MSSM, Msugra and the LSP at LEPII

I. Laktineh

_Institut de Physique Nucléaire de Lyon_

More than one year after the end of LEPII, many analysis activities are still going on to translate the negative search results of the four LEP experiments into solid limits on cross-sections and masses of SUSY particles. Many analyses based on the MSSM and Msugra models are presented in this paper. Preliminary results including the limit on the mass of the lightest supersymmetric particle (LSP) within the RP conservation hypothesis are also given.

1 INTRODUCTION

SUSY is an appealing theory since it solves many of the Standard Model (SM) problems while conserving its successful features. In SUSY each boson (fermion) of the SM, has a new fermionic (bosonic) partner with the same mass. Absence of experimental observation of partners having the same mass led to the conclusion that SUSY is broken. There is no clear indication how this is done. However, few scenarios were proposed to explain the way this breaking is propagated to the electroweak scale. In one of these scenarios, called the supergravity scenario, the breaking is mediated by gravitation interaction. The minimal supersymmetric extension of the Standard Model inspired by the previous scenario is called the MSSM. Although this model contains many parameters, only few of them are relevant for SUSY particle searches and can be summarized by the gaugino mass terms \( M_i \) \((i = 1, 3)\), the scalar fermion masses \( m_i \), the trilinear coupling constants \( A_i \), the ratio of the V.E.V of the two Higgs doublets \( \tan \beta \) and the mixing Higgs parameter \( \mu \). The number of these parameters is reduced when the unification relations are assumed. In this case, the gaugino mass terms are all identical \((m_{1/2})\) at the GUT scale as well as the sfermion masses \((m_0)\) and the trilinear coupling constants \((A)\). Using the Renormalization Group Equations (RGE), the gaugino mass terms are related to each other at low energy scale by the relations

\[
M_1 : M_2 : M_3 = 1 : 1.95 : 6.64
\]

The Msugra is even a more restricted model with only four parameters: \( m_0, m_{1/2}, A, \tan \beta \) and the sign of \( \mu \). In this model the electroweak breaking is induced by the SUSY breaking which explains the absence of \( \mu \) as a parameter.

In the two previous SUSY models (MSSM, Msugra), the lightest neutralino is the lightest

---

*In this case the MSSM is commonly called the constrained MSSM.

**Neutralinos are linear combinations of supersymmetric partners of \( \gamma, Z \) and Higgs field neutral components.
supersymmetric particle (LSP) for most of SUSY parameters. The lightest neutralino is therefore considered as the LSP for all the SUSY searches within the MSSM and Msugra models studied by the LEP experiments.

Each of the four LEP experiments (ALEPH, DELPHI, L3, OPAL) has accumulated an average luminosity of about $660 \, pb^{-1}$ at center of mass energies going from 189 to 208 GeV. This important luminosity has allowed to test many phenomenological aspects of the mentioned SUSY models. The absence of a significant deviation with respect to the SM prediction has then led to set limits on the SUSY parameters as well as SUSY particle masses.

This paper is organized as follows. In the first section we give a short description of the different SM backgrounds associated to SUSY experimental searches. In the second section the scalar fermion searches and their preliminary results are shown. Chargino and neutralino searches are quoted in the third section. In the fourth section details concerning the LSP mass lower limit are given. All the analyses presented in this paper are done within the R-Parity$^\dagger$ conservation(RPC) hypothesis.

\section{SM CONTRIBUTION}

Searching for SUSY particles at LEP within RPC framework is characterized by looking for events with missing energy. This is due to the production in the RPC hypothesis, in the final state, of two stable LSP particles escaping the detector. This makes the difference between the produced SUSY particle mass and the LSP one ($\Delta m = m(SUSY) - m(LSP)$) an important parameter for the experimental searches since the nature of the SM background depends strongly on it. At low $\Delta m$, the main contribution to the background of RPC-MSSM events is the two-photon physics in which the two electrons exchange two photons which collide giving birth to low energy particles whereas the two electrons go undetected in the vacuum tube. At intermediate and high values of $\Delta m$, physics processes like 2-fermion and 4-fermion final states such as $WW$, $ZZ$, $W\nu\nu$ and $f\bar{f}$, are the dominant ones. Since the new physics events should manifest themselves as an excess with respect to the SM physics events, the prediction of these SM events must be under control. This is indeed the case as can be shown in figure$^\ddagger$ where the cross section of the different SM processes are measured and compared to the predicted ones.

$^\dagger$This parity leads to a stable LSP.

$^\ddagger$This is indeed the case as can be shown in figure where the cross section of the different SM processes are measured and compared to the predicted ones.
3 SFERMION SEARCHES

SUSY partners of the SM fermions are scalars. There are two SUSY partners, named left and right, for each SM fermion. Left and right sfermions of each family have the same quantum numbers and can thus mix with each other giving rise to new mass eigenstates through the following matrix:

$$\begin{pmatrix}
m_f L & m_f(A - \mu f(\beta)) \\
m_f(A - \mu f(\beta)) & m_f R
\end{pmatrix}$$

where \(m_f L (m_f R)\) is the mass of the left (right) sfermion and \(m_f\) is its fermion partner mass and \(f = \tan(\beta)(\cot(\beta))\) for down(up)-like fermion respectively. The new mass eigenstates can be written as:

$$\tilde{f}_L (\tilde{f}_R) = f_L \cos \theta + (-) f_R \sin \theta$$

with \(\theta\) being the mixing angle. Since the mixing is proportional to the partner fermion mass, only mixing in the third generation (\(\tilde{\tau}, \tilde{b}, \tilde{t}\)) is of interest. Both sleptons and squarks, SUSY partners of leptons and quarks respectively, have been searched by the LEP experiments.

3.1 SLEPTONS

Assuming the same scalar mass \(m_0\) at GUT scale, masses of the different scalar leptons at the electroweak scale can be predicted through the RGE equations. The masses of charged left and right sleptons are given by:

$$m(\tilde{l}_L) = m_0^2 + 0.77M_2^2 - 0.27m_Z^2 \cos(2\beta), m(\tilde{l}_R) = m_0^2 + 0.22M_2^2 - 0.23m_Z^2 \cos(2\beta)$$

The scalar sneutrino mass is given by the formula:

$$m(\tilde{\nu}) = m_0^2 + 0.77M_2^2 + 0.5m_Z^2 \cos(2\beta).$$

For values of \(\tan \beta > 1\), right slepton is lighter than the left one. This determines the search strategy of scalar leptons like selectrons and smuons by looking first for the right sfermions, the more probably accessible at LEP.

SMUON: In addition to the missing energy, the signature of scalar muon \(\tilde{\mu}\) pair production is characterized by the presence in the detector of two acoplanar muons. These muons result from the decay of the scalar muons: \(\tilde{\mu} \rightarrow \mu + \chi^0\). The comparison between data and SM prediction at the different center of mass energies shows good agreement. LEP SUSY working group\(^3\) has combined the four experiments results to set a lower limit on the right smuon pair production cross-section in the plane \((m(\tilde{\mu}_R), m(\chi^0))\). The smuon pair production which takes place through the s-channel does not depend on SUSY parameters directly. It depends only on smuon mass. This allows to determine an exclusion area in the previous plane. A preliminary result shows that for \(m(\chi^0)\) less than 40\,GeV, LEP experiments exclude smuon mass up to 96.4\,GeV at 95\,% CL.

STAU: Scalar tau \(\tilde{\tau}\) pair production at LEP is searched by looking for two low multiplicity jets corresponding to the two produced taus from the stau decay: \(\tilde{\tau} \rightarrow \tau + \chi^0\). The notion of jet is extended here to take into consideration the leptonic decay of the tau. The difference with respect to the scalar muon case comes from the possibility of important mixing between left and right staus which may result into light stau (\(\tilde{\tau}_1\)). The mixing effect can be very important with respect to the pair production cross-section. Indeed for a mixing angle of \(\theta_\tau = 46^\circ\), \(\tilde{\tau}_1\) decouples from \(Z\) leading to a minimal scalar tau pair production. As in the scalar muon case, the absence of significant deviation with respect to SM prediction has been translated by the LEP SUSY working group into a lower limit on the \(\tilde{\tau}_1\) mass in the decoupling mixing scenario. For \(m(\chi^0) < 40\,GeV\) LEP excludes scalar tau mass up to 87.1\,GeV at 95\,%CL.

SELECTRON, SNEUTRINO: The scalar electron \(\tilde{e}\) pair production proceeds not only through the s-channel as for the previous sleptons but also through the t-channel. In this

\(^a\) which is the case if Higgs negative searches are included.
case the dependence on SUSY parameters is direct through the $e\tilde{\chi}_1^0$ coupling. The lowest pair production cross-sections are obtained for $\tan\beta \approx \sqrt{2}$ and negative values of $\mu(-50$ to $-200)$. The absence of data excess with respect to SM prediction in the $\tilde{e}_R$ pair production, characterized by two acoplanar electrons can be used, as before, to set a lower limit on the selectron mass. As for the other sleptons, when the right selectron is degenerate in mass with the lightest neutralino, the detection efficiency is very low and $\tilde{e}$ pair production may not be experimentally accessible through the two acoplanar electrons search. However, in contrast with the other scalar leptons, selectrons production is not restricted to $\tilde{e}_R\tilde{e}_R$ or $\tilde{e}_L\tilde{e}_L$ but also includes, through the $t$-channel, the $\tilde{e}_R\tilde{e}_L$ production. This additional contribution can be very helpful in the degenerate scenario as long as the $\tilde{e}_R\tilde{e}_L$ is kinematically accessible. In this case the two acoplanar electrons search can be replaced by looking for a single electron coming from the $\tilde{e}_L$ decay and possibly accompanied by another soft electron resulting from the $\tilde{e}_R$ decay.

Adding information from single electron analysis, the scalar electron exclusion can be extended. Figure 2 shows preliminary results from ALEPH using both single and two acoplanar electrons searches. Right selectron masses lower than 73 GeV are excluded at 95%CL. When unification relations are assumed, negative searches of right selectron as well as those in the gaugino sector can be translated into exclusion in the SUSY parameters space $m_0, m_{1/2}, \tan\beta$. This can be then used to set limits on left selectron and sneutrino masses. In this way ALEPH excludes left selectron masses lower than 107 GeV and sneutrino masses lower than 83 GeV at 95%CL. In addition, negative standard Higgs searches can be interpreted within SUSY context and translated into exclusion on $\tan\beta$ leading to increase the previous mass limits by few GeV as shown on the same figure 2.

### 3.2 Squarks

Squarks are expected to be heavier than sleptons because of their additional interaction through QCD with gluinos. Among the different scalar quarks, top $\tilde{t}_1$ and sbottom $\tilde{b}_1$ have been intensely studied at LEP. This is related to the fact that under mixing hypothesis, those two squarks can be light enough to be produced at LEP.

**STOP:** $\tilde{t}_1$ pair production has been searched within many scenarios corresponding to its relative mass with respect to other SUSY particles it may decay in. When $m(\tilde{t}_1) - m(\tilde{b}) > m(b) \approx 5 GeV$, the $\tilde{t}_1$ decays principally through: $\tilde{t}_1 \rightarrow bl\bar{v}$. In this case the stop pair production is searched by selecting events with two jets, two leptons and missing energy since the sneutrino decays into a neutralino and a neutrino both escaping detection. Negative results within this

*Gluinos are expected to be heavier than the other gauginos within the MSSM.*
scenario is shown by OPAL as an exclusion contour on the \( \tilde{t}_1 \) mass in figure [3]. When the previous channel is kinematically forbidden, stop decays through the less favored two FCNC processes: \( \tilde{t}_1 \to u\chi^0_1 \), \( \tilde{t}_1 \to c\chi^0_1 \). The second is dominant when the mass difference \( \Delta m = m(\tilde{t}_1) - m(\chi^0_1) \) is likely to be produced at LEP. Search strategy of this chargino in figure 3 with the conservative choice of a mixing angle of \( \theta_t = 56^\circ \) corresponding to the decoupling scenario. New stop decay channel namely \( \tilde{t}_1 \to ff\chi^0_1 \) proceeding through 4-body decay was recently studied by ALEPH in order to increase the sensitivity in the corridor region where \( \tilde{t}_1 \) is mass degenerate not only with \( \chi^0_1 \) but also with \( \chi^{\pm}_1 \).

\[ \text{SBOTTOM: The main decay process of } \tilde{b}_1 \text{ when the mass difference } \Delta m = m(\tilde{b}_1) - m(\chi^0_1) > m(b), \text{ is } \tilde{b}_1 \to b\chi^0_1. \] The sbottom pair production can be therefore investigated by looking for events with two acoplanar b-tagged jets and missing energy. The LEP experiments reported no excess in this channel setting as previously an exclusion area in the plane \( (m(\tilde{b}_1), m(\chi^0_1)) \) corresponding to the decoupling scenario with a mixing angle of \( \theta_b = 68^\circ \) as shown by ALEPH in figure [3].

4 GAUGINO SEARCHES

In SUSY the gaugino sector is made of charginos \( \chi^\pm_1, \chi^\pm_2 \) and neutralinos \( \chi^0_i (i = 1, 4) \). The first are charged mass eigenstates obtained as linear combinations of supersymmetric partners of \( W^\pm \) bosons and the charged higgsinos. The neutralinos are neutral mass eigenstates. They are linear combinations of supersymmetric partner of the photon, the \( Z \) boson and the two neutral higgsinos. Higgsinos are supersymmetric partners of the Higgs two doublet field components. Charginos and neutralinos are called gaugino-like(higgsino-like) when the gaugino(higgsino) components are larger than the higgsino(gaugino) ones respectively.

4.1 CHARGINOS

Only the lightest chargino \( \chi^+_1 \) is likely to be produced at LEP. Search strategy of this chargino is determined according to the mass difference \( \Delta m = m(\chi^+_1) - m(\chi^0_1) \). At high values of \( \Delta m (> 4\text{GeV}) \) the chargino decays immediately after its production whereas at low \( \Delta m (< 4\text{GeV}) \) its
decay can be delayed. This leads to different topologies when looking for charginos:

1-High $\Delta m$ chargino searches:
Each of the two charginos produced at the primary vertex decays either hadronically $\chi_1^{\pm} \rightarrow \chi_1^0 q\bar{q}$ or leptonically $\chi_1^{\pm} \rightarrow \chi_1^0 l\nu$. Charginos production has therefore three kinds of topology: jets, jets+leptons and only leptons. All of these topologies have been studied by the LEP experiments. The good agreement between data and the SM prediction in the four LEP experiments allows to constrain the SUSY parameters involved in the chargino production. The chargino pair production proceeds through s and t-channel. The t-channel contribution leads to a destructive interference and hence to a decrease of the cross-section. This decrease can be very high for low $\tilde{\nu}$ masses and negligible for high ones. Collecting the four LEP experiments chargino search results for $(\Delta m > 4 GeV)$, the SUSY working group at LEP set a preliminary lower limit on the chargino mass of 103.5 $GeV$ in case of sneutrino mass exceeding 300 $GeV$. The negative results in the neutralino sector can also be used to increase the lower limit on the chargino mass since it constrains the SUSY parameters and in some regions this leads to a chargino mass excluded up to more than 6 $GeV$ beyond the kinematic limit as shown by ALEPH.

2-Low $\Delta m$ chargino searches:
Three scenarios are essentially investigated by the LEP experiments. They depend on the value of $\Delta m$ and on the chargino decay length:

a- Quasi-stable charginos topology: This scenario occurs when the mass difference is lower than the pion mass. In this case the two charginos may not decay inside the detector, giving rise to two stable heavy muon-like particles. Absence of excess of this kind of events has been translated into chargino mass limit at very low $\Delta m$ as shown by OPAL.

b- Kink and secondary vertices topology: Here the $\Delta m$ is large enough to allow the chargino decay inside the detector but not at the primary vertex. This gives birth in large TPC detectors as those of DELPHI and ALEPH to events with kink. Systematic study of this kind of events has been done but no excess is observed.

c-ISR topology: In this case the chargino decays promptly. However the decay products are too soft to be detected and the event may not be triggered. Using an initial state radiation photon (ISR) can overcome this difficulty when the photon energy is large enough to trigger the event. A drawback of this technique is the low number of events due to the ISR requirement. Another difficulty is related to the main background contribution to this SUSY scenario which is the 2-photon physics not well simulated in this domain of very low energy. This increases the systematic uncertainty related to this scenario. The nature of the chargino is important here. Higgsino-like chargino with low $\Delta m$ is natural in the constrained MSSM model whereas for gaugino-like one relation between $M_1$ and $M_2$ should be relaxed. No excess was observed for this topology.

Combining results for both low and high $\Delta m$ leads to set an absolute lower limit on the chargino mass within the CMSSM as stated by L3 experiment which excludes the chargino mass up to 85.9 $GeV$ at 95 % CL as shown in figure.

4.2 NEUTRALINOS

The neutralino sector is very rich due to the presence of four different neutralinos. Almost all the combinations of neutralino pair production including the different decaying scenarios have been considered by the LEP experiments. Still, the most interesting one is the $\chi_1^0 \chi_2^0$ production because it is the most probable in term of accessibility at LEP since the $\chi_1^0 \chi_1^0$ goes undetected. The various scenarios of $\chi_2^0$ decay are studied. They include hadronic, leptonic and even radiative

\footnote{The t-channel proceeds through the exchange of a sneutrino.}
\footnote{Using ISR $\gamma$ is helpless because of the very low cross-section of this process.}
Figure 4: 1) Preliminary absolute mass limit on chargino mass from L3. 2) Exclusion region in the plane ($M_2, \mu$) set by ALEPH using chargino and neutralino negative searches.

decay $\chi_2^0 \rightarrow \chi_1^0 \gamma$. The other pair productions like $\chi_i^0, \chi_j^0 (i, j > 2)$ with multi-jet and multilepton as well as mixed leptons-jets final states have also been considered. Events with tau cascades resulting from $\chi_i^0$ decay: $\chi_i^0 \rightarrow \tilde{\tau} \tilde{\tau}$ have been studied carefully due to their importance in the LSP search as will be explained later. In all these channels the data show no significant deviation from the expected contribution of the Standard Model. The neutralino and chargino negative results are summed up to constrain the SUSY parameter space reducing considerably their domain. Figure 4 shows how negative results from ALEPH are translated into exclusion region in the ($M_2, \mu$) plane.

5 LSP

So far the SUSY searches within the MSSM framework have been sterile. The accumulated negative results either in the sfermion sector or in the gaugino one allow to constrain the SUSY parameters space. Since the LSP is the lightest neutralino for almost the entire SUSY parameter space, the lower limit that will be set on its mass will be the same for the LSP. $\chi_1^0$ mass depends on $M_2, \tan \beta, \mu$ and hence constraints on these parameters will lead to a constraint on the LSP mass. This is achieved by determining for different values of $\tan \beta$, the exclusion region in the plane ($M_2, \mu$) and then setting a lower limit on the LSP mass determined by these three parameters. Unfortunately, determining the exclusion zone in the plane ($M_2, \mu$) for a fixed value of $\tan \beta$ is not straightforward. It should take into account the different values of the other SUSY parameters ($m_0, A$) since they affect branching ratios and masses of sfermions and therefore may change dramatically the SUSY events topology. For example, low value of $m_0$ will lead to small mass sneutrino reducing the exclusion region from chargino negative searches. This scenario can become even worse when the sneutrino is slightly heavier than a chargino degenerate in mass with the lightest neutralino (the so-called corridor problem). $A$ parameter effect can be also very important since it affects $\tilde{\tau}, \tilde{t}$, and $\tilde{b}$ masses. If $A_\tau$ is such that $\tilde{\tau}$ is almost degenerate in mass with $\chi_1^0$, search for two acoplanar taus can become inefficient and needs to be completed by taus cascade configurations resulting from $\chi_2^0$ decay as mentioned in the previous section. These complications have pushed to use negative SUSY search results of all the possible decay scenarios in order to cover as much as possible those inaccessible regions. Considering all these configurations, the lower LSP mass limit may be expressed as a function of $\tan \beta$ with an absolute minimum obtained for $\tan \beta = 1$ as can be shown from the preliminary result from DELPHI in figure 5 where different values of $m_0$ and $A$ are considered. Negative standard Higgs search at LEP was interpreted in the frame of the MSSM Higgs sector leading

---

h Radiative decay may occur when the two neutralinos $\chi_2^0, \chi_1^0$ are of opposite natures.
to exclude low $\tan \beta$ values. This shifts upward the LSP lowest value by few GeV depending on the top mass. Indeed the Higgs exclusion analysis depends strongly on the top mass value through radiative corrections. Increasing $m(\text{top})$ from 175 to 180 GeV results in reducing the LSP mass limit by about 1 GeV. SUSY working group at LEP has started to merge results from the four experiments to set a LEP limit on the LSP. A preliminary result is presented in figure 5 where the Higgs negative results are used in a conservative way. The limit on the LSP is about 45 GeV at 95 % CL established at high values of $\tan \beta$. Using Msugra, the same group has set a lower limit of 52.2 GeV in the absence of the trilinear coupling ($A = 0$).

6 CONCLUSION

The LEP experiments have been looking for SUSY particles up to the kinematic limits for most of them. Many MSSM scenarios have been investigated but no new physics manifestation is observed. Preliminary limits on parameters, cross-sections and particles masses have been set and much more precise results will come soon. An important result is the exclusion of the LSP mass up to more than 40 GeV without including the negative Higgs results. This is a huge improvement of our knowledge with respect to the situation before LEPII.

Acknowledgments

I would like to thank J.J.Blaising, M.Chemarin, G.Coignet, J.Fay, J.P Martin and S.Rosier-Lees for useful discussions in preparing this conference.

References

1. For a SUSY review: H.P.Nilles, “Supersymmetry, Supergravity And Particles Physics”, Phys. Rep. 100(1984)1; H.E.Haber and G.L.Kane, “The Search For Supersymmetry: Probing Physics Beyond The Standard Model”, Phys.Rep 117(1985)75.
2. L.E Ibáñez, C.Lopez and C.Muñoz, Nucl.Phys. B256(1985)218.
3. http//lepsusy.web.cern.web.ch/lepsusy.
4. All the preliminary results quoted in this paper can be obtained from the four LEP experiments web pages accessible from: [http://greybook.cern.ch](http://greybook.cern.ch)