LEP results on SUSY: Sfermions and R-parity violation

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We present the most recent results on searches for the scalar supersymmetric partners of the SM fermions from the four LEP experiments, ALEPH, DELPHI, OPAL and L3. Most results include the data collected 1998 at E_{CMS} = 189 GeV. Each of the experiments collected between 160 and 180 pb^{-1} of data at this energy. As no excess of events with respect to the numbers expected from SM processes were seen, significant improvements on the limits for such processes are reported. The sfermion limits both consider the mSUGRA MSSM scenario with conserved R-parity, and with R-parity violation. We also report on the searches for neutralinos and charginos in the R-parity violating mSUGRA scenario. Here we show that the limits in the μ - M_2 parameter space are at the kinematic limit for chargino production for all m_0. Hence, violating R-parity does not weaken the limits for these processes.

I. INTRODUCTION

SuperSymmetry, a symmetry between fermions and bosons is is known to solve the naturalness problem, ie. the problem that in the SM the Higgs mass is not protected by any symmetry against arbitrarily large loop-corrections [1]. As SUSY postulates a symmetry between fermions and bosons, and fermionic and bosonic loops contribute with opposite sign to the radiative corrections, such loop-corrections to the Higgs mass cancel: divergences will be at most logarithmic.

It is also known that SUSY decouples from the SM, in that it predicts only very small deviations from the SM expectations, less than experimental limits,even the high precision measurements form LEP I.

The MSSM [2] is a SUSY with minimal particle content and conserved R-parity. This implies that its particle content is the super-symmetric partners to all the SM particles, and two Higgs doublets. It should be pointed out that the MSSM not per se "minimal" in the sense of having few free parameters. In fact, counting all particle masses, mixing matrix elements, Yukawa couplings, and the parameters of the Higgs sector, one finds that MSSM has in fact 124 free parameters [3].

R-parity conservation is introduced into SUSY to explain the absence of low-energy manifestations of it [4]. Such possible manifestations include FCNC, lepton-number non-conservation, lepton flavour non-conservation, proton decay, among others. The consequence of R-parity conservation is that sparticles must always come in pairs, both at the production and the decay vertecies, which implies that the lightest SUSY particle (the LSP) is stable.

SUSY is a broken symmetry. To conserve the properties solving the naturalness problem, it must be broken "softly", ie. in a way that does not re-introduce quadratic divergences. A commonly used model is the SUGRA inspired model (mSUGRA) [5]. This model largely reduces the number of parameters, e.g. the gaugino masses are equal at some unification scale, and are related at the EW scale. In the present note, mSUGRA will be used as a working hypothesis. MSSM breaking is assumed to occur in a hidden sector (i.e. with no tree-level interactions with the visible MSSM sector). The breaking is then transmitted by "messengers", which in the case of mSUGRA is the gravitino, as it assumes that the messenger mechanism is gravity. The unification scale is the GUT scale, and at this scale the gauginos have equal masses. By using the renormalization group equations to evolve down to the EW scale, the masses will no longer be equal. They will nevertheless be related, and can be described by a single parameter, usually taken to be the mass of the SU(2) gaugino at the EW scale, M_2. A similar behaviour also applies to the sfermions, where the common mass at the GUT scale is denoted by m_0. The Higgs sector is given by two parameters, μ and tan β. Finally, the trilinear Higgs-sfermion couplings are assumed to equal and flavour neutral, and are denoted by A. In this scheme, the LSP will be the lightest neutralino, or possibly a sneutrino.

A. Sfermion masses in mSUGRA

At the unification scale, all sfermion masses are equal to m_0. Using the RGE to evolve the masses to the weak scale, this degeneracy is broken [6]. The mass-parameters at the weak scale will be described by a function of m_0 and M_2, in addition to so called D-terms. These are of the order M_Z^2, and can be neglected as soon as the sum of M_2^2 and m_0^2 is large. Given the constraints of M_2^2 from chargino and neutralino searches, this is the case at almost all points in the parameter space [7].

The weak iso-spin doublet and singlet sfermions (which are denoted 'left-handed' and 'right-handed' after the helicity of the corresponding (ordinary) fermions) will acquire different masses at the weak scale. The right-handed sfermion will tend to be the lighter of the two.

Furthermore, the sleptons are predicted to get lower masses than the squarks, due to the contribution of coloured loops for the latter.

For the third generation sfermions, the Yukawa couplings can be large, in particular if tan β is large. As the contribution to the evolution of the masses from the unification scale to the weak scale due to such couplings is negative, the third generation sleptons might well have substantially lower masses than their counter-parts in the first and second generation.

The third generation might also show large mixing between the weak hyper-charge eigen-states, yielding an enhanced splitting between the two mass-eigenstates. Such an enhancement is not expected to occur for the first two generations, because the fermion mass enters into the off-diagonal elements of the mass-matrix.

Hence, within the mSUGRA scenario, one would expect a third generation sfermion to be lightest: the stop, the sbottom or the stau.

B. R-parity violation

The structure of the SUSY Lagrangian is such that there are a large number of terms yielding R-parity violation, and consequently the requirement of conserving R-parity demands that the coefficients of all these terms be zero. This is unnecessarily strict: many of these terms do not give rise to the low-energy processes excluded by experiment mentioned above. Hence a first step beyond the MSSM might be to allow certain R-parity violating processes. The SUSY Lagrangian contains R-parity violating terms describing slepton-lepton couplings (the "LLE" or "λ" terms), (s)lepton-(s)quark couplings (the "LQD" or "λ'" terms) and quark-squark couplings (the "UDD" or "λ''" terms). The absence of proton decay implies that the product of λ' and λ'' must be zero; the non-observation of lepton flavour non-conservation means that many combinations of different λ must vanish. Furthermore, limits on FCNC, lepton universality, and neutron oscillations implies that most single couplings cannot exceed 0.01 [8]. Nevertheless, certain couplings can be quite large, in particular for the third generation.

Common for all the R-parity violating processes is that the LSP no longer is stable. The LSP decays via a virtual sfermion to three fermions.

In addition, one might have direct sfermion decay (with or without lepton number violation), direct chargino decay, via a virtual sfermion to three fermions, and single sneutrino production.

II. SFERMION SIGNATURES AND BACKGROUND

At LEP, sfermions are assumed to be pair-produced in the s-channel, and to decay into the LSP (which is invisible) and the corresponding fermion. For some points, also cascade-decays via the second lightest neutralino is possible, with a branching-ration of 10 to 30%. In principle, decays via charginos are also possible, but as the experimental limits on chargino pair-production excludes chargino masses almost to the kinematical limit, they are not kinematically accessible [7]. However, since the top quark mass is higher than the stop mass in the region studied by LEP, stop decays via a virtual chargino must be considered.

As sfermions are scalars, their production will be isotropic, and will have a flat momentum distribution between two values determined by the sfermion mass, the LSP mass and the beam energy [9].

Hence, the experimental signature at LEP will be a pair of fermions with momentum not balancing, and with considerably less visible energy than in the initial e^+e^- system. Therefore, in all of the analyses one searches for events with two particles or jets, that are central in the detector, are acoplanar, and that have missing energy and momentum. When translating cross-section limits into limits in the SUSY parameter space, one also applies kinematic constraints on the fermion momentum.

A few special cases should be noted: For selectrons, also t-channel production via a neutralino is possible, so in this case the production is not isotropic. For the staus, the τ decay implies that the visible system have no lower limit for the momentum at any given point in the parameter-space. Also, stau-mixing is important to take into account, as it influences both the production cross-section and polarization of the τ lepton [10]. Finally, for the squarks, the fragmentation process makes the momentum distribution less flat. A certain theoretical uncertainty will arise from this, in particular for low mass-difference, where the squark life time might be long enough that it will hadronize before decaying.

The SM background to such topologies are: Four-fermion processes, mainly W^+W^- and ZZ production, with neutrinos among the vector bosons decay-products (yielding the missing momentum signature typical for sfermions); Single Z production, accompanied with a hard ISR photon ("radiative return") where the ISR photon was not detected; $\gamma\gamma$ processes; Other 4 fermion processes; Bhabha scattering; Cosmics. Each of these processes have properties different than those expected for sfermion production, hence it is possible to more or less efficiently suppress them. In particular: The W^+W^- backgrond is not isotropic, and the momenta of the seen system is typically larger. For the radiative return process, the ISR photon is lost down the beam-pipe, hence the event is balanced in a projection perpendicular to the beam-axis. The $\gamma\gamma$ background has low momentum, is not central, and has limited transverse momentum. Other 4-fermion processes typically have low cross-section (lower than the expected signal) and/or higher momenta. Finally, both bhabhas and cosmics have low acollinearity, even if they might have substantial missing transverse momentum, due to measurement errors [11].

III. RESULTS ON SFERMIONS

None of the experiments have reported any excess in any of the studied channels. Therefore all results reported here will be in the form of 95 % exclusion regions.

A. Sleptons

The ALEPH, DELPHI and L3 collaborations have searched for sleptons in the data taken at 189 GeV. The preliminary results presented here follow the same procedure as the published results at lower energies [12]. Figure 1 shows the 95 % exclusion regions for selectrons, smuons and staus obtained by ALEPH, L3 and DELPHI, respectively. In the case of the selectrons, specific values of μ and tan β have been used : μ = -200 GeV and tan $\beta=\sqrt{2}$. (For smuons and staus these variables have no influence on the limit).

TABLE I. Slepton limits at large $\Delta(M)$

	Mass limits (in Gev/c^2) for:		
	Selectron	Smuon	Stau (Right-handed)
ALEPH	87.0	83.0	73.0
DELPHI	88.0	75.0	75.0
L3	89.0	77.0	65.0

For the stau, the limits for a stau at a mixing angle yielding the lowest possible cross-section is given as well as the case of a pure right-handed stau. In the case of minimal coupling, there is no stau-Z coupling (only stau-γ), and hence LEP I can not contribute to the limit. Table I shows a summary of the limits obtained by the various experiments, for the case of a large difference between the slepton and the LSP masses.

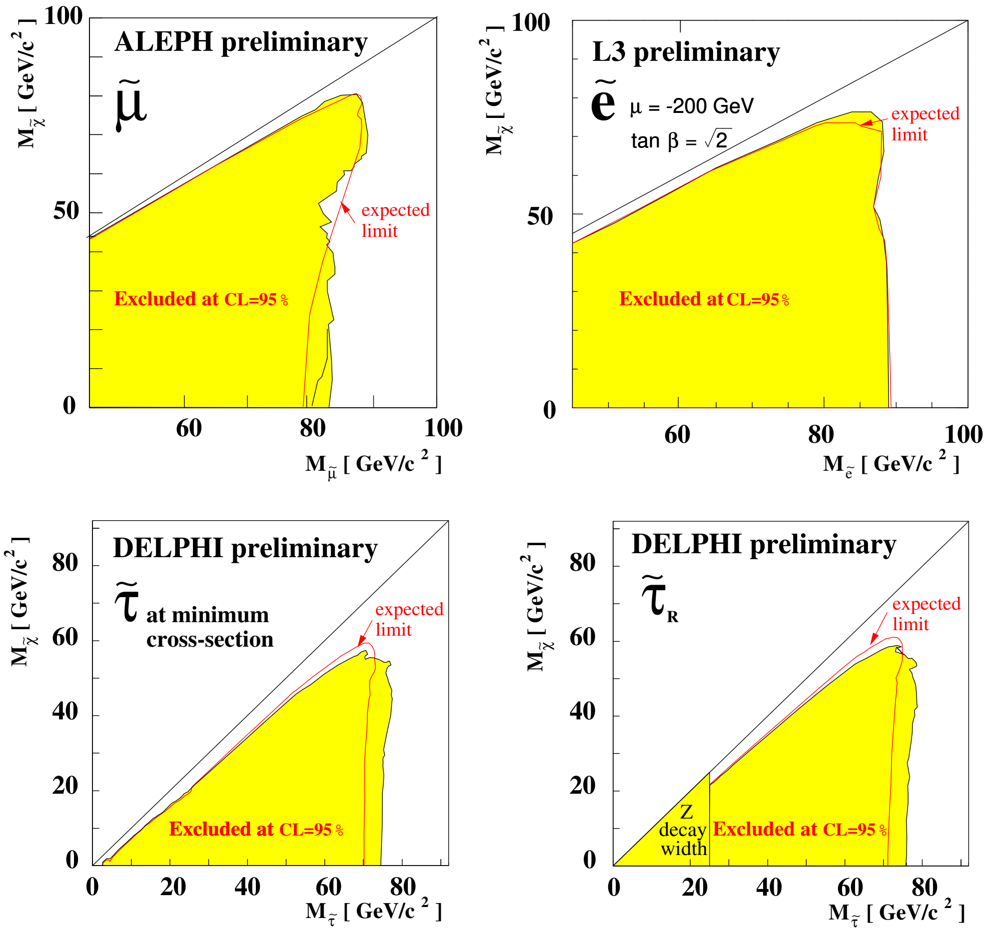

FIG. 1. Limits on slepton production.

B. Squarks

The LEP experiments have also searched for squarks in the data taken last year. Once again, the preliminary results presented here use the same procedures as were used for the results at lower energies [13].

Figure 2 shows the exclusion regions for the third generation squarks: sbottom from the ALEPH collaboration, stop from OPAL, and stop in the case where a sneutrino (rather than a neutralino) is the LSP, from ALEPH. When applicable, the limits from CDF are also shown [14], as well as the effect of varying the stop-mixing angle.

Table II summarizes the limits from the various experiments.

TABLE II. Right-handed squark limits at large $\Delta(M)$

	Mass limits (in Gev/c^2) for:	
	Stop	Sbottom
ALEPH	84.0	86.0
DELPHI	84.0	87.0
OPAL	90.0	89.0
L3	83.0	-

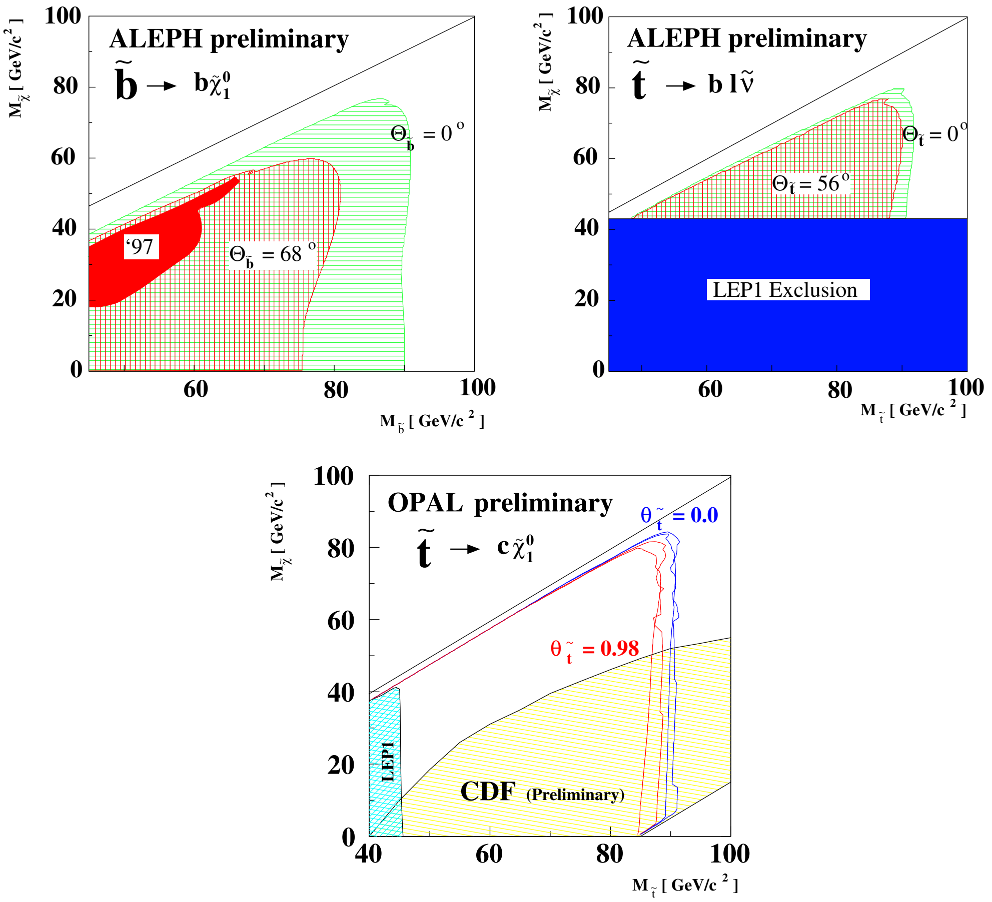

FIG. 2. Limits on squark production.

IV. R-PARITY VIOLATION

A. Experimental signatures

In the case of violated R-parity, the lightest neutralino is no longer stable, but decays into three fermions. Therefore, the generic signal will be 8 fermions in the final state. These might be all quarks, yielding 8-jet events, all leptons, yielding charged leptons and missing quantities (due to the presence of neutrinos), or mixes of these. In the case of cascade decays of eg. the chargino, even more complicated topologies might arise. It is also possible that the LSP is not neutral, and could eg. be a sfermion. In this case the LSP decay would be direct into two (ordinary) particles.

B. Charginos and Neutralinos in RPV

ALEPH have already performed the search for charginos in their data taken last year for all the cases (ie. LLE, LQD and UDD couplings). In each of the cases, they can exclude chargino production up to the kinematic limit. The preliminary analysis follows that described in [15]. The exclusion plot in the case of the LLE coupling is shown in figure 3.

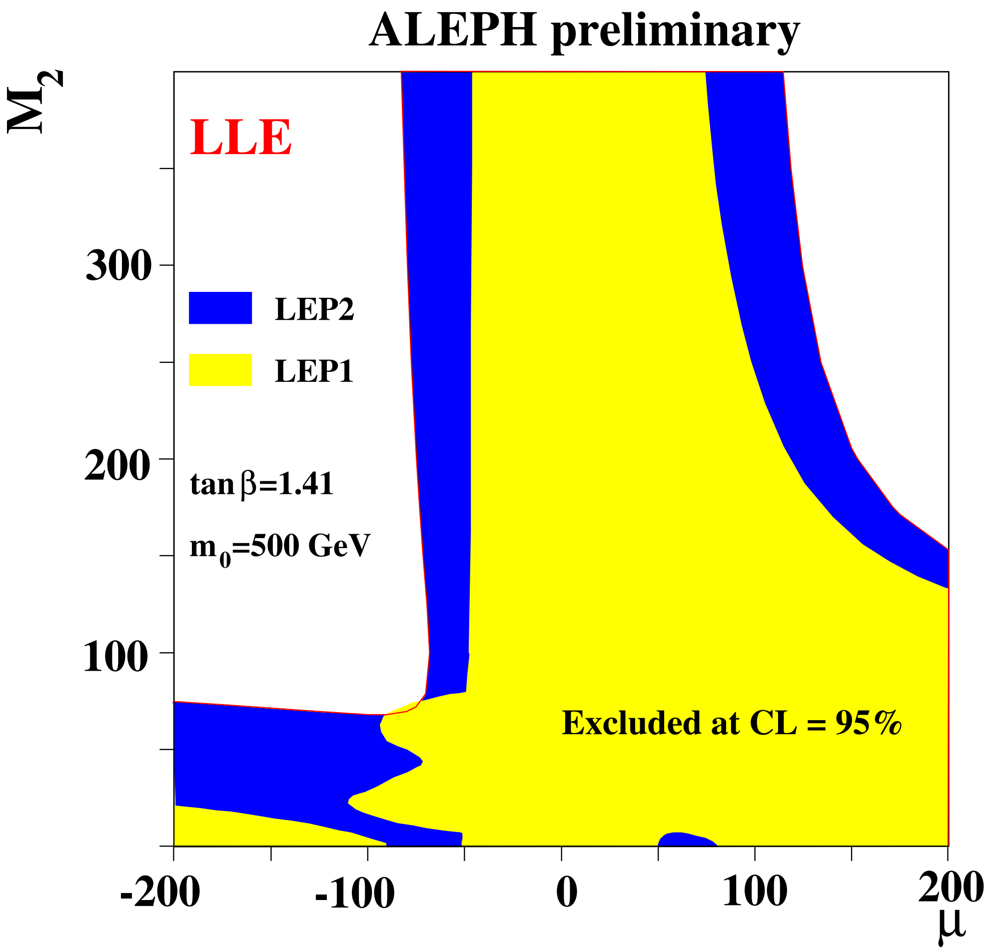

FIG. 3. Limits in the μ - M_2 plane from searches for charginos with non-zero LLE couplings.

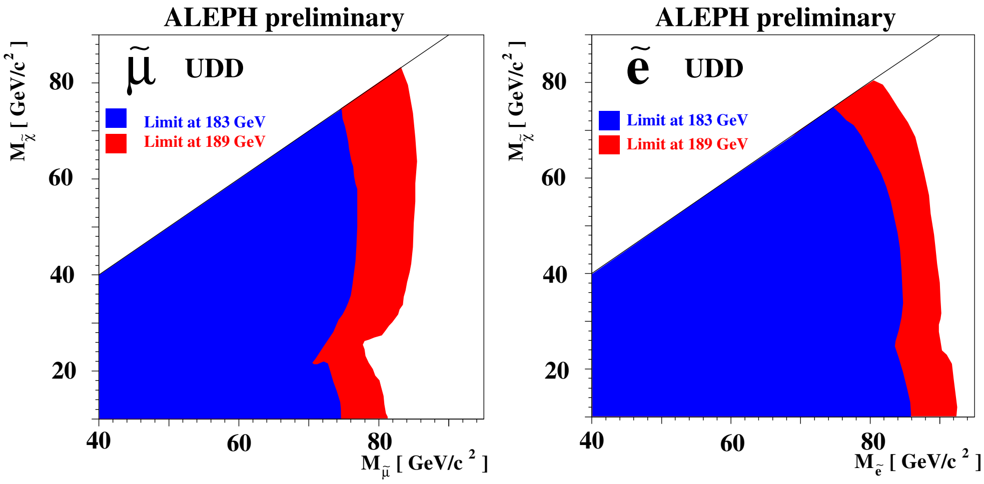

FIG. 4. Limits on selectrons and smuons from searches assuming non-zero UDD couplings.

C. Sfermions in RPV

ALEPH have also presented limits on sleptons production in the case of a dominating UDD-coupling, with indirect decays of the slepton, see fig 4. Here, the analysis follows that described in [16]. It should be noted that the results from previous analyses of ALEPH [16] and OPAL [17] indicate that the limits in the the UDD case tend to be intermediate: LLE yielding stronger limits and LQD weaker ones. As mentioned above, one should also consider the case of direct decays, with the sfermion being the LSP, ie. the region above the diagonal in fig 4. The analysis of OPAL at lower energies [17], indicate that the limits in this case are slightly lower than for the cascade decay.

V. CONCLUSIONS

After a year of very successful running at 189 GeV and integrated luminosities of 160 to 180 , the four LEP experiments have been able to ameliorate the limits on sfermions.

In mSUGRA frame-work, and for high mass-differences between the LSP and the sfermions, the limits for right-handed sfermions are summarized in the following table:

TABLE III. Limits on sfermion masses for large $\Delta(M)$

Selectron Mass	>	89 Gev/c^2
Smuon Mass	>	83 Gev/c^2
Stau Mass	>	75 Gev/c^2
Stop Mass	>	90 Gev/c^2
Sbottom Mass	>	89 Gev/c^2

These limits are close to the kinematic limit, both for squarks and sleptons. The cross-section limits are around 80 fb (190 fb for the stau). Within the RPV scenario, the limits in the M$_2$-μ-plane are identical to those for R-parity conserved, essentially at the chargino kinematic limit. Also for sfermions, the limits for RPV are quite similar to those for R-parity conserved, but the analysis of the 189 GeV data is on-going. Nevertheless, one might conclude that whether R parity is conserved or not, the experiments at LEP attains the same limits on the MSSM parameters.

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