maximize the m_h for any given M_2 , while avoiding the tachyonic stop. Limit on the m_h set by LEP at low $\tan \beta < 6$ sets a limit on M_2 for $\tan \beta < 2.4$, and for $\tan \beta < 4$ a limit on the combination of m_0 and M_2 is set which excludes the region of chargino-sneutrino degeneracy (where chargino searches are ineffective). At higher $\tan \beta$ this region is covered by the slepton searches (primarily \tilde{e}_R), and the value of the neutralino mass limit at large $\tan \beta$ depends directly on the value of the selectron mass limit for $m_{\tilde{\chi}_1^0} \simeq 45 \text{ GeV}/c^2$. The details of the limit derivation can be found in [29]. "LEP combined" Higgs, chargino and selectron searches were used.

DELPHI has obtained a similar limit assuming that mixing in the third family is of the form ($A_\tau - \mu \tan \beta$, $A_b - \mu \tan \beta$, $A_t - \mu/\tan \beta$, with $A_b = A_\tau = 0$ and A_t in the range $(0, \pm \text{maximal mixing})$, see figure 3.

If $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$ is allowed by the large mixing in the stau sector (the dotted line) the limit drops at high $\tan \beta$ to $45.5 \text{ GeV}/c^2$, because another hole in chargino and stau searches develops. This "hole" is partially covered by neutralino and "degenerate" chargino searches [20, 32]. As before, the limit for "any m_0 " with no mixing drops at $\tan \beta > 10$ due to the "hole" in chargino searches, where the chargino is close in mass to the sneutrino. The "hole" is partially covered by selectron and neutralino searches, and by the Higgs searches, which, in "no-mixing" scenario exclude $\tan \beta < 9.7$. The $\tan \beta$ region excluded by Higgs searches both in no-mixing, and in maximal mixing scenario depends on the mass of the top quark and on the details of the Higgs mass calculations.

However, both in "mixing" and in "no-mixing" scenario the neutralino mass limit is set at large $\tan \beta$, where the Higgs search has no effect. While in the no-mixing scenario it is determined by the selectron mass limit, in the mixing scenario it depends on the stau mixing model, and on the interplay between chargino and neutralino searches with $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$.

ALEPH and DELPHI have presented limits on the neutralino mass, in which stau mixing is

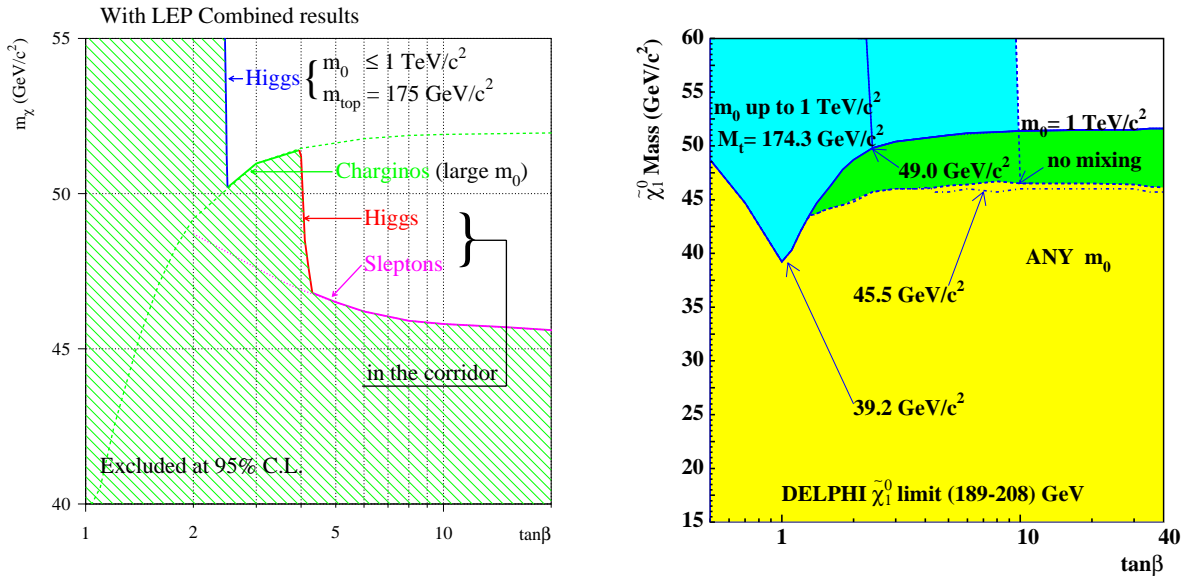


Figure 3. The lower limit at 95 % confidence level on the mass of the lightest neutralino, $\tilde{\chi}_1^0$ as a function of $\tan\beta$ assuming a stable $\tilde{\chi}_1^0$. Left hand side: The limit is set by the “LEP combined” Higgs, chargino and selectron searches assuming gaugino and sfermion mass unification. It is valid for small (no) mixing in the stau sector. Right hand side, DELPHI: The solid curve shows the limit obtained for $m_0 = 1000$ GeV/ c^2 , the dashed curve shows the limit obtained allowing for any m_0 assuming that there is no mixing in the third family ($A_\tau = \mu \tan\beta$, $A_b = \mu \tan\beta$, $A_t = \mu/\tan\beta$), and the dash-dotted curve shows the limit obtained for any m_0 allowing for the mixing with $A_\tau = A_b = A_t = 0$. The steep solid (dashed) curve shows the effect of the searches for the Higgs boson for the maximal $M_{H_1^0}$ scenario (no mixing scenario), $m_0 \leq 1000$ GeV/ c^2 and $M_t = 174.3$ GeV/ c^2 , which amounts to excluding the region of $\tan\beta < 2.36(9.7)$

independent on stop or sbottom mixing, and has an arbitrary μ dependence. In such a case stau can be made degenerate with the lightest neutralino for any value of M_2 and m_0 . As the sensitivity of neutralino (degenerate chargino) searches used in this case drops (grows) with m_0 the limit is set on the ridge of the exclusion from chargino and neutralino searches. The limit is close to 41 GeV/ c^2 and represents the most conservative scenario.

What would be the neutralino mass limit, if the “sneutrino” hole and “stau” hole were avoided? The most pesymistic case is still the “light sneutrino scenario”, which renders chargino production cross-section small and enhances invisible decays of $\tilde{\chi}_2^0$. For the sneutrino lighter than the chargino and lighter than 65 GeV/ c^2 DELPHI alone sets a limit on the chargino mass of around 100 GeV/ c^2 , independent of $\tan\beta$ (see [30]). Similar limit can be set for the sneutrino mass just above the chargino mass. If the data from all LEP experiments are combined the gap in the sneutrino masses 65-100 GeV/ c^2 is closed down to $\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\nu}} \sim 10$ GeV/ c^2 , resulting in the chargino mass limit ~ 100 GeV/ c^2 , and neutralino mass limit of ~ 50 GeV/ c^2 (valid as long as $\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\nu}} > 10$ GeV/ c^2). Alas, no official combination of this decay channel was performed so far. It is also interesting to note, that outside the stau and sneutrino hole the limit on the neutralino mass can be set which is *independent of the sfermion unification assumption*.

Limits on the masses of other sparticles

Limits on the masses of other sparticles can be set within the CMSSM, which do not

depend on a specific decay channel, but take into account all decay channels appearing in the model. Also limits on the masses of sparticles, which are not directly visible or produced at LEP can be set, due to their relations to the masses of observable sparticles (see section 2.1).

Aleph and DELPHI have set limits on the $m_{\tilde{\nu}}$ and $m_{\tilde{e}_R}$ which are valid within the CMSSM (see figures 4).

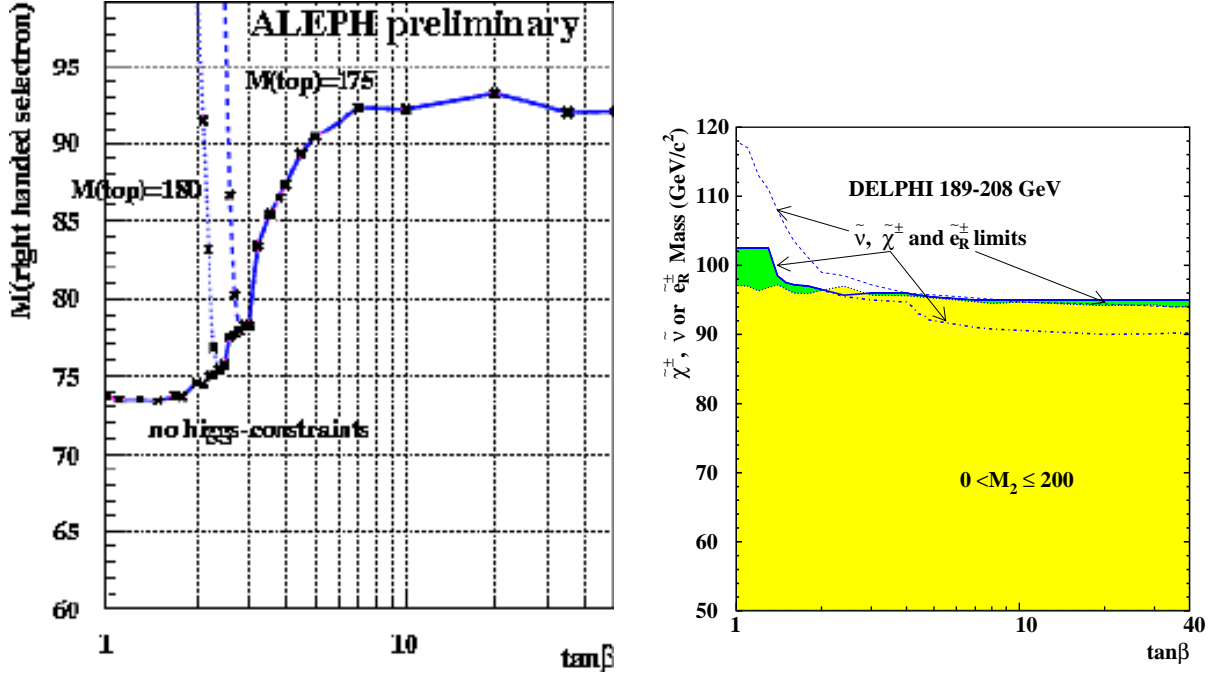


Figure 4. Left hand side: The minimum \tilde{e}_R mass in the CMSSM from Aleph. The full line shows the limit without the constraint from Higgs search. Right hand side, DELPHI: the minimum sneutrino mass (dark shading and dashed curve) allowed by the slepton and neutralino searches, as a function of $\tan\beta$, together with the limits on the chargino mass (solid curve and dash-dotted curve), and the \tilde{e}_R mass (dotted curve and light shading). The chargino mass limit indicated by the solid curve and the sneutrino and selectron mass limits were obtained assuming no mass splitting in the third sfermion family ($A_\tau - \mu \tan\beta = 0$ in particular). The chargino mass limit is valid for $M_2 \lesssim 1500 \text{ GeV}/c^2$. The selectron mass limit is valid for $m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0} > 10 \text{ GeV}/c^2$. The chargino mass limit indicated with the dash-dotted curve was obtained allowing for mass splitting in the third sfermion family, with $A_\tau = A_b = A_t = 0$.

Aleph limit is also valid for the mass configurations where the selectron is degenerate with the lightest neutralino, which occur at small $\tan\beta$. At higher $\tan\beta$ the $m_{\tilde{e}_R}$ ($m_{\tilde{\nu}}$) mass limit is close to 92-94 GeV/c^2 (88-94 GeV/c^2). These limits were set for no mixing in the stau sector, which represents in this case the most conservative scenario.

Limits on the masses of the partners of light quarks and on the gluino mass can be set as well, due to their relation to the chargino and slepton masses (see section 2.1 and [18]). L3 collaboration [35] has used chargino-gluino mass relation to set an indirect lower limit on the gluino mass of $\sim 300 \text{ GeV}/c^2$ (see figure 5). A lower mass limit on “light” squarks was set as well, exploiting the stop and sbottom searches, and assuming that all squarks are mass-degenerate.

The relation between the chargino (M_2), slepton (m_0, M_2) and light squark masses (m_0, M_2) was exploited in [18] to set an indirect limit on the \tilde{d} mass of $\sim 300 \text{ GeV}/c^2$.

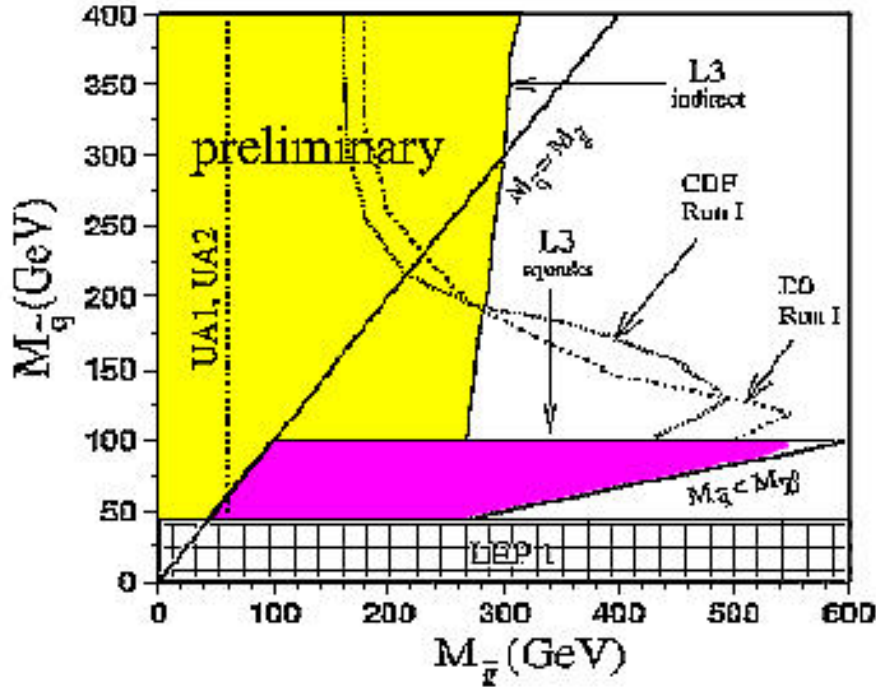


Figure 5. The minimum gluino mass in the CMSSM from L3 (light shading). Dark shading shows the limit on the squark mass, with the assumption that all three squarks are mass-degenerate.

4.2. Limits in the mSUGRA scenario

Limits on the mSUGRA model for $A_0 = 0$ were discussed in detail in ex. [17, 16]. The Higgs search plays a major rôle in setting these limits, and the value of m_{h_0} depends crucially on $A_t \simeq 0.25A_0 - 2m_{1/2}$, as it was noted in for example [18, 34]. A range of A_0 was studied by the LEP SUSY working group [29, 35], and the dependence of the results on the value of the top mass was discussed. Even with the top mass fixed there is an additional dependence of the exclusion on the accuracy of the m_{h_0} calculations.

Exclusion regions in the mSUGRA scenario obtained by the LEP SUSY working group can be seen on figure 6 for an example value of $\tan \beta$ and for a range of A_0 values.

Excluded regions in $m_{1/2}$ and m_0 can be translated into limits on $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm}$ and other sparticles. Limits on $m_{\tilde{\chi}_1^0}$ obtained by LEP SUSY WG [29] are illustrated on figure 6 for several values of A_0 and m_{top} . $m_{\tilde{\chi}_1^\pm}$ is close to $2m_{\tilde{\chi}_1^0}$.

As shown in [18] for large negative values of A_0 Higgs searches do not exclude higher $m_{1/2}$ than the chargino searches already at moderate $\tan \beta$ thus the limit on the neutralino mass is set at the value of around 50 GeV/ c^2 by the chargino searches, with neutralino and slepton searches covering the stau and sneutrino hole.

ALEPH [36] obtained limits on selectron (\tilde{e}_R, \tilde{e}_L) and sneutrino masses within mSUGRA for $A_0 = 0$. An example $m_{\tilde{e}_R}$ limit as a function of $\tan \beta$ is shown on figure 7. The limit is set by the Higgs searches at low $\tan \beta$. At high $\tan \beta$ where the stau mixing is important also for lower $m_{1/2}$ the m_0 (and thus selectron mass) is pushed up by the requirement that the stau is not the LSP. Both the Higgs exclusion and stau-LSP region depend on the value of A_0 .

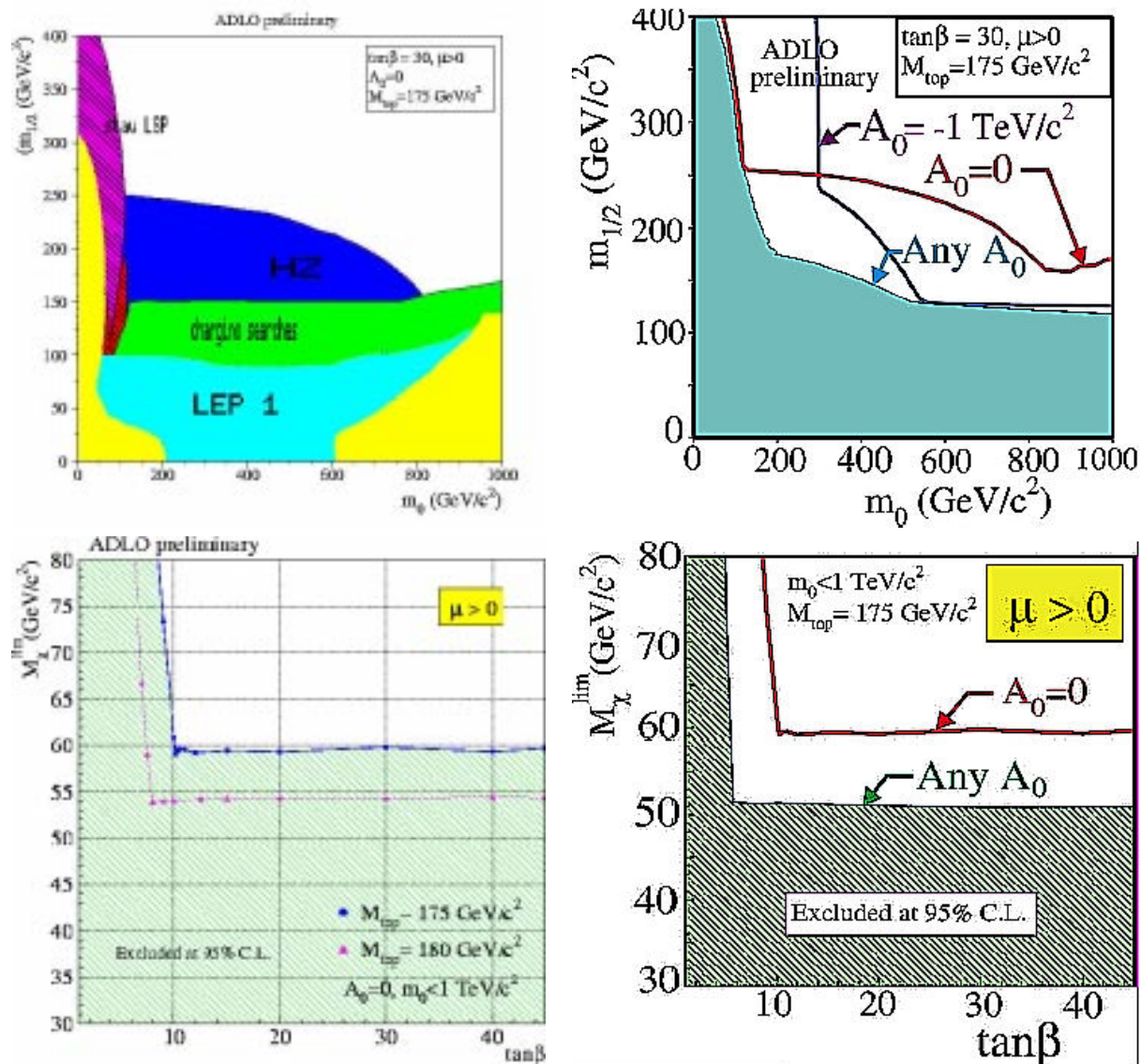


Figure 6. Upper plots: Exclusion regions in the mSUGRA scenario from Higgs and SUSY searches at LEP for a range of A_0 values. On the right-hand side plot effects of various searches are illustrated. Light shaded horizontal region is excluded by chargino searches, hatched bands are excluded by slepton searches (\tilde{e}_R and $\tilde{\tau}_1$). Dark shading shows Higgs exclusion. Dedicated neutralino search excludes area close to “stau lsp” region, complementing the chargino search. Light shading shows the region where there is no good mSUGRA solutions (either due to charged LSP or no good EWS breaking) Left-hand side plot shows effect of changing A_0 . For large negative A_0 the region of the stau LSP grows, while the Higgs exclusion shrinks. Lower plots: The lower limit on the mass of the lightest neutralino, $\tilde{\chi}_1^0$, in mSUGRA [29]. Both plots are for positive μ which represents a more conservative scenario. The left-hand side plot illustrates the change of the limit with the change of the top mass ($m_{top} = 180.0 \text{ GeV}/c^2, m_{top} = 175 \text{ GeV}/c^2$). The right-hand side plot shows the limit obtained changing A_0 in the bounds allowed by none of the third family sfermions become tachyonic or the LSP. The LSP limit degrades in this case down to the one set by chargino searches and neutralino searches for $\tan \beta > 15$.

Similar limits for sleptons for several values of A_0 are presented in [18]) along with limits on squarks and gluino.

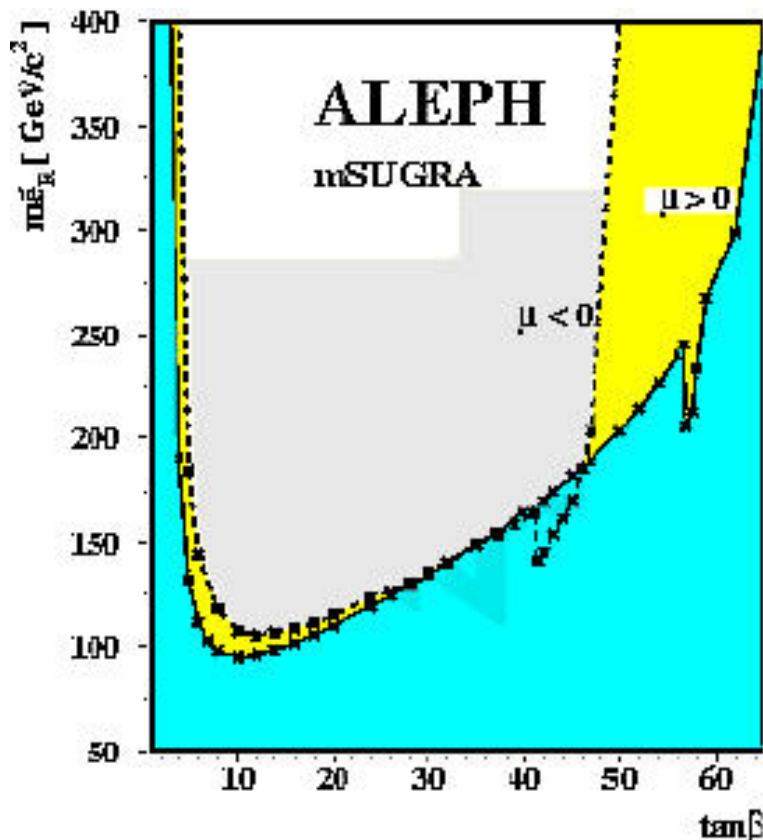


Figure 7. The lower limit at 95 % confidence level on the mass of the right-handed selectron, in mSUGRA [29] with $A_0 = 0$. At low $\tan\beta$ light selectrons are excluded by the limit on the Higgs mass (which imposes a limit on $m_{1/2}$) and at large $\tan\beta$ low $m_0, m_{1/2}$ values are excluded by stau being the LSP. Both “end” of the selectron exclusion depend on the A_0 value (see text).

5. Summary

LEP places relevant direct and indirect limits on the masses of nearly all predicted sparticles. Direct limits are typically limited by the kinematic reach of LEP and are valid for a specific decay channel of a sparticle. Indirect limits often reach beyond the kinematic limit, and are valid for all decays appearing in a specific more constrained version of the MSSM. However, they make use of relations between the sparticle masses, which are specific for the model in question (CMSSM or mSUGRA).

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