In the final run in the year 2000 the four experiments at the electron positron collider LEP have accumulated data corresponding to an integrated luminosity of more than 210 pb$^{-1}$ per experiment at centre-of-mass energies up to 208 GeV. These data have been used to extend the search for supersymmetric particles in the new energy domain. In the present paper the results of searches for sfermions, charginos and neutralinos are described, assuming the minimal supersymmetric standard model with R-parity conservation. In addition, the determination of a lower mass limit of the lightest neutralino is discussed.

1 Introduction

The search for particles predicted by supersymmetric theories (SUSY) is one of the main motivations for the physics programme at LEP2. SUSY provides an elegant solution for several deficiencies of the Standard Model (SM). The minimal supersymmetric extension of the Standard Model (MSSM) predicts scalar partners for both helicity states of SM fermions (sfermions) and fermionic partners of SM gauge bosons (gauginos). Neutral (charged) gauginos will mix with the supersymmetric partners of the higgs bosons to form four neutral states (neutralinos) and two charged states (charginos). Since the predicted degeneracy between particles and their supersymmetric partners is not observed supersymmetry must be broken.

In the searches described in the following a gravity mediated breaking of supersymmetry is assumed. In addition, the conservation of R-parity is assumed, which implies the pair production of supersymmetric particles, their decay into an odd number of such particles and the stability of the lightest supersymmetric particle (LSP), which is assumed to be the lightest neutralino. The soft SUSY breaking introduces gaugino mass parameters $M_i$ into the theory, which are considered as free parameters together with the ratio of the vacuum expectation values of the two Higgs doublets, $\tan \beta$ and the mass parameter in the Higgs sector $\mu$. For the interpretation
of results in the MSSM the unification relation $M_1 = \frac{5}{3} \tan^2 \theta_W M_2$ is assumed. This relation is important for fixing the masses and the field content of charginos and neutralinos.

Results presented in this paper have been obtained using data taken during the run in the year 2000, combined with lower energy data, where appropriate. At center-of-mass energies in the range between 203 and 208 GeV data corresponding to an integrated luminosity of more than 210 pb$^{-1}$ have been collected by each experiment.

2 Searches for Sfermions

At LEP scalar partners of leptons and quarks are produced in pairs via the s-channel annihilation diagram. For selectrons an additional contribution via t-channel neutralino exchange appears. In the SUSY scenario considered, sfermions decay predominantly into the corresponding SM fermion and the LSP, the lightest neutralino $\tilde{\chi}^0_1$. These events are therefore characterised by two acoplanar leptons or jets accompanied by missing energy. For the first two generations the mass eigenstates correspond to the right- and left-handed states. Since production cross sections are lower for $\tilde{f}_R$ than for $\tilde{f}_L$, the $\tilde{f}_R$ states are used to set conservative limits. In the third generation $\tilde{f}_R$ and $\tilde{f}_L$ are not necessarily mass eigenstates. The off-diagonal terms in the mass matrix are of the form $m_f(A_f - \mu \cot \beta)$ for the stop, and $m_f(A_f - \mu \tan \beta)$ for sbottom and stau and can cause substantial mixing.

2.1 Sleptons

Searches for acoplanar leptons have been used to set exclude regions in the $(M_{\tilde{l}} - M_{\tilde{\chi}^0})$-plane. These masses are the main parameters in searches for the first two generations: the slepton mass determines the production cross section, the mass difference $\Delta M$ to the LSP is related to the visible energy and thus to the selection efficiency and background composition. Due to the t-channel neutralino exchange contribution, which can substantially enhance the production cross section, the results for selectrons depend in addition to the mass parameters strongly on the choice of $\tan \beta$ and $\mu$. In Fig. examples of the excluded regions in the mass plane are shown for selectrons (from the L3 collaboration) and staus (from the ALEPH collaboration). Both the regions excluded by the experimental data and the limits expected assuming the known efficiencies and background expectations are shown. For selectrons the exclusion is shown for $\tan \beta=2.0$ and $\mu=-200$ GeV.

The production of staus depends in addition on the nature of the lighter stau, which is a composition of right- and left-handed states: $\tilde{\tau}_1 = \tilde{\tau}_L \cos \theta + \tilde{\tau}_R \sin \theta$. The most conservative limits are obtained choosing the mixing angle such that the production cross section is minimal, which is close to the decoupling from the $Z^0$. In the Figure both the no-mixing case (full line) as well as the case of minimal cross section (dashed line) are shown.

The results of the four LEP experiments have been combined and preliminary limits using the full LEP data set have been extracted. The results are summarized in Table. Assuming a mass value of 40 GeV for the lightest neutralino, mass limits in the range between 87.1 (for staus) and 99.4 (for selectrons) have been extracted. There is good agreement between the observed and expected limits. This is also true in the case of the staus. The new data collected in the year 2000 by all LEP collaborations do not enhance the excess of stau candidates which has been observed during the 1999 running. For example, the ALEPH collaboration observes 19 events in their high $\Delta M$ analysis for data collected in the year 2000, whereas 18.3 events are expected from known background sources.
Figure 1: Excluded regions (95% C.L.) in the $M_{\tilde{\tau}} - M_{\chi_0^1}$-plane for selectrons (left) and staus (right). In the case of staus the limit is shown for the no-mixing case (full line) and for the case of minimal coupling of the lightest stau to the $Z^0$. In both cases also the expected limit is shown (full and dotted line for $\tilde{e}$ and $\tilde{\tau}$ respectively).

2.2 Squarks

Due to the large top mass, mixing in the stop sector can be large and the lightest stop can become the lightest squark. Also the mass of the sbottom could be low, in particular if $\tan \beta$ takes large values.

Sbottom squarks will mainly decay into $b\tilde{\chi}_1^0$, generating events with two acoplanar b-jets and missing energy. At LEP the equivalent channel is not open for stops. Stop squarks can decay via loops into $c\tilde{\chi}_1^0$ or via a virtual chargino into $b\tilde{\nu}$, if the sneutrino is light enough. In Fig. 4 examples of the excluded regions in the $(M_{\tilde{q}} - M_{\chi_1^0})$-plane are shown for stop (from the OPAL collaboration) and sbottom decays (from the DELPHI collaboration). The sbottom exclusion

| Decay | Mass limit 95% C.L. | condition |
|-------|----------------------|-----------|
| Selectron | $\tilde{e}_R \rightarrow e\tilde{\chi}_1^0$ | $99.4 \text{ GeV}$ | $m_{\tilde{e}_R} = 40 \text{ GeV}$ |
| Smuon | $\tilde{\mu}_R \rightarrow \mu\tilde{\chi}_1^0$ | $96.4 \text{ GeV}$ | $m_{\tilde{\mu}_R} = 40 \text{ GeV}$ |
| Stau | $\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$ | $87.1 \text{ GeV}$ | $m_{\tilde{\tau}_1} = 40 \text{ GeV}$ |
| Stop | $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ | $95 \text{ GeV}$ | $\Delta M = 40 \text{ GeV}$ |
| | $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ | $65 \text{ GeV}$ | independent of $\Delta M$ |
| | $\tilde{t} \rightarrow b\tilde{\nu}$ | $97 \text{ GeV}$ | $\Delta M = 40 \text{ GeV}$ |
| Sbottom | $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ | $95 \text{ GeV}$ | $\Delta M = 20 \text{ GeV}$ |
is show for the decoupling case, the stop exclusion is given for both the no-mixing case and the case of minimal coupling to the $Z^0$. For low $\Delta M = M_{\tilde{t}} - M_{\chi^0_1}$ values the stop lifetime becomes sizeable. The ALEPH collaboration has performed an analysis looking for stable stop particles and stop particles decaying with a sizeable lifetime. This analysis allows to derive an absolute lower limit of 65 GeV on the mass of the stop, independent of $\Delta M$. The minimum is taken for a $\tan \beta$-values of 2.7. For larger $\Delta M$ values the limits on the stop and sbottom are significantly higher. The results obtained from the combination of the four LEP experiments are included in Table 1. Depending on the decay mode, stop and sbottom squarks are expected to be heavier than 95 to 97 GeV for a $\Delta M$ value of 40 GeV.

3 Searches for charginos and neutralinos

At LEP charginos can be pair produced via a $Z^0$ or a photon exchange in the s-channel or a sneutrino exchange in the t-channel. For large sfermion masses they predominantly decay via a $W^*$ into a $f f' \tilde{\chi}_1^0$ final state, which result in the detector in four jets, two jets and a charged lepton or two charged leptons, and missing energy due to neutralinos and neutrinos. Due to the t-channel contribution chargino mass limits depend on the sneutrino and the field content of the lightest chargino. Mass limits on the charginos are usually used to exclude regions in the $(\mu - M_Z^2)$-plane, as shown in Fig. 4 for the case where $\tan \beta = 2.0$ and a universal scalar mass parameter $m_0$ at the GUT scale of 500 GeV has been chosen. The excluded parameter regions can still be enlarged beyond the kinematic limits for chargino production by a search for pair production of neutralinos. Neutralino pair production proceeds via a $Z$-boson exchange in the s-channel and via selectron exchange in the t-channel. Since pair production of the lightest neutralino is not directly observable one searches for events in which at least one of the heavier neutralinos is produced in association with the $\tilde{\chi}_1^0$. For smaller values of the parameter $m_0$ which corresponds to a scenario with lighter sfermions and sneutrinos the production cross
Given the light sfermion and sneutrino masses the leptonic branching ratio via light sfermions also increases. Combining the chargino search with the search for sleptons allows also in this case to exclude charginos with masses close to the kinematic limit. An analysis has been performed by the L3-collaboration, where the chargino limit is determined as a function of the sneutrino mass for a parameter point at low tan\( \beta \) in the gaugino region (\( \tan \beta = 2.0, \mu = -200 \text{ GeV} \)). At this parameter point, charginos with masses below 98.6 GeV are excluded independent of the sneutrino mass and thereby the parameter \( m_0 \).

For very low mass differences \( \Delta M \) below a few GeV, the standard chargino analyses become inefficient. To cover also this case, dedicated analyses have been developed, which either search for events with an ISR photon or for events with heavy charged particles passing through the detector. The latter search covers a possible long lifetime scenario of the chargino, which appears if the chargino becomes nearly degenerate in mass with the neutralino. Such analyses have been performed by all LEP collaborations. For large \( m_0 \) values, charginos with masses below about 90 GeV can be excluded, independent on the mass difference \( \Delta M \) to the lightest neutralino.

The minimum as a function of \( \tan \beta \) is found for \( \tan \beta = 1.0 \).

The OPAL collaboration has presented a limit for the lightest neutralino independent of the \( m_0 \) value. The results of the chargino, neutralino and slepton searches have been combined and the SUSY parameters \( M_2, \tan \beta, \mu \) and \( A_0 \) have been scanned in the range \( 0 < M_2 < 2000 \) GeV.
GeV, \(|\mu| < 500\) GeV and \(A_0 = 0, \pm M_2\). In this analysis the limit of the lightest neutralino is determined to be 36.3 GeV.

A discussion of the LSP limit for any \(m_0\) has also been presented by the DELPHI collaboration\(\textsuperscript{5}\). In Fig. 3 the lower limit for \(m_{\chi_0}\) is shown as a function of \(\tan \beta\) for any value of \(m_0\). The \(m_0\)-independent limit, resulting from a combination of chargino, neutralino and slepton searches, follows the large \(m_0\) limit up to \(\tan \beta = 1.4\). Then a lower value is taken due to the opening of the chargino-sneutrino mass degeneracy. For large \(\tan \beta\) values (\(\tan \beta > 5.0\)) the LSP limit takes its lowest value of 36.7 GeV due to the mass degeneracy between the lightest stau and the lightest neutralino. In this case mixing in the stau sector is taken into account by setting the parameter \(A_\tau\), which appears in the off-diagonal matrix element of the stau mass matrix \((A_\tau - \mu \tan \beta)\), to zero. For a more detailed discussion of the stau mixing effects the reader is referred to Ref.\(\textsuperscript{5}\).

4 Conclusions

LEP2 has made significant contributions in the exploration of the SUSY landscape. Up to the highest LEP2 energies around 208 GeV no evidence for the production of SUSY particles has been found. Stringent limits on the masses of sfermions, charginos and the lightest neutralino have been set in the framework of the MSSM, assuming R-parity conservation and the lightest neutralino to be the lightest supersymmetric particle. The analyses of the final LEP data are already well advanced. Future analyses will concentrate on more complete interpretations, including, for example, stau mixing effects, and on the combination of the data of all LEP experiments.

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References

1. P.Fayet and S.Ferrara, \textit{Phys. Rep.} \textbf{32}, 249 (1977);
   H.P.Nilles, \textit{Phys. Rep.} \textbf{110}, 1 (1984);
   H.E.Haber and G.Kane, PREP \textbf{117}, 75 (1985).
2. ALEPH Collaboration, \textit{Phys. Lett.} B \textbf{488}, 234 (2000).
3. L3 Collaboration, L3 note 2644 (2001).
4. OPAL Collaboration, OPAL physics note PN-470 (2001).
5. DELPHI Collaboration, DELPHI 2001-010 CONF 451 (2001).