SUSY SEARCHES AT LEP 2

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Searches for supersymmetric particles with the data collected at LEP 2 at centre-of-mass energies up to 183 GeV have been performed. Many results in scenarios with R-parity conserving and with R-parity violation, in framework of Minimal Supersymmetric Standard Model, and in the gravitino LSP are reviewed. No signal has been found in the searched topologies. Limits on the productions have been derived and interpreted in the context of the different theoretical models.

1 Introduction

Supersymmetry [1] (SUSY) is one of most motivated theory beyond the Standard Model. It predicts the existence of supersymmetric particles, boson and fermion partner for each fermion and boson Standard Model (SM) particle respectively. The fermions acquire spin-0 partners, while the gauge bosons acquire spin-1/2 partners. Apart from the spin, the "superpartners" have the same quantum numbers as the corresponding SM particles. Since we don't observe this symmetry at low scale SUSY must be broken. Soft SUSY breaking Lagrangian terms break the degeneracy between ordinary and SUSY particles, leaving the exact relation between the couplings. These terms are the free parameters of the theory: m_0, the common mass of spin-0 sfermions at the GUT scale, M_i (i=1,2,3) the mass of the U(1), SU(2) and SU(3) sectors, μ, the supersymmetric Higgs mass term, and $\tan\beta$, the ratio of vacuum expectation values of the two Higgs doublet.

In the Minimal Supersymmetric Standard Model (MSSM) the SUSY breaking occurs at very high scale, propagates to the visible sector by gravity interaction and, since the gravitino mass is related to the breaking scale, the gravitino is heavy.

In the other models the SUSY breaking should occur at lower energy and propagate to the visible sector by gauge interactions. As a consequence the gravitino is the lightest supersymmetric particle.

A discrete multiplicative quantum number, called R-parity [2], is introduced in the theory: the standard model particles have R=+1 while the SUSY particles have R=-1. Three natural term in the SUSY Lagrangian can break the R-parity, leading to the barion and lepton number violation. They are of the form:

$$\mathcal{L}_{RPV} \propto \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

The simultaneous presence of the last two terms leads to fast proton decay, in conflict with the experimental limit on proton lifetime. In MSSM the R-parity is assumed to be an exact symmetry, excluding the three terms from the Lagrangian. As a consequence the SUSY particles must be produced by pair and decay to another supersymmetric particle and SM particles. In addition, the Lightest Supersymmetric Particle (LSP) is stable and, by cosmological bounds on stable colored particle, the LSP must be neutral and colorless [3]. The phenomenological consequence in this case is that the main signature for Supersymmetry is missing energy and mass from the LSP, which escapes detection. The scenario with R-parity violating terms [4] has been also studied assuming only one of the three terms different from zero at one time. In this case all the SUSY particles can decay to the SM ones so that missing energy and momentum are not necessarily present in the detected final state and SUSY particles can be produced singly.

In this paper an overview is made of the results obtained by the 4 experiments ALEPH, DELPHI, L3 and OPAL by analysing the data collected at LEP 2 at the centre-of-mass energy of 183 GeV in 1997, when $\approx 57\ pb^-1$ were delivered per experiment.

2 Search in MSSM with R-parity conservation

The kinematics of the signal is essentially determined by the mass M of the produced particle and the difference $\Delta M = M - M_{LSP}$, where M_{LSP} is the mass of the final state LSP.

In the small ΔM region the signal events are characterised by a small multiplicity, small visible mass and energy and they look very similar to 2-photon events ($e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-f\bar{f}$). For the high ΔM region the background come from 2-fermion production through Z or γ exchange and from 4-fermion processes (WW, ZZ, Weν, Zγ^*). These processes have small missing mass and energy and a large visible mass. The most relevant difference between signal and background is the total visible energy (E_{vis}). For a small M or a large ΔM the E_{vis} spectra for the signal will always be wide enough to allow the opening of a window where the main background sources are heavily reduced. A general feature of all the analysis is to define different topological selections, optimized for different ΔM regions, and the best combination of analyses to apply depending on ΔM, following the $\bar{N}_{95}$ prescription [5].

No excesses of number of events with respect to the Standard Model expectation have been found. The good agreement between the predicted and observed numbers give the idea of the effectiveness of the selections calculated with the Monte Carlo

The results of the search is given, first of all, in term of model independent upper limit at 95% C.L. on the signal cross section. This is generally plotted in $M_{\tilde{p}}, M_{\chi}$ plane. The experimental results are compared to the theoretical cross section (including the Branching Ratio) calculated as a function of SUSY parameter. The diversity of topological selections allows interpretation under a variety of model assumptions. Therefore, limits on sparticle are interpreted in the MSSM. All the results reported here should be considered as preliminary.

2.1 Charginos and neutralinos

The charginos ($\chi^{\pm}$) would be pair produced through an s-channel Z/γ^* exchange and for gaugino-like chargino through the t-channel $\tilde{\nu}$ exchange. This contribution can be large if the sneutrino is light. The s- and t-channel diagrams interfere destructively, causing a decrease in the cross section. In the higgsino region the cross section is lower than in the gaugino region for heavy sneutrinos, but not affected by the sneutrino mass. The kinematic limit will easily be reached with even a modest integrated luminosity.

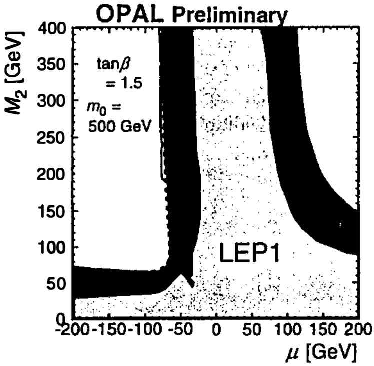

Figure 1: Limits on the chargino mass derived in the (μ, M_2) plane, for $\tan\beta = 1.5$ and $m_0 = 500$ GeV/c^2 from OPAL. The dark shaded area shows the additional excluded region, with respect to LEP 1, using the data at 183 GeV. The kinematic boundary for the $\chi^{\pm}$ production are shown by dashed curves. The light shaded region extending beyond this boundary is due to the interpretation of the direct $\chi\chi'$ search

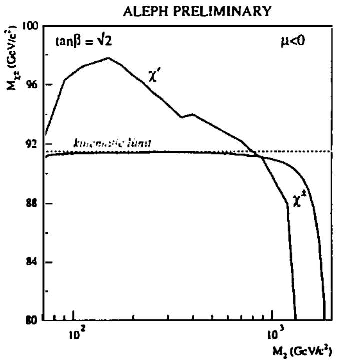

Figure 2: The limit, from ALEPH, on the chargino mass as a function of M_2, from the chargino search and from the neutralino search translated into the chargino mass limits.

Charginos decay to Standard Model particles and the LSP, assumed to be the neutralino or the sneutrino. The chargino will decay to a neutralino via a virtual W, slepton and squark exchange. Depending on B.R. the possible final states are acoplanar leptons (not necessary of the same flavour), 4-jets plus missing energy, 2-jets plus lepton plus missing energy. In much of MSSM parameter space the W* B.R. is assumed, but light sleptons affect chargino decays through an enhancement of the decay through virtual sleptons, increasing the fraction of charginos decaying to leptons.

The four neutralinos (χ, χ', χ'', χ''') of MSSM are produced via s-channel Z exchange and, if the selectron is light, via the selectron t-channel diagram. The most promising neutralino production process at LEP 2 is the $e^+e- \to \chi\chi'$. The χ' decays mainly into $\chi\ell\bar{\ell}$, $\chi q\bar{q}$ or $\chi\gamma$ depending on the χ and χ' field composition. The combined results of the chargino and neutralino search are generally displayed as excluded regions in (M_2,μ) plane for fixed slepton masses and fixed $\tan\beta$ value. The exclusion plot is given in Figure 1 where the OPAL result is shown under the assumption of high sfermion masses and gauge mass unification at GUT scale (this condition implies that at the electro-weak scale $M_2 = \frac{3}{5\tan^2\theta_W}M_1$). The neutralino searches are complementary to the chargino ones and can improve the sensitivity in the higgsino region ($M_2 \gg |\mu|$) where the neutralino cross section and efficiency are large: due to the low mass difference between chargino and LSP, the chargino search is affected by low efficiency and by high $\gamma\gamma$ contamination and in this case the neutralino specific search can contribute significantly. In Figure 2 for low $\tan\beta$ and negative μ the neutralino search, realized by ALEPH, excludes region inaccessible via chargino search. In the gaugino sector when the chargino mass is close and above the sneutrino mass giving a lower cross section and an enhanced leptonic B.R., the exclusion can be very difficult due to the low efficiency in detecting very soft lepton: indirect limits in this region are obtained by the search of sleptons.

2.2 *Limit on the LSP*

Direct limit on the lightest neutralino is difficult to obtain since it is characterised by invisible final states. Indirect limits are derived by the constraint on chargino and the second lightest neutralino searches, which are translated into a lower limit on the mass of the lightest neutralino. Preliminary results are given considering the gaugino mass unification at GUT scale and high m_0. The ALEPH result, obtained on the basis of this assumption, is reported in Figure 3. In this figure the lower limit of 29.8 GeV/c^2 is set for $m_0 = 200$ GeV. For low m_0, there is a region not covered by the chargino and neutralino searches which can be covered by slepton limits. For any value of $\tan\beta$, and for any m_0, the lightest neutralino must have mass greater than 25.9 GeV/c^2. The result obtained by L3 is shown in Figure 4.

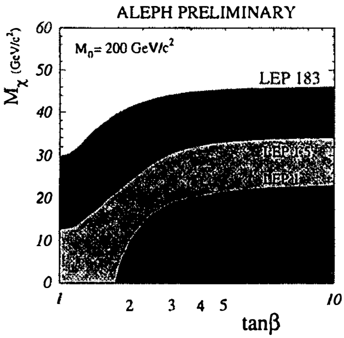

Figure 3: Mass limit on lightest neutralino as a function of $\tan\beta$ and for heavy sfermion (m_0 = 200 GeV/c^2) from ALEPH. The limit from chargino search alone is shown as dashed line.

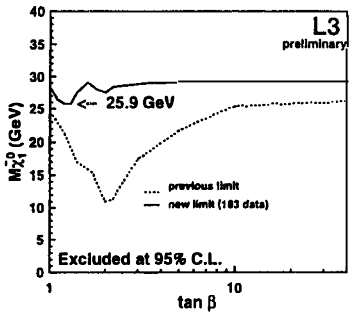

Figure 4: Lower limit on the lightest neutralino mass as a function of $\tan\beta$ for any value of m_0 from L3

2.3 *Slepton*

There are two heavy scalar particles associate with the standard chiral leptonic states, which are called left-handed and right-handed slepton.

The mass of these states depends on the common scalar mass m_0 and on the gaugino mass parameter M_2 and $tan\beta$. They can be calculated via the renormalisation group equation. The right-handed sfermion is always lighter than the left-handed sfermion. If R-parity is assumed the sleptons are produced by pairs via the photon and the Z s-channel exchange. The t-channel neutralino exchange is open only in the selectron pair production. This term enhances the cross section with respect to the other slepton, but it is model dependent and the limits depend from the parameter chosen. The slepton are expected to decay into the corresponding charged lepton

Table 1: Summary of the slepton results at LEP 2 for the χ LSP scenario with R_P conservation.

Slepton	95 % CL Mass Lower Limit GeV/c^2	Assumptions
$\tilde\tau_R$	65	$\Delta M \geq 15$ GeV/c^2
$\tilde\mu_R$	65	$\Delta M \geq 4$ GeV/c^2
$\tilde e_R$	78	$\Delta M \geq 2$ GeV/c^2 $\mu = -100$ GeV $\tan\beta = 1.5$
l	65	$\mu = -100$ GeV $\tan\beta = 2$

and neutralino. The experimental signature for these particles is the presence of two acoplanar leptons of the same flavour with missing momentum.

A new search has been developed by ALEPH to cope with the low sensitivity of the analysis in the region of small mass difference between right-handed selectron and the lightest neutralino. In this case the $\tilde{e}_R\tilde{e}_L$ production leads to final states with single electron. This search has been used by ALEPH to combine results for right-handed and left-handed sleptons, assuming a common scalar mass at GUT scale. The summary of results, in most pessimistic cases, for the slepton search is reported in Table 1.

2.4 Squark

The scalar quarks $\tilde{q}_L$ and $\tilde{q}_R$ are the SUSY partner of left-handed and right-handed quarks. They can mix to give the mass eigenstates. Because this mixing is growing up with the increasing fermion masses, it is important for the top squark and, in case of large tanβ, for the bottom. Stops and sbottoms are pair-produced at LEP 2 through Z and γ s-channel exchange. The coupling of these two squarks to the Z strongly depends on the mixing angle (θ_{mix}). Pairs produced stops have been searched in the acoplanar jet topology arising from the decay channels $\tilde{t} \to c\chi$. If the mass of the light stop is greaten than $M_b + M_\chi$ the decay in $\tilde{t} \to b\ell\tilde{\nu}$ via a virtual chargino exchange is dominant. The phenomenology of the sbottom is similar to the phenomenology of the stop. The sbottom decay as $\tilde{b} \to b\chi$. The limits are always also given in the most pessimistic case, when the squarks decouples from Z (when they can only be produced through photon exchange) and the cross section is lower. Limits from LEP 2 are competitive with those from the Tevatron for low mass difference between $\tilde{q}$ and χ. For $\Delta M > 10$ GeV/c^2 the lower limit of about 81 GeV/c^2 at 95% C.L. has been reached by OPAL in the channel $\tilde{t} \to c\chi$. Also the 95% C.L. exclusion regions in the plane ($M_{\tilde{t}}, M_\chi$) for different values of θ_{mix} has been determined by ALEPH and OPAL in the channel $\tilde{t} \to b\ell\tilde{\nu}$. The ALEPH lower limit is set at 82 GeV/c^2 at 95% C.L. for $\theta_{mix} = 56°$ and $\Delta M > 10$ GeV/c^2. OPAL sets a limit of 54.4 GeV/c^2 on the sbottom mass for the most pessimistic case and $\Delta M \geq 7$ GeV/c^2. Assuming unification of all gaugino masses and scalar mass at GUT scale, the constraint from LEP 2 have been compared with those inferred at Tevatron from the squark and gluino searches [6 7]. Limits on the production of the lighter four squarks, under the assumption that they are degenerate, have been set by ALEPH. The Figure 5 gives the regions excluded by CDF and D0 in the gluino-squark mass plane. The ALEPH results cover the hole in the exclusion plan for heavy gluino thanks to the good performance of the low ΔM analysis. The limit on $M_{\tilde{q}}$ is at least 87 GeV/c^2 up to $M_{\tilde{g}} \sim 545$ GeV/c^2 (535 GeV/c^2 if D0 values are used) and $\Delta M > 5$ GeV/c^2

2.5 Search in MSSM with R-parity violation

The search of SUSY particles with R-parity violation has been realized assuming only one coupling dominant and the coupling large enough to ensure negligible lifetime. Separate analyses have been developed assuming either LLE, the LQD or the UDD operator to be present. Since the LSP is no more stable the characteristic signature is no longer missing energy but multi-leptonic and multi-jets final states. The selection for a dominant LLE operator has been realized by ALEPH, DELPHI and OPAL in the chargino and neutralino sector considering topologies with multi-lepton final states. For high m_0 the kinematic limit on the chargino mass has been reached. Neutralino mass > 24 GeV/c^2 independent from m_0, is set by DELPHI.

For the case of dominant LQD operator, ALEPH searches pair produced lepton with R-parity violation decay of sparticle (direct decay), giving four jet final states. The mass limits for $\tilde{\nu}$ and $\tilde{\mu}_L$ have been set at 95% C.L. at 60 GeV/c^2 and 61 GeV/c^2 respectively. DELPHI and OPAL performed the search in the framework of direct stop decay in electron and d-quark. The

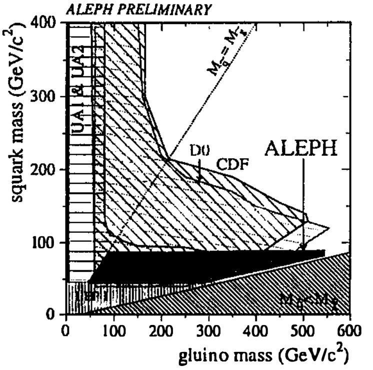

Figure 5: The ALEPH results for degenerate squark, $\tilde{q}_L$ and $\tilde{q}_R$ production, shown in the squark-gluino mass plane. A small region not excluded by CDF and D0 has been covered.

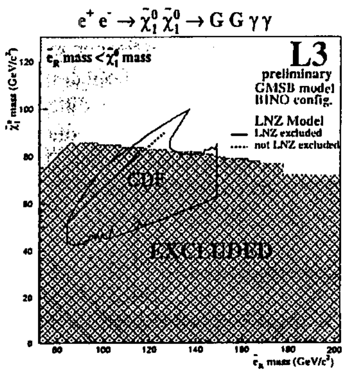

Figure 6: Excluded region, from L3, in the $(M_\chi, M_{\tilde{e}})$ compared to the region compatible with the GMSB model interpretation of the CDF event.

main signature consists of hadronic activity possibly with some lepton and/or missing energy. The negative results has been translated into lower limit of 82 GeV/c^2 for any value of θ_{mix}. ALEPH realized also the UDD search for pair production of chargino and neutralino, giving in case of direct decays six jets in final states. When the chargino decays indirectly to a W* and neutralino the final states are characterised by higher jet multiplicity perhaps associate with lepton and missing energy. Also in this scenario the exclusion region, given in (M_2, μ) plane, is set up to the kinematic region for high m_0 value.

3 Search in gravitino LSP scenario

In the Gauge Mediated SUSY Breaking [8] (GMSB) scenario the gravitino ($\tilde{G}$) is the lightest SUSY particle and the lightest Standard Model superpartner is the next to lightest SUSY particle (NLSP). The NLSP is unstable and decay in its partner plus gravitino. The lifetime of NLSP depends on gravitino mass and for very light gravitino this decay can take place in the detector. The main search has been realized by LEP in neutralino NLSP scenario, where it can decay by $\chi \to \gamma + \tilde{G}$. The main signature is the presence of single photon (from $e^+e^- \to \tilde{G}\chi \to \tilde{G}\tilde{G}\gamma$) or two acoplanar photons (from $e^+e^- \to \chi\chi \to \tilde{G}\tilde{G}\gamma\gamma$) plus missing energy and mass. The Standard Model background for these events are $\nu\nu\gamma(\gamma)$ and $\gamma\gamma(\gamma)$. This kind of processes can explain the famous CDF event [9] containing two high energy electron and two high energy photons with large missing transverse energy. The interpretation in GMSB model is $q\bar{q} \to \tilde{e}\tilde{e} \to \chi\chi e^+e^- \to \tilde{G}\tilde{G}\gamma\gamma e^+e^-$. Since in these models the χ is expected to be pure bino, at LEP 2 the production would proceed via t-channel selectron exchange and the cross section depends on $\tilde{e}$ mass. The negative results of the search can be translated in limit on $(M_\chi, M_{\tilde{e}})$ mass plane. In Figure 6 the L3 excluded region in this plane is shown. The region compatible with the GMSB model interpretation of the CDF event is also shown. Most of the CDF region is excluded at 95% C.L. by this analysis. The CDF event can also be explained in the standard higgsino LSP scenario with $e^+e^- \to \chi'\chi'$ and subsequent decay in $\chi' \to \gamma\chi$. The data are in good agreement with the prediction of the Standard Model and are used to set limits on cross section for anomalous photon production. These limits are presented by DELPHI as a function of the mean decay length of the χ' (which can fly detectable distance before decaying), also including the search of a single no pointing photon. The upper limit on cross section is set at 105-130 fb for $M_{\chi'} = 60 - 80$ GeV/c^2 and path decay length = 0.

4 Conclusion

A review of results on searches for supersymmetric particles with the data collected at LEP 2 for centre-of-mass energies up to 183 GeV has been reported. A big effort has been devoted to cover a large variety of experimental topologies and high sensitivity analyses have been realized. No signal has been found in any of the searched topologies and new excluded regions on the parameters of Supersymmetry have been set. In the MSSM the charginos and neutralinos searches allow the exclusion of chargino for masses up to the kinematic limit in various region of the parameter space. Indirect limits on the lightest neutralino have been set at 25.9 GeV/c^2, for any value of m_0 and $\tan\beta \geq 1$. In MSSM with R-parity violation limits on charginos, neutralino and slepton masses have been set, assuming different dominant couplings. No excess of anomalous photon production has been found. The new search for acoplanar photons has extended the exclusion region allowed by the GMSB model interpretation of the CDF event.

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