MSSM searches at LEP

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Data collected by the LEP collaborations ALEPH, DELPHI, L3 and OPAL at centre-of-mass energies up to 208 GeV have been analysed in search of charginos, neutralinos and sfermions in the framework of the Minimal Supersymmetric Standard Model (MSSM) with R-parity conservation. No evidence for a signal was found in any of the channels. The results of each search were used to derive upper limits on production cross-sections and masses, in most cases by combining the data of the four experiments. Combining the result of all searches excludes regions in the parameter space of the constrained MSSM, leading to a limit on the mass of the LSP.

1. Introduction

This paper reports on experimental results from LEP on the search for evidence for the Minimal Supersymmetric extension to the Standard Model (MSSM) [1] with conserved R-parity. That R-parity is conserved implies that the Lightest Supersymmetric Particle (the LSP) is stable. As suggested by astrophysical limits, it is further assumed that the LSP is neutral and weakly interacting. It is assumed that sparticle decays are prompt, except if limited by phase-space. It will be assumed that sparticles with a decay-length large in comparison to the scale of the detectors are excluded up to the kinematic limit of LEP.

Some of the studies will further specialise to the Constrained MSSM (CMSSM)[2], which in addition to the above assumes gaugino and sfermion mass-unification at some (high) scale. By running the theory down from this high scale, using the appropriate RGE:s, this assumption will yield various mass-relations at the EW-scale.

Other analyses will even further specialise to the gravity-mediated soft-SUSY breaking framework (mSUGRA). In mSUGRA it is assumed that SUSY explains EWSB, and that all scalar masses (ie. both sfermions and higgses) unify. Hence, the Higgs search will constrain SUSY. It is also assumed that there is a single SUSY-breaking trilinear coupling (A) at the high scale, which will, together with the mass-unification, imply that limits on one sfermion will constrain others.

Within this framework the experimental signals are as follows: The sfermions typically would be observed in the process $e^+e^- \rightarrow Z/\gamma \rightarrow \tilde{f}\bar{\tilde{f}} \rightarrow f\bar{f}\tilde{\chi}^0\tilde{\chi}^0$. The $\tilde{t}$ and the $\tilde{e}$ are a special cases, due the high mass of the top-quark, or to the possibility of $\tilde{e}$ production via a t-channel $\tilde{\chi}^0$ exchange, respectively. Since the $\tilde{\chi}^0$:s are invisible, the signal is always two fermions of the same flavour and missing momentum. Furthermore, since the sfermions are scalars, the production is central, contrary to most SM-processes. The neutralinos and charginos would be produced via $e^+e^- \rightarrow Z/\gamma \rightarrow \tilde{\chi}\tilde{\chi}$, and possibly via t-channel $\tilde{e}$ or $\tilde{\nu}_e$ exchange. The bosinos then each decay to a gauge-boson (which subsequently will decay to a fermion-antifermion pair) and a lighter $\tilde{\chi}$, or to a fermion-sfermion pair (the sfermion will decay as above, yielding $f\tilde{\chi}^0$). This repeats until the lightest $\tilde{\chi}^0$ is reached. As the lightest neutralino is invisible, the signal is always pair(s) of fermions and missing momentum.

The main backgrounds to such processes are four-fermion events containing neutrinos, two-fermion events with an energetic γ in the beam-pipe and $\gamma\gamma\rightarrow \ell\ell(\mathrm{e^+e^-})$. The first channel, important at large ΔM ($=M_{sparticle}$ - M_{LSP}), can be reduced by the difference in momentum and angular distributions between signal and background. The second channel, also important at large ΔM, can be reduced by the fact that these events are back-to-back when projected onto the plane perpendicular to the beam-axis. The third channel, which dominates at low ΔM, can be reduced by demanding that there is little energy at low angles, which forces the $\mathrm{e^+e^-}$-pair to be in the beam-pipe, in turn putting a constraint on the missing transverse momentum, $\not{P}_t$, which is therefore required to be sizable for candidate events.

2. Sleptons

The sleptons are the scalar partners to the SM leptons. As described above the signature of their presence at LEP would be events with two acoplanar charged leptons and missing momentum.

The mass-limits obtained for sleptons are "theory independent": it is only needed to make the basic SUSY assumption (particles and sparticles have the same couplings) to relate cross-section to masses. The nature of the LSP is not important for these searches, only that it is invisible[1].

All four LEP experiments have searched for $\tilde{\mu}$:s, $\tilde{\mathrm{e}}$:s and $\tilde{\tau}$:s in all the available data [3][4][5][6], and the results have been combined within the LEP SUSY working-group [7].

Figure 1 shows the 95% CL exclusion regions for $\tilde{\mu}$:s in the $M_{\tilde{\mu}}$ - M_{LSP} plane. For this plot $\tan\beta$=1.5 and μ=-200 was assumed, which gives a non-zero branching-ratio for the $\tilde{\mu}_{\mathrm{R}}\tilde{\chi}^0_2$ decay-channel if ΔM is large. $\tilde{\mu}$:s are excluded at this level of confidence below 94.5 GeV/c^2 if M_{LSP}= 0 GeV/c^2, and below 96.5 GeV/c^2 at M_{LSP}= 40 GeV/c^2. The corresponding expected limits are 91.4 GeV/c^2 and 94.7 GeV/c^2. The limits hold for all ΔM>4 GeV/c^2.

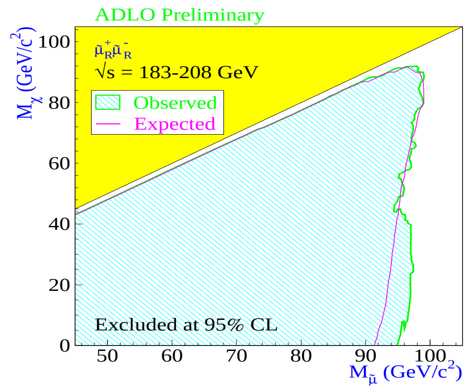

Figure 1. Limit in the $M_{\tilde{\mu}}$- M_{LSP} plane.

For the $\tilde{\mathrm{e}}$, the cross-section and angular distributions depend on the bosino-sector, due to the contribution of the t-channel $\tilde{\chi}^0$-exchange. Figure 2 shows the production cross-section that is excluded at 95% CL in the $M_{\tilde{\mathrm{e}}}$ - M_{LSP} plane. The SUSY working group also gives the corresponding excluded masses at a specific theory point, namely $\tan\beta$=1.5, μ=-200 (fig 3). At this point, $\tilde{\mathrm{e}}$:s are excluded at 95% CL below 99.6 GeV/c^2 if M_{LSP} = 0 GeV/c^2, below 99.4 GeV/c^2 at M_{LSP} = 40

[1] If cascade decays are possible, there will be a branching-ratio dependence on the mass-limits. However, in most points in the parameter-space, not otherwise excluded, branching ratio to $\mathrm{f}\tilde{\chi}^0_1$ is 100 %.

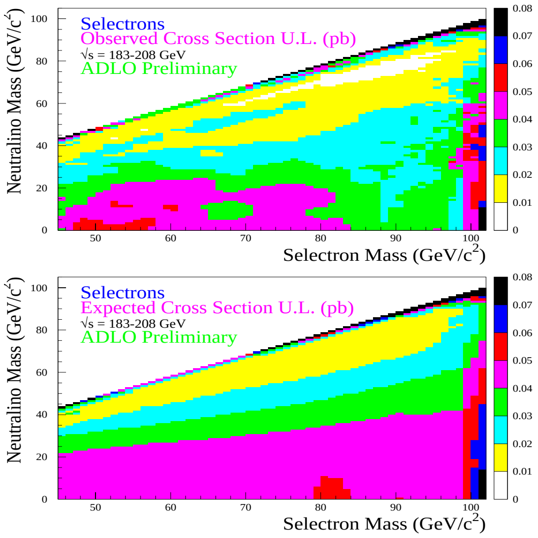

Figure 2. Observed and expected upper cross-section limits for ẽ in the $M_{\tilde{e}}$ - M_{LSP} plane.

GeV/c^2. The corresponding expected limits are 99.2 GeV/c^2 and 99.4 GeV/c^2. Also these limits hold for all ΔM>4 GeV/c^2.

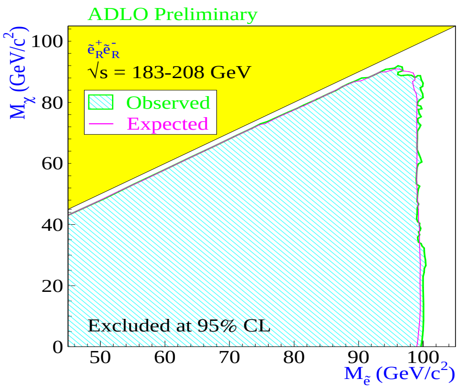

Figure 3. Mass limit in the $M_{\tilde{e}}$ - M_{LSP} plane, for tan β=1.5 and μ=-200.

For the $\tilde{\tau}$:s, the cross-section depend on the stau-mixing. The mixing angle that yields the lowest cross-section depends on the coupling to the Z and is given by the SM. Assuming the mixing to be minimal, and that tan β=1.5 and μ=-200, LEP excludes (at 95 % CL) $\tilde{\tau}$:s below 85.0 GeV/c^2 if M_{LSP} = 0 GeV/c^2, and below 92.5 GeV/c^2 at M_{LSP} = 40 GeV/c^2. The corresponding expected limits are 84.7 GeV/c^2 and 88.8 GeV/c^2. The limit hold for all ΔM>7 GeV/c^2. If the lightest $\tilde{\tau}$ is a pure $\tilde{\tau}_{\mathrm{R}}$, the limits become about 1 GeV/c^2 stronger (fig 4).

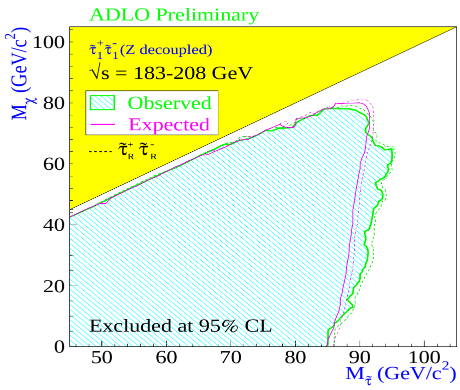

Figure 4. Mass limit in the $M_{\tilde{\tau}}$ - M_{LSP} plane, for the mixing yielding minimal cross-section, and pure $\tilde{\tau}_{\mathrm{R}}$.

Due to the possibility of a mixing angle such that the $\tilde{\tau}$ does not couple to the Z, there is no absolute limit from LEP I on its mass. DELPHI have therefore searched for $\tilde{\tau}$:s at the lowest possible ΔM(=M_τ)[4]. At the minimal cross-section they find the excluded region shown in fig 5. The limit is at 25 GeV/c^2 (expected limit 28 GeV/c^2), and is valid for all mixing angles and all ΔM.

3. Squarks

The squarks are the scalar partners to the SM quarks. In most of the MSSM parameter plane, they are expected to be beyond the reach of LEP, but due to mixing between the hyper-charge states, the low-

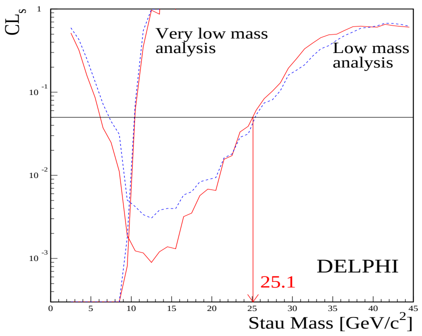

Figure 5. CL_s as a function of $M_{\tilde{\tau}}$ for $\Delta M = M_{\tau}$. Solid line: observed, dashed line: expected

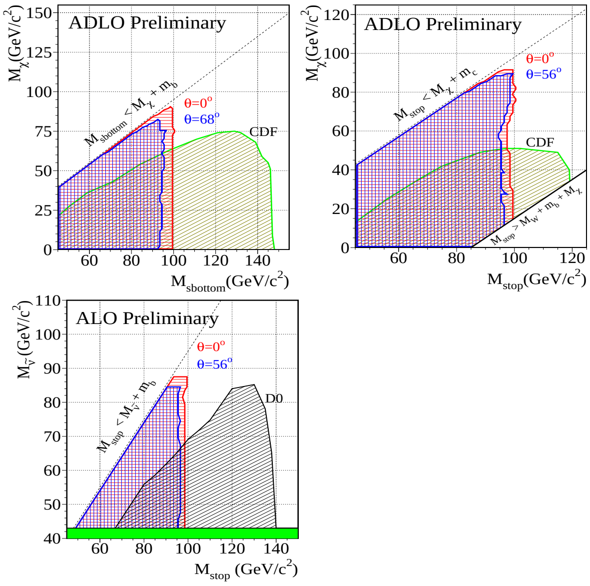

Figure 6. Mass limits in the $M_{\tilde{\mathrm{q}}}$ - M_{LSP} plane for the mixing yielding minimal cross-section, and pure $\tilde{q}_{\mathrm{R}}$. Top left plot: $\tilde{\mathrm{b}}$. Top right plot: $\tilde{\mathrm{t}}$, in the $\mathrm{c}\tilde{\chi}^0$ channel. Bottom plot: $\tilde{\mathrm{t}}$, in the $\mathrm{b}\ell\tilde{\nu}$ channel.

est mass-eigenstate might be within reach. As the size of the off-diagonal term in the mass-matrix is proportional to the fermion mass, such effects might be sizable in the third generation. The LEP searches have therefore concentrated on the $\tilde{\mathrm{b}}$ and the $\tilde{\mathrm{t}}$. The $\tilde{\mathrm{b}}$ decays to $\mathrm{b}\tilde{\chi}^0$ yielding a signature of two b-jets and missing momentum. Due to the high mass of the top-quark, the $\tilde{\mathrm{t}}$ must decay via flavour changing higher order processes, either to $\mathrm{c}\tilde{\chi}^0$ (via a $\mathrm{b\,W}\tilde{\chi}^{\pm}$ loop), or, if kinematically possible, to $\mathrm{b}\ell\tilde{\nu}$ (via a virtual $\tilde{\chi}^{\pm}$). Hence, the signal might be either two c-jets and missing momentum, or two leptons and two b-jets and missing momentum.

In the same sense as for the sleptons, the mass-limits are "theory independent" - they only depend on the basic SUSY assumption.

All LEP experiments have searched for $\tilde{\mathrm{b}}$:s and $\tilde{\mathrm{t}}$:s in all the available data [8][4][9][6], and the results have been combined within the LEP SUSY working-group [10]. Figure 6 show the 95% CL exclusion regions in the $M_{\tilde{\mathrm{q}}}$ - M_{LSP} plane. Also shown are the results from CDF [11] and D0 [12]. For the $\tilde{\mathrm{b}}$, and $\tilde{\mathrm{t}}$ in the $\mathrm{c}\tilde{\chi}^0$ channel, the limit is 95 GeV/c^2. For $\tilde{\mathrm{t}}\rightarrow \mathrm{b}\ell\tilde{\nu}$, the limit is 96 GeV/$c^2$. These values are valid for the mixing angle yielding the minimal cross-section. If there is no mixing, the limit is between 3 and 4 GeV/c^2 stronger.

The $\tilde{\mathrm{t}}$ can only decay via higher-order diagrams, so it might have a macroscopic decay-length at ΔM well above the c-mass. In addition, the four-body decay $\tilde{\mathrm{t}}\rightarrow \mathrm{b\,f\,\bar{f}}\tilde{\chi}^0$ is of the same order of perturbation-theory as the $\mathrm{c}\tilde{\chi}^0$ channel, and might well be competing. These possibilities was studied by ALEPH [8], and figure 7 shows the limit as a function of $c\tau$ and ΔM and as a function of the branching ratio of the two channels and ΔM. If ΔM> 5 GeV/c^2, the limit does not depend on $c\tau$, and if ΔM is in the range 15 to 25 GeV/c^2, it does not depend on the branching-ratio. The limit never descends below 61 GeV/c^2.

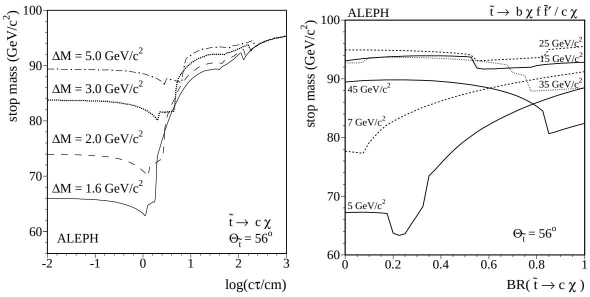

Figure 7. The $M_{\tilde{t}}$ limit as a function of the proper lifetime (left), and the branching ratio of $\tilde{t} \rightarrow c\tilde{\chi}^0$. The different curves corresponds to different ΔM values, as indicated next to the curves.

4. Bosinos

The bosinos are the SUSY partners to the SM bosons, ie. the gauginos and the higgsinos. They mix to give two charged states - the charginos - and four neutral states - the neutralinos.

At LEP, the production and decay might give rise to many different channels, with different topologies, from lepton-pairs to multi-jet events, possibly accompanied by γ:s. The experimental signatures vary depending on ΔM. There will often be competing channels, giving rise to to interference effects, and demanding that experimental analyses carefully treats double-counting issues. There will often be cascades decays, and they might include sfermions as well as other bosinos. Therefore, while the cross-section limits are "theory independent", the mass-limits will in general not be.

The charginos would be detected in the channel $e^+e^- \rightarrow Z/\gamma \rightarrow \tilde{\chi}^+\tilde{\chi}^- \rightarrow \tilde{\chi}^0 W^+ \tilde{\chi}^0 W^-$. Due to the invisible $\tilde{\chi}^0$, the signature will always include missing momentum . Depending on the W decays, one might get four jets, two jets and one charged lepton, or two charged leptons. The proportions depend on the W properties, not SUSY. If the $\tilde{\chi}^0$-$\tilde{\chi}^\pm$ mass difference is small, the visible system will be soft, demanding a custom analysis. It is also possible that there are cascade-decays via heavier neutralinos or via sfermions. Of particular importance is the "$\tilde{\tau}$-hole": If the $\tilde{\tau}$ is lighter than the $\tilde{\chi}^\pm$, $\tilde{\chi}^+\tilde{\chi}^- \rightarrow \tilde{\tau}\nu_\tau\ \tilde{\tau}\nu_\tau$ will be important, and if the $\tilde{\tau}$ is almost degenerate with the $\tilde{\chi}^0$, this mode will be hard to exclude - it will depend on the lowest allowed stau-mass (any mixing, any ΔM). More constraints are needed to exclude this possibility, eg. the coupling between different sfermions given by the mSUGRA hypothesis.

In the analysis of the high ΔM case, the analyses of acoplanar jets, of acoplanar jets with isolated leptons and of acoplanar lepton are combined. Cuts are optimised depending on ΔM and the different decay-channels are combined. As the branching-ratios depend on the properties of the W and the kinematics, theory independent cross-section limits can be derived. These analyses have not yet been combined within the SUSY WG, and figure 8 shows the result from OPAL [6] on the production cross-section that is excluded at 95% CL in the $M_{\tilde{\chi}^\pm}$ - $M_{\tilde{\chi}^0}$ plane. If the constraints of mSUGRA are added, the cross-section as a function of $M_{\tilde{\chi}^\pm}$ and $M_{\tilde{\chi}^0}$ is predicted, and exclusion region in the mass plane can be calculated, also shown in the figure.

If the mass-difference between the $\tilde{\chi}^\pm$ and the $\tilde{\chi}^0$ becomes small (less than a few GeV/c^2) [2], the visible system is hard to detect, since it becomes similar to the $\gamma\gamma$ background. However, if there is a detected ISR-photon, the initial e^+e^--system will have a known transverse mo-

[2] If the mass-difference is very small (<200 MeV/c^2), the $\tilde{\chi}^\pm$will decay after a macroscopic distance, and can be excluded to a very low cross-section.

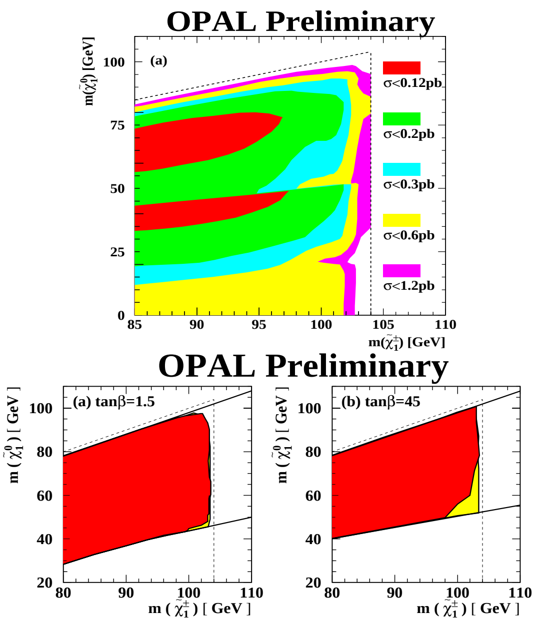

Figure 8. Top figure: Observed upper cross-section limits for $M_{\tilde{\chi}_1^\pm}$ in the $M_{\tilde{\chi}_1^\pm}$ - $M_{\rm LSP}$ plane. Bottom figure: Mass limit in the $M_{\tilde{\chi}_1^\pm}$ - $M_{\rm LSP}$ plane, for $\tan\beta$=1.5 (left), and $\tan\beta$=45 (right).

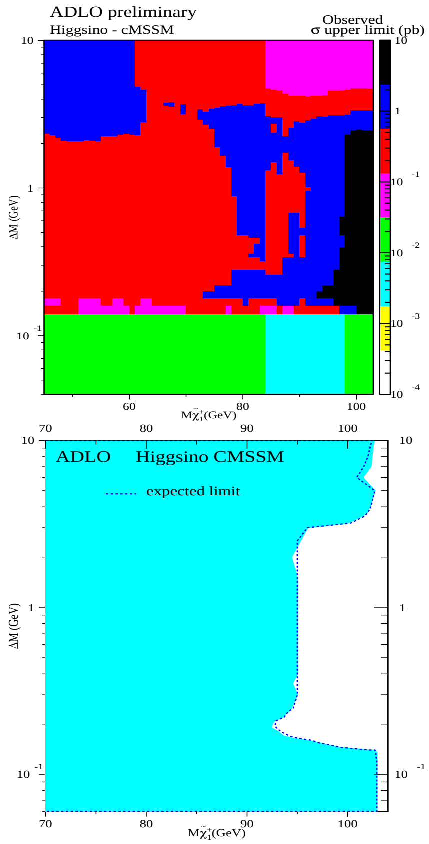

Figure 9. Left figure: Observed upper cross-section limits for $M_{\tilde{\chi}_1^\pm}$ in the $M_{\tilde{\chi}_1^\pm}$ - ΔM plane. Right figure: Mass limit in the $M_{\tilde{\chi}_1^\pm}$ - ΔM plane.

mentum, and one can probe lower missing momenta. Special analyses were carried out by all experiments to detect such events [13][4][9][6]. These results have been combined within the SUSY WG [14], which studied two cases: If there is gaugino mass-unification at the large scale, the low ΔM occurs for a higgsino-like $\tilde{\chi}^\pm$. If M_1 and M_2 are close to equal, it occurs for a gaugino-like $\tilde{\chi}^\pm$. The latter case gives about twice the production-rate. The excluded cross-section and the corresponding excluded mass-region in the higgsino case is shown in figure 9. The limits at 95 % CL, valid for any ΔM, are 91.9 GeV/c^2 in the gaugino scenario, 92.4 GeV/c^2 in the higgsino scenario. The corresponding expected limits are 91.9 GeV/c^2 and 92.8 GeV/c^2. This analysis can be applied to the "$\tilde{\tau}$-hole": at large m_0, the destructive interference between the s-channel and the $\tilde{\nu}$-exchange becomes small and the $\tilde{\chi}^\pm$ cross-section is large enough to exclude such events, even when the detection of an ISR photon is required.

The neutralinos would be detected in the channel $e^+e^- \to Z/\gamma \to \tilde{\chi}_1^0\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ \tilde{\chi}_1^0$ Z. Due to the invisible lightest $\tilde{\chi}^0$ the signature will always contain missing momentum. Depending on the Z decay, one might get two jets or two leptons, and the branching ratio depends on the Z properties. The cross-section is lower than for $\tilde{\chi}^\pm$, so the ISR method for very small ΔM cannot be used, but nevertheless the $\tilde{\tau}$-hole for $\tilde{\chi}^\pm$ can be covered by $\tilde{\chi}^0$: If $\tilde{\chi}^\pm \to \tilde{\tau}\nu_\tau$, then $\tilde{\chi}_2^0 \to \tilde{\tau}\tau$ usually is open which would be visible, even if the $\tilde{\tau}$ and the $\tilde{\chi}_1^0$ are quasi-degenerate. This channel becomes more important at low m_0, since the s-channel and the $\tilde{e}$-exchange interferes constructively.

In the $\tilde{\chi}^0$ analysis, the acoplanar jet and acoplanar lepton analyses are combined. As in the $\tilde{\chi}^\pm$ case, cuts are optimised depending on ΔM. The decay-channels are combined to yield the cross-section limit. As the branching-ratio does not depend on SUSY, this limit is theory independent. Figure 10 shows the cross-section limit obtained by L3[9], as well as the limits in the mass-plane once the mSUGRA constraints have been applied, for low and high $\tan\beta$,respectively.

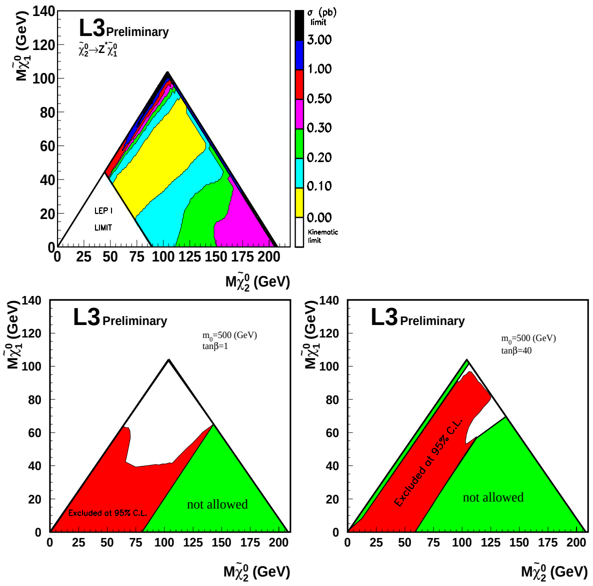

Figure 10. Top figure: Observed upper cross-section limits for $\tilde{\chi}_1^0\tilde{\chi}_2^0$ in the $M_{\tilde{\chi}_2^0}$ - $M_{\tilde{\chi}_1^0}$ plane. Bottom figure: Mass limit in the $M_{\tilde{\chi}_2^0}$ - $M_{\tilde{\chi}_1^0}$ plane, for $\tan\beta$=1 (left), and $\tan\beta$=40 (right).

5. Theory parameter constraints

To put constraints on the parameter-space, one combines all searches, taking care not to double-count events that would enter as candidates to more than one search. The parameter-space is then scanned. It is verified that a given parameter point does not yield a charged LSP or tachyons. A simulation program or an efficiency-parametrisation is used to determine how many events are expected from SUSY - all open channels confused - at each parameter-point. If this excess is larger than the experimentally excluded excess of events, the parameter point can be excluded. Figure 11 shows the regions in the μ-M_2 plane excluded by DELPHI [4] at different values of m_0, and different amounts of mixing in the sfermion-sector. The result can be given in terms of a limit on M_{LSP}, which strongly linked to the $\tilde{\chi}^\pm$, due the the unification assumption. Figure 12 shows how the limit evolves with $\tan\beta$, under several different assumptions on mixing and m_0, with and without constraints from the Higgs searches.

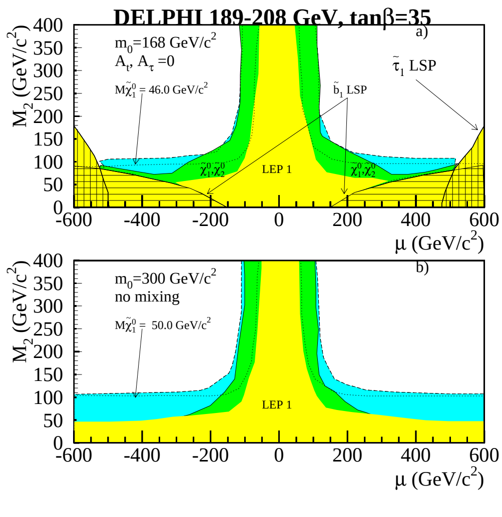

Figure 11. Parameter constraints in the CMSSM in the μ-M_2 plane, at two values of m_0 and different assumptions on the sfermion mixing, at $\tan\beta$=35.

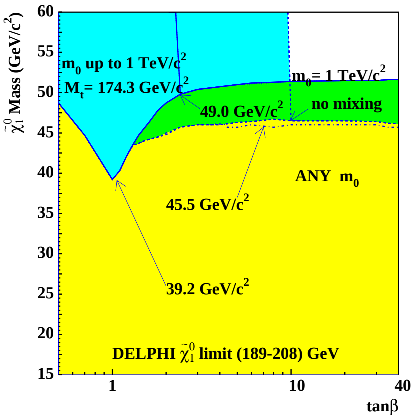

Figure 12. Parameter constraints in the CMSSM. The limit on $M_{\tilde{\chi}_1^0}$ as a function of $\tan\beta$. Solid line: m_0=1 TeV/c^2, dashed line: any m_0, and no sfermion mixing, dash-dotted line: any m_0, and A=0 at the EW-scale. The steep branches of the solid and dashed lines indicates the effect of including the Higgs search.

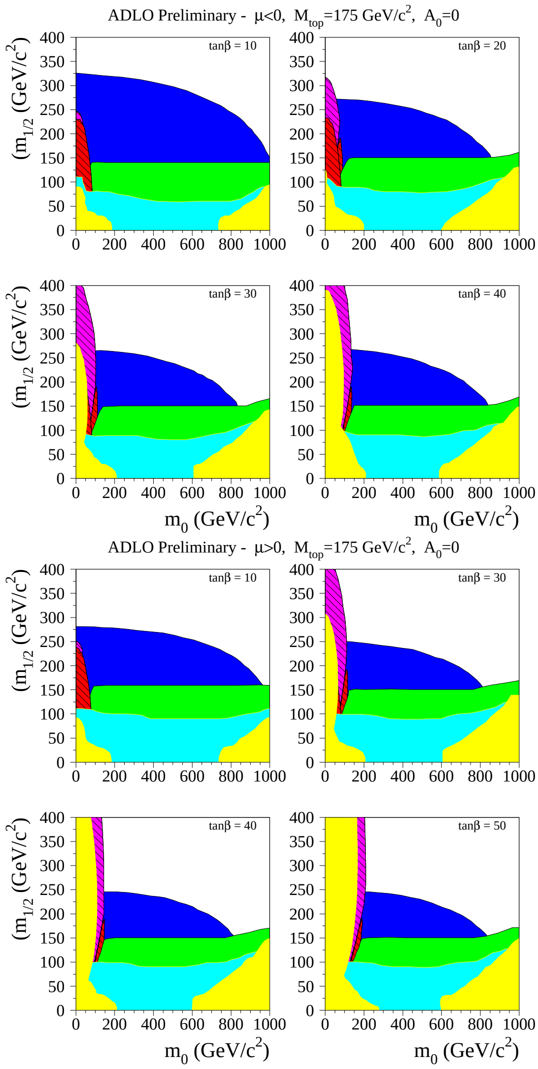

Figure 13. Parameter constraints in mSUGRA for negative μ (top four figures) and positive μ (bottom four figures), in the m_0-$m_{1/2}$ plane, at various values of $\tan\beta$. The unhatched regions, going from the lightest to the darkest shading indicate regions excluded by: No valid mSUGRA solution; LEP I precision measurements; $\tilde{\chi}^{\pm}$ searches; Higgs searches. The light hatched region indicate the region excluded by the search for heavy long-lived charged particles (applied to the $\tilde{\tau}$), and the dark hatched region the one excluded by the standard $\tilde{e}$ or $\tilde{\tau}$ search. There is a narrow region between the two latter, not visible in the plots, that is excluded by the $\tilde{\chi}_2^0 \to \tilde{\tau}\nu_\tau$ search.

The SUSY WG have performed parameter scans using the combined results of all four experiments in the more restricted mSUGRA model [15], in which the limits form the Higgs search strengthens the limits at low $\tan\beta$. By also imposing a single SUSY-breaking tri-linear coupling (A) the regions where the $\tilde{\tau}$-hole appeared are not valid points, usually because they correspond to tachyonic squarks.

Figure 13 shows the combined exclusions in the m_0 - $m_{1/2}$ plane, and figure 14 shows how the limit on $M_{\tilde{\chi}^0}$ evolves with $\tan\beta$. Within mSUGRA, LEP excludes an LSP below 59.0 GeV/c^2 for μ >0, below 58.6 GeV/c^2 for μ <0. This limit is weakened by 5 GeV/c^2 if the top-mass is 5 GeV/c^2 higher than the current world average.

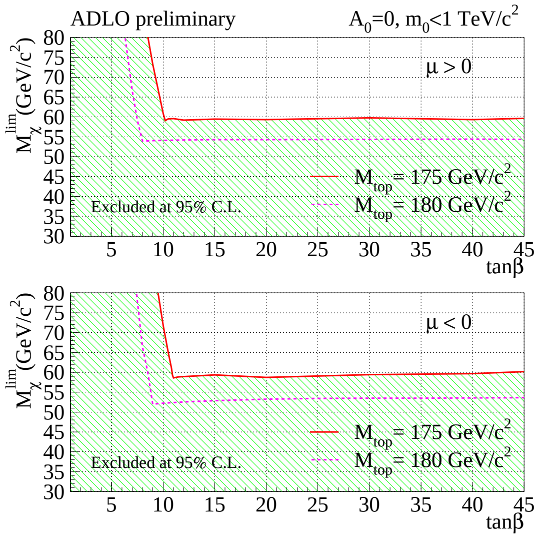

Figure 14. The limit on $M_{\tilde{\chi}_1^0}$ as a function of $\tan\beta$ and different signs of μ

6. Conclusions

The four LEP experiments have searched for sparticles. No excess with respect to the SM was observed in any channel. The data of most of these searches have been combined within the LEP SUSYWG. Within the framework of R-parity conserving MSSM, all sparticles have been excluded for masses lower than ≈ 90 GeV/c^2, except the Lightest neutralino or sfermions, if ΔM is small (few GeV/c^2). Within mSUGRA, limits on the allowed parameters have been set, in particular $M_{\rm LSP}$ must be > 59 GeV/c^2.

REFERENCES

1. P.Fayet, S. Ferrara, Phys. Rep. **32** (197) 249; H.P. Nilles, Phys. Rep. **110** (1984) 1; H.E. Haber, G.L. Kane, Phys. Rep. **117** (1985) 75
2. R. Aronwitt, A. Chamseddine, P. Nath, *N=1 Supergravity*, World Scientific, Singapore, 1984.
3. ALEPH coll., Phys. Lett. **B526** (2002) 206.
4. DELPHI coll., DELPHI 2002-027 CONF 561.
5. L3 coll., L3 note 2731
6. OPAL coll., OPAL note PN470
7. LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL experiments, note LEPSUSYWG/02-01.1
8. ALEPH coll., Phys. Lett. **B537** (2002) 5.
9. L3 coll., L3 note 2707
10. LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL experiments, note LEPSUSYWG/02-02.1
11. CDF coll., Phys. Rev. Lett. **84** (2000) 5704
12. D0 coll., Phys. Rev. Lett. **88** (2000) 171802
13. ALEPH coll., Phys. Lett. **B533** (2002) 223.
14. LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL experiments, note LEPSUSYWG/02-04.1
15. LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL experiments, note LEPSUSYWG/02-06.1

The relevant WWW addresses are:
SUSYWG:
`lepsusy.web.cern.ch/lepsusy/Welcome.html`
ALEPH: `alephwww.cern.ch/WWW/`
DELPHI:
`delphiwww.cern.ch/Welcome.html`
L3: l3.web.cern.ch/l3/
OPAL: `opal.web.cern.ch/Opal/PPwelcome.html`