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Constraints on SUSY parameters from LEP data

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Abstract: The absence of supersymmetry signals in the final LEP data sample sets stringent constraints on the parameter space of Minimal Supersymmetric extensions of the Standard Model. Under GUT unification assumptions the combination of such constraints allows to set lower limits on the mass spectrum of gauginos and in particular on the mass of the lightest neutralino, of great interest as a possible cosmological component of non-baryonic cold dark matter.

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) is the supersymmetric (SUSY) extension of the Standard Model with minimal field content [1]. The mass degeneracy of ordinary particles to their SUSY partners is lifted by soft SUSY breaking terms (M_i and m_j) whose scale should not exceed $\sim 1\,\mathrm{TeV/c^2}$ in order for supersymmetry to remain a solution of the naturalness problem. Ordinary particles and their SUSY partners are distinguished by their R-parity, which is here assumed to be conserved to ensure lepton and baryon number conservation. As a consequence SUSY particles (or sparticles) must be produced in pairs and decay to the Lightest Supersymmetric Particle (LSP), assumed here to be the lightest neutralino, which is stable and weakly interacting. Searches for R-parity conserving SUSY particles productions in the LEP data have been reported in ref.[2], and no evidence for such signals has been found, leading to upper limits on all possible production cross sections in electron-positron collisions up to 208 GeV centre-of-mass energies. In this paper such cross-section upper limits will be interpreted in the framework of constrained MSSM models with unification of the gaugino sector at the GUT scale, leading to the unified GUT gaugino mass $m_{1/2}$ and to the relation $\frac{M_1}{M_2} = \frac{5}{3}\tan^2\theta_W \simeq \frac{1}{2}$ at the electroweak scale. Further also the sfermion sector is assumed to obey GUT universality, so that sfermion masses unify to m_0. Therefore the MSSM parameter space for gauginos and sfermions can be constrained by four main variables $(\mu, M_2, \tan\beta, m_0)$, with the addition of m_A for the Higgs sector and possible mixing parameters in the third scalar family. In the following all derived MSSM exclusions and limits are quoted at 95% Confidence Level.

2. Exclusions with heavy sfermions

If all sfermions are substantially heavier than W and Z bosons ($m_0 > 500\text{GeV}/c^2$), sparticles are produced and decay via photon, W and Z exchanges. In this scenario direct chargino and neutralino production cross sections are expected to be large ($\geq$ 1pb when kinematically accessible) so that their limits allow to exclude portions of the (μ, M_2) plane for any value of $\tan\beta$, as depicted in figure 1 for $\tan\beta = \sqrt{2}$.

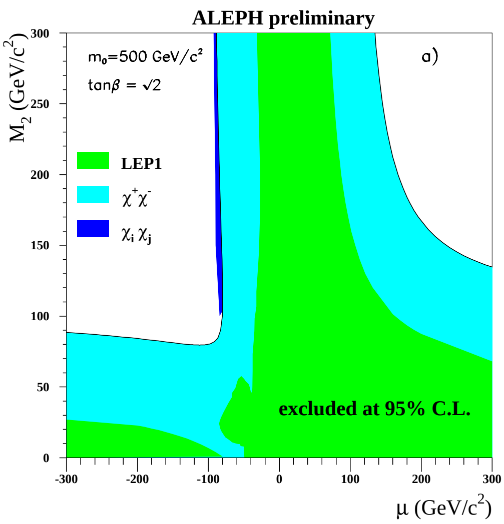

Figure 1: ALEPH excluded domains from direct gaugino searches up to $\sqrt{s}$=208GeV in the (μ, M_2) plane for $\tan\beta = \sqrt{2}$ and heavy sfermions ($m_0 > 500\text{GeV}/c^2$).

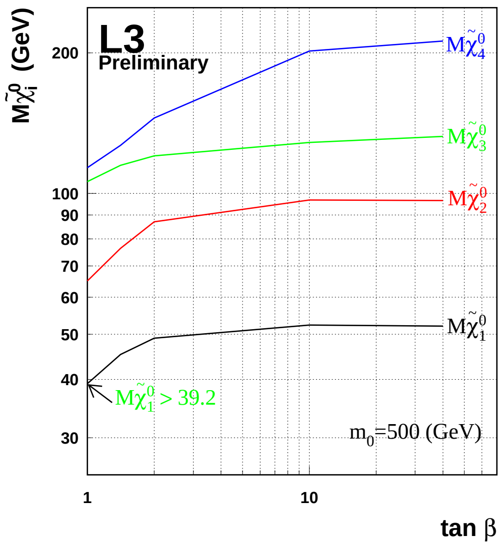

Figure 2: L3 lower limits on neutralino masses $M(\chi_j^0)$ as a function of $\tan\beta$ for heavy sfermions ($m_0 > 500\text{GeV}/c^2$), when combining chargino and neutralino searches.

These excluded domains correspond to chargino masses up to the production kinematic limit implying $M(\chi_1^+) \geq \sqrt{s}/2 \approx 100\text{GeV}/c^2$. Such exclusions also allow to set lower mass limits for the neutralino fields, as shown in figure 2 as a function of $\tan\beta$. The lowest limit on the mass of the neutralino-LSP is set at $\tan\beta = 1$ around $M(\chi_1^0) \geq 40\text{GeV}/c^2$ [3].

3. Exclusions with light sfermions

The effect of light sfermions (lower m_0) is significant in both the production and decay of gauginos. But as lower m_0 values correspond to smaller slepton masses, direct slepton searches can be used to restrict the allowed configurations of the MSSM parameter space. The use of exclusions from searches dedicated to different decay topologies [2] and the interplay of sfermion, gaugino, and Z constraints as shown in figure 3 allow to cover the (μ, M_2) space in a similar way as in the case of large m_0. The absolute mass limit on the neutralino-LSP is then degraded at $\tan\beta \approx 1$ to 37-38GeV$/c^2$, and from $\sim$50GeV$/c^2$ to $\sim$45GeV$/c^2$ at high $\tan\beta$ where it is limited by a chargino and sneutrino mass degenerate scenario [3]. In the same framework the lower limit on the mass of the lightest chargino is around ~75GeV/c^2 set in the higgsino region ($|\mu| \ll M_2$) where $\Delta M = M(\chi_1^+) - M(\chi_1^0) <$ 1GeV/c^2, by dedicated searches [4].

4. Exclusions from Higgs boson searches

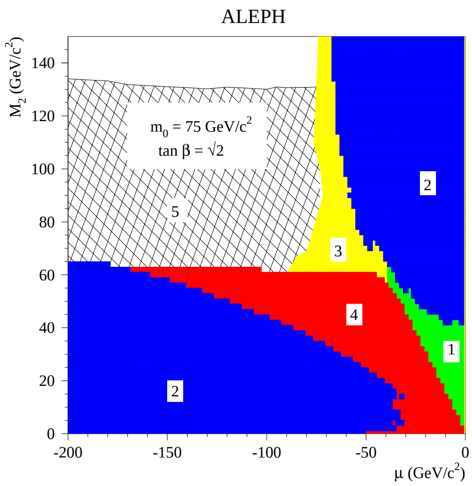

Figure 3: Regions in the (μ, M_2) plane excluded by LEP1 Z^0 data (1), and of chargino (2), neutralino (3), and slepton (4) searches at LEP2 for $\tan\beta = \sqrt{2}$ and $m_0 = 75$GeV/c^2. The region additionally excluded by Higgs boson searches at LEP2 is also shown (5). Exclusions with data only up to $\sqrt{s} = 183$GeV.

The LEP lower mass limits for the Higgs boson ($m_h > 114.1$GeV/c^2 if Standard Model like [5]) can be also used to further constrain the MSSM parameter space, leading to effective exclusions of the low $\tan\beta$ regions as intuitively from the tree level relation $m_h < m_Z|\cos 2\beta|$. Given m_0 and $\tan\beta$ values, and starting from limits on the largest predicted m_h corresponding to large m_A values (~ 1TeV/c^2), radiative corrections to the Higgs sector are used to derive minimum values for the stop mass $m_{\tilde{t}}$ and hence lower limits on M_2, as shown in figure 3. Taking into account mixing in the stop sector, it is in fact the interplay between the Higgs boson and stop mass lower limits which allows M_2 to be constrained for low $\tan\beta$ values. In summary the inclusion of the negative outcome of Higgs searches at LEP2 effectively constrains $\tan\beta \geq 2-3$, bringing the LSP mass limits in the high $\tan\beta$ regions as shown in figure 4.

5. Stau mixing effects

The inclusion of stau mixing effects allows the opening of more mass degenerate scenarios of the LSP with the stau, and weakens the gaugino mass limits quoted previously at high $\tan\beta$. To cope with lower $\tilde{\tau}_1$ masses and large tau decays, dedicated searches for $\chi^+\chi^-$ with $\chi^+ \to \tilde{\tau}_1\nu_\tau$, and $\chi_2^0\chi_1^0$ or $\chi_2^0\chi_2^0$ signals with $\chi_2^0 \to \tilde{\tau}_1\tau$ are performed [6]. The interplay of different dedicated searches is shown in figure 5, where the effect of stau mixing is studied decoupled from other MSSM mixing parameters, as a function of the mixing angle ϕ_τ [7]. At extreme stau mixing angles the chargino plus ISR search [4] is needed to cover the stau-LSP mass degeneracy at large m_0. Combining these additional and dedicated searches the mass limits on the neutralino-LSP at high $\tan\beta$ in the gaugino region turn out to be robust against stau mixing effects, still holding at $M(\chi_1^0) \geq 43$GeV/c^2 [3][7].

6. Combined limits in minimal supergravity (mSUGRA)

In the framework of mSUGRA the MSSM parameters are further reduced [1], removing m_A and μ, and leaving $m_{1/2}, m_0, A_0, \tan\beta$ and the sign of μ. Large regions are excluded

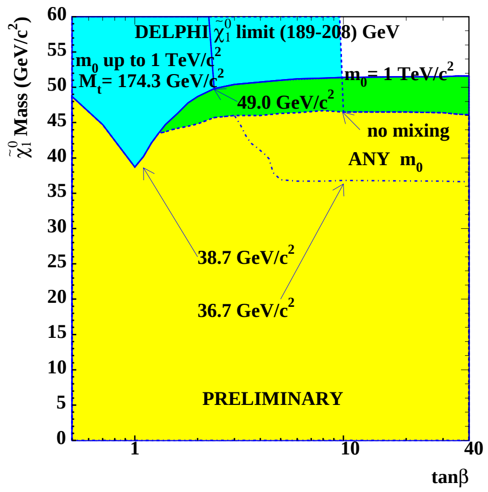

Figure 4: DELPHI lower limit on the LSP neutralino mass as a function of $\tan\beta$. The solid curve shows the limit for m_0 = $1\text{TeV}/c^2$, the dashed curve for any m_0 but no scalar mixing, and the dash-dotted curve for any m_0 allowing mixing with A_i=0. The steep curves show the effect of Higgs boson searches with maximal m_h, or no mixing.

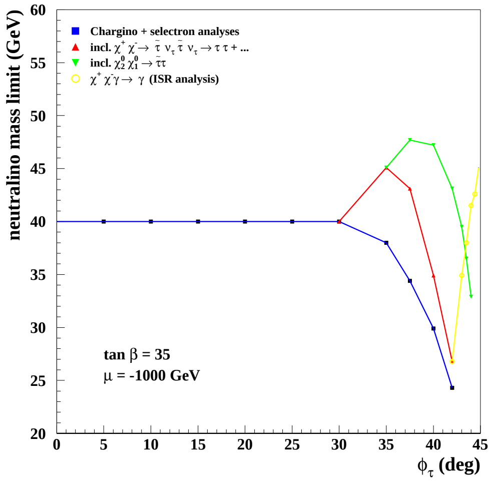

Figure 5: ALEPH limits on the mass of the lightest neutralino (LSP) as a function of the stau mixing angle ϕ_τ for $\tan\beta = 35$ and $\mu = -1\text{TeV}/c^2$ (LSP-gaugino region). The interplay of exclusions of different searches with the increase of mixing effects is indicated by the different curves.

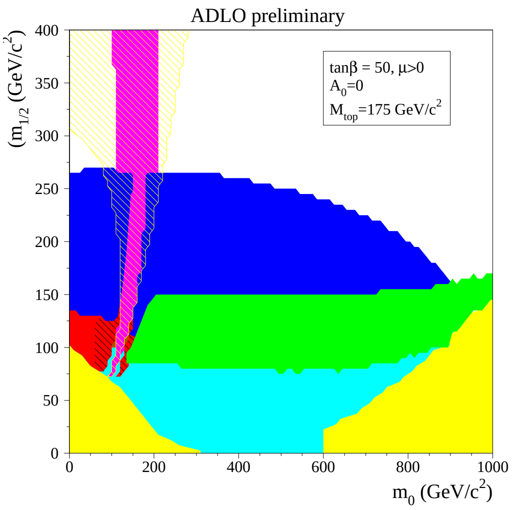

Figure 6: LEP combined excluded regions in the $(m_{1/2}, m_0)$ mSUGRA space at $\tan\beta = 50$, $A_0 = 0$ and $\mu > 0$.

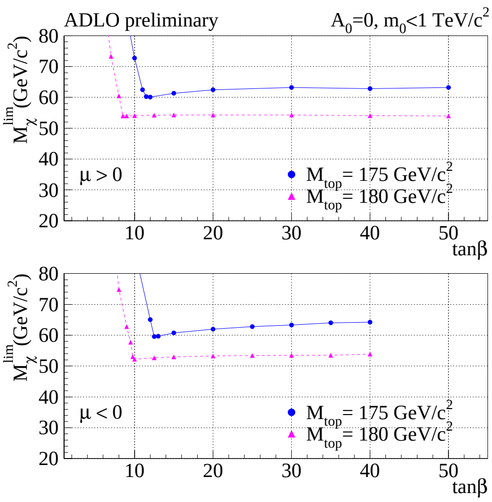

Figure 7: mSUGRA limits on the neutralino LSP mass. Also shown is the important effect of the top mass value on the limits.

by Higgs boson searches, in particular at low $\tan\beta$. Slepton searches contribute effectively for low m_0, while the constraints from LEP1 Z measurements, and LEP2 gaugino searches exclude low $m_{1/2}$ values [8]. Exclusion domains in the $(m_{1/2}, m_0)$ plane are shown in figure

6 for large $\tan\beta$, positive μ and $A_0 = 0$. From these exclusions, constraints on the mass of the neutralino-LSP are also derived and shown in figure 7 as a function of $\tan\beta$ for $A_0 = 0$. Again the Higgs constraints cut out the small $\tan\beta$ region, while at large $\tan\beta$ the limit is determined by the chargino searches sensitivity. The final mSUGRA lower mass limits on χ_1^0 depend on the top quark mass values resulting in $M(\chi_1^0) \geq 50 - 60\mathrm{GeV}/c^2$.

7. Conclusions

The negative outcome of searches for productions of R-parity conserving SUSY particles at LEP up to the final centre-of-mass energy of $\sqrt{s} = 208\mathrm{GeV}$, have been interpreted in the framework of MSSM models with GUT unification assumptions in the various sectors. The combination and interplay of many different LEP searches for charginos, neutralinos, sleptons, squarks and Higgs bosons allow to constrain severely the parameter space of such MSSM models, and to derive lower mass limits for gauginos fields. The lightest non excluded chargino fields are higgsino-like ($|\mu| \ll M_2$) setting the limit $M(\chi^+) \geq 75\mathrm{GeV}/c^2$. The lightest non excluded neutralino-LSP is gaugino-like ($M_2 \ll |\mu|$) setting the limit $M(\chi^0) \geq 45\mathrm{GeV}/c^2$. These limits have been proven to be robust against possible mixing effects in the third scalar family. With the inclusion of full minimal supergravity assumptions, the neutralino-LSP mass limits improve to $M(\chi^0) \geq 50 - 60\mathrm{GeV}/c^2$, where a major uncertainty is driven by the uncertainty of the top quark mass.

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