SUPERSYMMETRIC PARTICLE SEARCHES AT LEP

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Abstract

Searches for supersymmetric particles performed at LEP 1 and LEP 2 are reviewed. Using the MSSM with R-parity conservation as a reference model, the various analyses are briefly described, and the results are presented in terms of mass and coupling limits. Further implications of these results are discussed, including lower limits on the mass of a neutralino LSP, assuming the MSSM with GUT relations. Less conventional scenarii, among which those involving R-parity violation, are also investigated.

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1 Introduction

1.1 The LEP history

From 1989 to 1995, LEP, CERN’s large $e^+e^-$ collider, operated at centre-of-mass energies close to the Z mass. Each of the four experiments, ALEPH, DELPHI, L3 and OPAL, collected an integrated luminosity in excess of 150 pb$^{-1}$, corresponding to more than 4 million hadronic Z decays. Starting in the autumn of 1995, the beam energy was raised in steps with the adjunction of superconducting RF cavities: the centre-of-mass energy reached 136 GeV at the end of 1995, 161 GeV (just above the threshold for W pair production) in the summer of 1996 and 172 GeV in the autumn of 1996. Integrated luminosities around 6, 11 and 11 pb$^{-1}$ were accumulated by each experiment at 130 – 136, 161 and 170 – 172 GeV, respectively. It is foreseen that the operation in 1997 will take place at an energy of 183 GeV, with further increases to 192 GeV in 1998 and possibly close to 200 GeV in 1999. In the following, the operation at and near the Z peak will be referred to as LEP 1, the operation at 130 – 136 GeV as LEP 1.5, and the operation at higher energies as LEP 2.

1.2 General features of supersymmetric particle searches at $e^+e^-$ colliders

Most of the searches for supersymmetric particles at $e^+e^-$ colliders are inspired by the phenomenology of the Minimal Supersymmetric extension of the Standard Model (MSSM), although their results often apply in a broader framework. In particular, it is generally assumed that R-parity is conserved and that the Lightest Supersymmetric Particle (LSP) is the lightest neutralino $\chi$. This leads to the celebrated signature of supersymmetry: missing energy.

Since all charged supersymmetric particles are fairly democratically produced via $s$ channel $\gamma/Z$ exchange in $e^+e^-$ annihilation, the searches are naturally directed toward the Lightest Charged Supersymmetric Particle (LCSP), typically a scalar lepton or a chargino. This is in contrast to the situation at hadron colliders where only strongly interacting particles such as squarks or gluinos are abundantly produced. Moreover, in actual model calculations, it usually turns out that cascades do not play an important role in the decay of the LCSP. The phenomenology is therefore rather straightforward, again in contrast to the situation at hadron colliders. As an example, if the LCSP is the right smuon $\tilde{\mu}_R$, the only production mechanism is $s$ channel $\gamma/Z$ exchange, with well defined couplings. The only decay mode is $\tilde{\mu}_R \rightarrow \mu \chi$ (at least if $m_{\chi'} > m_{\tilde{\mu}_R}$), which leads to a final state consisting of a $\mu^+\mu^-$ pair with missing energy. The absence of any signal in a given data sample is easily translated into a mass lower limit for the smuon.

This simple approach needs to be refined however, in particular when the production of neutral supersymmetric particles is taken into account. The lightest neutralinos or the sneutrinos can be pair produced via $s$ channel Z exchange, in which case they contribute to the invisible Z width, while the production of heavier neutralinos may lead to
observable final states, possibly with an energy threshold lower than the one of LCSP pair production. For instance, it is a rather common feature in supersymmetric models that \(m_\chi + m_\chi' < 2m_\chi^+\), in which case \(e^+e^- \to \chi\chi'\) could be kinematically allowed while \(e^+e^- \to \chi^+\chi^-\) is not. The value of the \(Z\chi\chi'\) coupling is however highly model dependent, and the search result usually cannot be translated into mass limits in a simple way. This unpleasant feature is more than compensated by the fact that, at the expense of fairly simple and general hypotheses, the results from searches in different channels can be combined in a consistent way, sometimes leading to more powerful constraints than could have naively been expected.

1.3 Specific features of the searches at LEP 1 and LEP 2

With the steady increase of the LEP beam energy since 1995, it could be expected that only the most recent results, namely those obtained at the highest energies, are relevant for supersymmetric particle searches. While this \textit{a priori} belief is indeed found to be valid when comparing the results from LEP 2 and LEP 1.5, it does not fully hold when considering the LEP 1 results for two reasons. Firstly, the precision measurement of the \(Z\) boson properties, in particular of its total width, allow mass limits on supersymmetric particles to be obtained independently of their decay patterns. Secondly, the large statistics collected at LEP 1 allow \(Z\) decay branching ratios at the \(10^{-6}\) level to be probed, which provides irreplaceable constraints in the neutralino sector.

As already mentioned, the main signature of supersymmetry is missing energy, at least when \(R\)-parity is conserved. From this point of view, there are big differences between LEP 1 and LEP 2. For processes such as chargino or slepton pair production, the kinematic limit of \(m_Z/2\) had been reached at LEP 1 within months, with only a few thousand \(Z\) decays collected. The reason is that there is no irreducible background from standard model processes: energy can be lost along the beam axis in \(\gamma\gamma\) interactions \((e^+e^- \to e^+e^\mp f\bar{f})\) where the final state electrons escape undetected in the beam pipe, or inside jets in the form of neutrinos from heavy flavour semileptonic decays in hadronic final states; both of these backgrounds can be eliminated by simple cuts on the direction and the isolation of the missing momentum. For processes such as \(Z\) decays into neutralinos, much smaller signal to background ratios deserve attention so that rare effects have to be considered such as fake missing energy due to instrumental effects or wrong missing momentum direction due to a conspiration of missing energy sources; this renders the analysis much more involved, but the techniques used are identical to those developed for the standard model Higgs boson search \([\text{I}]\) in the \(e^+e^- \to H\nu\bar{\nu}\) channel and they will not be detailed here.

At LEP 2, on the contrary, new standard model processes take place which lead to large missing energy in configurations much more difficult to disentangle from those expected from signals of supersymmetry. Examples of such processes are \(W\) pair production, with at least one \(W \to \ell\nu\) decay, \(ZZ\) or \(Z\gamma^*\) pair production, with \(Z \to \nu\bar{\nu}\), or single \(W\) production in the process \(e^+e^- \to \text{We}\nu\). It has nevertheless been possible to reduce these backgrounds to a level which remains negligible, at least with the modest integrated luminosities collected until now, without giving up too much signal efficiency, as will be
explained in some detail further down. As the statistics accumulated increases, it may however become necessary to accept some level of background; but the situation is better from this point of view than at LEP 1 in the sense that this background is due to well calculable processes rather than to less controllable instrumental effects.

1.4 Synopsis and warnings

The rest of this chapter is organized as follows. The conventional scenario, with R-parity conservation and with a neutralino LSP, will be discussed first, starting with the basic facts, namely the mass and coupling limits obtained at LEP 1 and LEP 2, and then proceeding toward the interpretation in the MSSM, with in particular the derivation of mass limits for the LSP. Less conventional scenarios will be considered next, involving for instance a light gravitino or R-parity violation. Finally, a brief outlook toward the future will be given.

Unless otherwise stated, all limits are given at 95% confidence level (CL). The results quoted are, as much as possible, extracted from published papers. However, when no publication was available on a given topic at the time of writing, preliminary results submitted to the Summer '97 conferences, and to which the author had access, have been used. There has been no attempt toward a complete list of references. Only those from which the quoted results have been extracted are explicitly given. Moreover, it has not been judged useful to give theoretical references since the necessary theoretical background can be found in this book. Finally, although a major prediction of supersymmetry is the existence of a light Higgs boson, which could well lie within the reach of LEP 2, no discussion of this issue is presented here since the searches for supersymmetric Higgs bosons at LEP are described in detail in Ref. [1].

2 The conventional scenario: basic facts

In the conventional scenario, R-parity is conserved and the lightest supersymmetric particle is colourless and electrically neutral. This leaves the gravitino, a sneutrino or the lightest neutralino as possible candidates, which implies in turn that the LSP is weakly interacting with ordinary matter, hence the missing energy signature of supersymmetry. The conventional choice for the LSP is the lightest neutralino $\chi$.

Although most of the searches for supersymmetric particles at LEP have been conducted using the MSSM as a reference model, the results obtained are often fairly general. It is the purpose of this section to review these basic facts.

2.1 Constraints from the Z width

One of the principal goals of the LEP 1 run, and in particular of the scans performed in the vicinity of the Z peak, was the precise determination of the parameters of the Z
resonance: mass, total and partial decay widths, cross section at the peak. In the standard model, these parameters can be accurately computed as a function of the mass of the top quark and, to a lesser extent, of the Higgs boson, these heavy particles contributing via virtual effects, in particular in the Z boson propagator. This allowed the top quark mass to be predicted where it was finally measured, and now gives indications in favour of a light Higgs boson, a feature in agreement with the expectation from supersymmetry. Contributions from heavy supersymmetric particles to the Z parameters are however too small to allow interesting constraints to be obtained in a similar way.

On the other hand, if supersymmetric particles (or any kind of new particles) are light enough to be produced in Z decays, they will increase, often in a significant fashion, the total Z width with respect to the standard model expectation. Therefore, the agreement between the predicted and measured Z widths allows constraints on supersymmetric particles kinematically accessible in Z decays to be inferred. The Z width is now measured to be $2494.7 \pm 2.6$ MeV. The prediction is 2502.0 MeV, for a top mass of 175 GeV/$c^2$, a Higgs mass of 150 GeV/$c^2$, and a value of 0.118 for the strong coupling constant $\alpha_S$. This prediction is decreased to 2498.4 MeV, allowing for values as low as 0.115 for $\alpha_S$ and 169 GeV/$c^2$ for the top mass, corresponding to a one standard deviation change for each $\alpha_S$. The value of 150 GeV/$c^2$ for the Higgs mass is an upper limit in supersymmetry, so no further decrease of the predicted Z width is possible from this origin. This leaves a maximum of 3.4 MeV for any contribution to the Z width due to supersymmetric particle production (at 95% CL, using Bayesian statistics). This corresponds to 2% of the partial width $\Gamma_\nu$ of the Z into a single flavour of $\nu \bar{\nu}$ pair.

Very light charginos would contribute $4.5\Gamma_\nu$ if pure gauginos, or $\sim 0.5\Gamma_\nu$ if pure higgsinos. This is large enough to exclude charginos practically up to $m_\chi/2$, irrespective of their field content. This limit is much lower than the typical ones achieved nowadays at LEP 2, but it applies independently of the chargino decay pattern and remains the only one to be valid in some extreme configurations, as will be discussed further down.

Light sneutrinos would contribute $0.5\Gamma_\nu$ for each flavour. Because the phase space factor is less favourable than for charginos, this results into a limit of only 43 GeV/$c^2$ for a single flavour. For three mass degenerate flavours, the limit is again half the Z mass. Constraints on an invisible sneutrino, applicable if it is the LSP or even if the decay mode $\tilde{\nu} \rightarrow \nu \chi$ is dominant, can be inferred in a similar way from the measurement of the Z partial width into invisible final states (or equivalently from the effective number of neutrinos). In contrast to the situation of a few years ago, they turn out to be hardly stronger than those inferred from the total width measurement.

Somewhat weaker limits can also be derived from the Z width for sleptons or squarks. In the case of neutralinos, the couplings to the Z are highly model dependent (and even parameter dependent within a given model). The coupling is largest for higgsino-like neutralinos, and vanishes for pure gauginos. The best that can be done is therefore to set coupling (or branching ratio) upper limits as a function of the involved neutralino masses. However, these are superseded by those obtained from direct searches, except in the $Z \rightarrow \chi\chi$ case where the final state is invisible.
2.2 Constraints from direct searches at LEP 1

As discussed just above, it is only in the case of neutralinos that direct searches at LEP 1 play a major role. The most relevant channels leading to visible final states are \( Z \rightarrow \chi \chi' \), kinematically the most favourable, and to a lesser extent \( Z \rightarrow \chi' \chi' \). The main \( \chi' \) decay mode is \( \chi' \rightarrow \chi f \bar{f} \) which is accessed through virtual Z or sfermion exchange (\( \chi' \rightarrow \chi Z^* \); \( \chi' \rightarrow \bar{f} f \)). In some particular instances the \( \chi' \rightarrow \chi \gamma \) mode, which proceeds via loops, can become significant or even dominant. (This happens for small \( \chi' - \chi \) mass differences or if one of the neutralinos is almost purely higgsino and the other one almost purely photino.) The possible final states resulting from \( \chi \chi' \) production are therefore: purely invisible \( (\chi \chi \nu \bar{\nu}) \), lepton pairs \( (\chi \chi \ell^+ \ell^-) \), jets \( (\chi \chi q \bar{q}) \) or single photons \( (\chi \chi \gamma) \) with missing energy.

At LEP 1, the only significant standard sources of lepton or jet pairs are Z decays and \( \gamma \gamma \) interactions. In the first case there is no missing energy, ignoring for the moment neutrinos involved in \( \tau \) or heavy flavoured hadron decays. In \( \gamma \gamma \) interactions, on the contrary, the spectator electrons (i.e. the electrons which radiated the photons participating in the collision) tend to remain undetected in the beam pipe, giving rise to a large amount of missing energy. The direction of the missing momentum is however close to the beam axis and there is only little missing transverse momentum \( p_T \). In both Z decays and \( \gamma \gamma \) interactions, the leptons or the jets therefore appear back-to-back in the plane transverse to the beam axis. Even for \( \tau \) pairs, this (almost) coplanar topology is preserved in the visible decay products, and the same holds in the case of semileptonic decays of heavy flavoured hadrons. This feature is the basis of all searches for “acoplanar” leptons or jets. Of course, the detectors should be as hermetic as possible to ensure that no additional particles, for instance photons radiated at large angle, escape detection, thus inducing fake missing \( p_T \). In the case of single photons, radiative Bhabha events \( (e^+e^- \rightarrow e^+e^-\gamma) \) with both electrons remaining undetected in the beam pipe can be eliminated by a cut on the transverse momentum of the photon corresponding to the maximum \( p_T \) that these two electrons can carry without entering the detector acceptance. The same cut also rejects events from \( e^+e^- \rightarrow \gamma \gamma \), with two photons close to the beam axis. The actual analyses performed by the LEP experiments follow those general principles, but they ended up being appreciably more involved both because the detectors are not ideal and because standard physics is more complicated. (For instance, while a two-jet event with missing energy in one of the jets remains coplanar, this is no longer the case for a three-jet event.)

Events from irreducible standard model backgrounds are expected to be selected, but at a very low level. Indeed, a few spectacular “monojet” events were found [4], but they can be explained with not unreasonably small probabilities as originating from four fermion final states such as \( \ell^+\ell^-\nu\bar{\nu} \) or \( q\bar{q}\nu\bar{\nu} \), reached through the process \( e^+e^- \rightarrow Z^*\gamma^*, \) with \( Z^* \rightarrow \nu\bar{\nu} \) and \( \gamma^* \rightarrow \ell^+\ell^- \) or \( q\bar{q} \). Such an event is shown in Fig. 1(top). Similarly, no single photon signal was observed beyond the background expected from \( e^+e^- \rightarrow Z^*\gamma \). With the full LEP 1 statistic, upper limits at the level of a few \( 10^{-6} \) have thus been set [5] for the product branching ratios \( \text{BR}(Z \rightarrow \chi'\chi)\text{BR}(\chi' \rightarrow \chi Z^*) \) and \( \text{BR}(Z \rightarrow \chi'\chi)\text{BR}(\chi' \rightarrow \chi \gamma) \), as shown in Fig. 2.
2.3 Results from the searches at LEP 2

The searches for supersymmetric particles performed at LEP 2 address sleptons, stops, charginos and neutralinos. Sneutrinos are expected to decay invisibly ($\tilde{\nu} \rightarrow \nu \chi$) and cannot be searched for efficiently. Gluinos are not produced directly in $e^+e^-$ collisions and have therefore not been considered. In contrast to the case of generic squarks, for which the limits obtained at the Tevatron cannot be rivaled at LEP, large mixing can be expected in the stop sector, as will be discussed further down. This may lead to a top squark significantly lighter than all other squarks, hence the relevance of stop searches at LEP.

2.3.1 Sleptons and stops

Sleptons are pair produced and have been searched in the decay mode $\tilde{\ell} \rightarrow \ell \chi$, i.e. in final states consisting of acoplanar lepton pairs of the same flavour. Similarly, pair produced stops have been searched in the acoplanar jet topology expected to arise from the $\tilde{t} \rightarrow c \chi$ decay mode. (The normal decay mode, $\tilde{t} \rightarrow t \chi$, is kinematically forbidden.) This effectively flavour changing neutral current process occurs at the one loop level, and the corresponding decay width is small enough for the top squark to hadronize into a stop hadron before decaying, a feature which has been implemented by the LEP collaborations in their Monte Carlo generators. In the particular case where the sneutrino is lighter than the stop, the $\tilde{t} \rightarrow b \ell \tilde{\nu}$ decay mode is expected to become dominant. This rather peculiar mass hierarchy has also been addressed at LEP, but it will not be considered further here.

A number of backgrounds to these acoplanar lepton and acoplanar jet searches have already been discussed in the context of neutralino searches at LEP 1. Furthermore, abundant fermion pair production occurs through radiative return to the Z ($e^+e^- \rightarrow \gamma Z \rightarrow \gamma f \bar{f}$), leading mostly to final states with large missing energy along the beam axis. All these essentially coplanar backgrounds are reduced at LEP 2 in a way similar to that at LEP 1. In addition, new backgrounds arise from processes such as $e^+e^- \rightarrow W^+W^-$, We$\nu$, Zee or ZZ$^*$ which lead to four-fermion final states with missing energy originating from leptonic decays such as $W \rightarrow \ell \nu$ or $Z \rightarrow \nu \bar{\nu}$ or from electrons escaping undetected in the beam pipe in the case of We$\nu$ or Zee. Although these backgrounds are irreducible at some point, their kinematic properties are nevertheless sufficiently different from those expected from slepton or stop pair production to allow almost background free samples to be selected with the presently accumulated integrated luminosities. In the case of smuon searches for instance, requiring two leptons identified as muons selects only 1% of the W pairs. Moreover, the typical momentum of muons from smuon decay is smaller than that of muons from W decay, a feature which becomes more and more pronounced as the neutralino mass increases. In the case of acoplanar jets, the background from W$^+W^-$ with $W \rightarrow \ell \nu$ is reduced by a veto against energetic leptons, and even against isolated particles to cope with $W \rightarrow \tau \nu$ decays. An additional requirement that the mass of the visible system should not exceed some value slightly lower than the W mass also helps in reducing the We$\nu$ background. In the end, a few events are selected, compatible with the background from standard model processes, typically W$^+W^-$ with $W \rightarrow \tau \nu$, or ZZ$^*$ with
\[ Z \rightarrow \nu \bar{\nu}. \] An example of an event probably due to this last process, with \[ Z^* \rightarrow \tau^+ \tau^- , \] is shown in Fig. \[ \text{bottom}. \]

Almost model independent mass limits can be derived for smuons and staus which are produced only via \( s \) channel \( \gamma/Z \) exchange, with well defined couplings, under the assumption that \( \tilde{\mu} \rightarrow \mu \chi \) and \( \tilde{\tau} \rightarrow \tau \chi \) are the only decay modes. (In the MSSM, this assumption is usually valid for right sleptons within the mass range of interest here, given the other constraints existing in the chargino/neutralino sector.) At the time of writing, a \( \tilde{\mu}_R \) mass limit of 59 \( \text{GeV}/c^2 \) is obtained \[ for \] \( \tilde{\mu}_R-\chi \) mass differences exceeding 10 \( \text{GeV}/c^2 \). In the case of selectrons, \( t \) channel neutralino exchange also contributes, usually increasing the production cross section. But this contribution is model dependent and no fully general result for selectrons can be extracted. In Fig. \[ \text{left}, \] an example of \( \tilde{e}_R \) mass limit is presented \[ for \] valid in the MSSM for the set of parameters indicated. (Here, account has been taken of decay modes other than \( \tilde{e}_R \rightarrow e \chi \).)

It is worth mentioning at this point that results from lower energy machines in this sector can still be relevant. The single photon final state has been studied at PEP, PETRA and TRISTAN. In the standard model, it originates through initial state radiation from the reaction \( e^+e^- \rightarrow \gamma \nu \bar{\nu} \). A supersymmetric contribution could arise in a similar way from the process \( e^+e^- \rightarrow \gamma \chi \chi \), mediated by \( t \) channel selectron exchange. The absence of any excess above the standard model expectation allows selectrons with masses up to 79 \( \text{GeV}/c^2 \) to be excluded (90\% CL) in the case of an almost massless and photino-like LSP \[ for \] chargino and neutralino production is mediated by \( s \) channel \( \gamma/Z \) exchange, with destructive interference between the two processes. The influence of sneutrino exchange is largest for light sneutrinos and for gaugino-like charginos. The main chargino decay mode is \( \chi^+ \rightarrow \chi \ell^+ \bar{\nu} \) which is accessed through virtual W or sneutrino exchange \( (\chi^+ \rightarrow \chi W^* ; \chi^+ \rightarrow \ell^+ \bar{\nu} ) \). For gaugino-like charginos and sleptons significantly lighter than squarks, the latter contribution enhances leptonic decays. If sneutrinos are sufficiently light, two-body decays open up \( (\chi^+ \rightarrow \ell^+ \bar{\nu} ) \). The possible final states resulting from chargino pair production are therefore: acoplanar leptons \( (\chi \nu \ell^+ \chi \ell^- \nu \ell^- \ell^+ \ell^- \), purely hadronic with missing energy \( (\chi q \bar{q} \ell ) \) or mixed \( (\chi \nu \ell q \bar{q} \ell) \).

The searches for acoplanar leptons from charginos are similar to those designed for slepton pairs, with minor differences: the two leptons need not be of the same flavour, but their momenta are softer than in the case of sleptons. With four primary quarks, the topology of the purely hadronic final states is not identical to the acoplanar jet topology.
encountered in the case of stop pair production, which again induces modifications to the analyses: the visible mass cut is somewhat relaxed, but the events are required to exhibit a more spherical pattern. Undoubtedly, the gold plated topology is the mixed one: with an isolated lepton and missing energy in a hadronic environment, the backgrounds from fermion pair production and from $\gamma\gamma$ interactions are easy to reduce to a negligible level; the \textit{a priori} harmful background from $e^+e^- \to W^+W^- \to \ell\nu\ell'\ell'$ can be distinguished from the signal by the mass of the hadronic system (close to the $W$ mass for the $W^+W^-$ background, smaller for a signal in the mass reach of LEP 2) and by the missing mass (close to zero for the $W^+W^-$ background, significantly larger for the signal, a feature which is enhanced as the $\chi$ mass increases). In practice, the signal topology and the background conditions are also affected by the $\chi^+\chi^-$ mass difference which controls the amount of visible energy: the $\gamma\gamma$ background and the trigger conditions are of greater concern for small mass differences, while the $W^+W^-$ background is most dangerous for large mass differences. Therefore, the LEP collaborations were led to design matrices of analyses according to the type of final state and to the mass difference.

Small numbers of events were selected by the various experiments, but at a level compatible with the expectation from standard model processes. In the absence of signal, results on chargino production have been expressed in an almost model independent way in terms of cross section upper limit as a function of the $\chi^+$ and $\chi$ masses, assuming dominance of the decay through virtual $W$ exchange (\textit{i.e.} heavy sleptons and squarks). (The “almost” restriction comes from the fact that, for a given $\chi^+$ mass, the decay kinematics depend not only on the $\chi^+\chi$ mass difference but also, however to a much lesser extent, on the detailed $\chi^+$ and $\chi$ field content.) An example of such limits [9] is given in Fig. 4(right). Further specification of the model is needed to translate these results into chargino mass limits. The statement can however be made in a fairly general way that the kinematic limit of 86 GeV/$c^2$ is practically reached for gaugino-like charginos when all sfermion masses are very large.

Neutralino production, $e^+e^- \to \chi_i\chi_j$ where $\chi_i$ and $\chi_j$ stand for any of the neutralinos $\chi, \chi', \chi'', \ldots$ proceeds via $s$ channel $Z$ exchange and via $t$ channel selectron exchange. In contrast to chargino production, the interference is normally constructive. The process with the lowest threshold leading to visible final states is $e^+e^- \to \chi\chi'$. As already discussed in the context of LEP 1, acoplanar lepton pairs and acoplanar jets are the relevant topologies. The analyses are thus similar to those set up to search for sleptons or stops. Further selections were developed for the other processes, involving multileptons or isolated photons. The range of application of these selections depends strongly on the field contents of the various neutralinos involved, as they control both the production cross sections and the decay branching ratios, including cascade decays. It is therefore difficult to express the results in a way at the same time general and meaningful. In the absence of any signal up to a centre of mass energy of 172 GeV, the discussion of the implications of the searches for neutralinos is deferred to the next section.
3 The conventional scenario: interpretation

As indicated a number of times in the previous section, the results obtained by the various LEP collaborations usually cannot be translated directly into general supersymmetric particle mass limits; further specification of the model is needed for that purpose. After specifying the theoretical framework commonly referred to under the logo MSSM by the LEP collaborations, the basic facts presented in the previous section will be turned into constraints on the parameters of this model, and it will be shown how the combination of various inputs allows mass lower limits on the lightest neutralino to be inferred.

3.1 Theoretical framework

In the Minimal Supersymmetric Extension of the Standard Model (MSSM), the gauge group of the minimal standard model is assumed, and only the minimal field content is introduced. In particular, there are just two Higgs doublets, and hence four neutralinos. The parameters needed to specify the model are a set of soft supersymmetry breaking masses and trilinear couplings, $m_i$ and $A_i$, for all scalar doublets and singlets, and of soft supersymmetry breaking masses, $M_i$, for the three gauginos. In the Higgs sector, a supersymmetric Higgs mass term, $\mu$, is introduced, and the ratio $v_2/v_1$ of the vacuum expectation values developed by the Higgs fields coupling to the up-type and down-type quarks is denoted $\tan \beta$.

Additional simplifying assumptions are commonly made, inspired by Supergravity (SUGRA) models: for all matter sfermions, a universal scalar mass $m_0$ and a universal trilinear coupling $A$ at the Grand Unification (GUT) scale; and for the three gauginos, a universal mass $m_{1/2}$ at the GUT scale. The low energy parameters are then determined using the renormalization group equations. The gaugino masses evolve in the same way as the gauge coupling constants. As a result, the gluino is expected to be much heavier, typically 3.5 times, than the lighter chargino in large regions of the parameter space. It is also expected that sleptons are lighter than squarks, and right sleptons or squarks lighter than their left counterparts; the sneutrino mass should be similar to the left slepton mass, unless $\tan \beta$ is large in which case sneutrinos become lighter. Mixing among the left and right scalars is expected to be small, except in the stop sector because of the large mass of the top quark, and possibly for staus if $\tan \beta$ is large.

In “Minimal SUGRA”, the hypothesis of universal scalar masses is extended to the Higgs sector, and the spontaneous breaking of the electroweak symmetry is triggered at low energy by radiative corrections to the Higgs masses. Imposing the proper mass for the $Z$ boson reduces the set of parameters further: the $\mu$ parameter is determined from the others, up to its sign.
3.2 Experimental results

An example of results obtained within the framework of the MSSM has already been given for right selectrons in Fig. 3(left). Here, The GUT relation among gaugino masses has been assumed to calculate the contributions of the various neutralino exchanges in the production process and the branching ratio for the decay $\tilde{e}_R \rightarrow e\chi$. The results are presented for a specific value of tan $\beta$, and for two representative choices of $\mu$. The searches for all slepton flavours can be further combined assuming scalar mass universality, and turned into an exclusion region in the $(m_0, M_2)$ plane, as shown in Fig. 3(right). ($M_2$ and $m_{1/2}$ are related by $M_2 = 0.82m_{1/2}$.) Again, this exclusion is valid for the specified tan $\beta$ and $\mu$ values.

Results on chargino production such as those shown in Fig. 4(right) are commonly translated into exclusion domains in the $(M_2, \mu)$ plane, for chosen values of tan $\beta$. Since the cross section limits depend not only on the chargino mass but also on the mass of the lightest neutralino, the GUT relation between $M_1$ and $M_2$ has to be assumed. This allows in turn account to be taken of possible reductions in the detection efficiency due to cascade decays such as $\chi^+ \rightarrow \chi'Z^*$. The analysis is simplest with the assumption that all sfermions are sufficiently heavy not to affect the production cross section nor the decay branching ratios. Exclusion domains determined in this way are presented in Fig. 5 for two values of tan $\beta$, 1.41 and 35. (Such values are typical of the low and large tan $\beta$ solutions in the so-called infra-red quasi fixed point scenario.) With the same hypotheses, all neutralino production cross sections and decay branching ratios can be calculated from the same set of parameters ($M_2$, $\mu$ and tan $\beta$, still with the assumption of heavy sfermions). The additional exclusion domains resulting from the neutralino searches are also displayed in Fig. 5.

These exclusion contours can in turn be translated into chargino mass limits, as shown in Fig. 6 where the limit is displayed as a function of $\mu$ for gaugino-like charginos and as a function of $M_2$ for higgsino-like charginos. The decrease in the limit for very large values of $M_2$ is due to the fact that the $\chi^+ - \chi$ mass difference, and hence the selection efficiency, diminishes as $M_2$ increases. The impact of the neutralino searches is clearly visible for moderate values of $M_2$, allowing chargino masses to be indirectly excluded beyond the kinematic limit.

These results are modified for lower sfermion masses. Light sneutrinos reduce the production cross section for gaugino-like charginos, while light selectrons increase the production cross section for gaugino-like neutralinos. Since also the decay branching ratios are affected by the sfermion masses, the assumption of a universal scalar mass $m_0$ is made so that the various production and decay processes are correlated. The influence of light sfermions is shown in Fig. 6(left). For $m_0 = 75$ GeV/$c^2$, for instance, it can be seen that the chargino mass limit is reduced by $\sim 10$ GeV/$c^2$, and it would degrade even further for $\mu > -100$ GeV/$c^2$ if the constraints from the neutralino searches were not taken into account.

Altogether, even if no hard number can be given as a lower mass limit for charginos, masses smaller than 75 to 85 GeV/$c^2$ are excluded over most of the parameter space.
There remains however a loophole when the sneutrino mass is very close to but smaller than the chargino mass. In such a case, the two-body decay $\chi^+ \rightarrow \tilde{\nu} \ell^+$ dominates, but the final state lepton has too little energy and the detection efficiency vanishes. There is nothing to be recovered from the neutralino searches because the dominant decay mode, $\chi' \rightarrow \tilde{\nu} \nu$, is invisible, and the only limit remaining is the one deduced from the Z width measurement which is insensitive to the chargino decay pattern.

3.3 Neutralino LSP mass limits

Direct searches for the lightest neutralino $\chi$ cannot be performed efficiently at LEP 2. The relevant process is $e^+e^- \rightarrow \chi\chi$, leading to an invisible final state. At energies well below the Z peak, initial state radiation tagging ($e^+e^- \rightarrow \gamma\chi\chi$) had been used, leading to correlated constraints on the neutralino and selectron masses, as already mentioned in the context of selectron mass limits. This technique is however useless at LEP 2 energies because of the overwhelming background from $e^+e^- \rightarrow \gamma\nu\bar{\nu}$.

However, once the model is sufficiently specified, indirect limits can be obtained from the constraints on charginos and on the more massive neutralinos. For instance, by scanning the domain remaining unexcluded in Fig. 5, no set of $(M_2, \mu)$ value can be found for which the mass $m_\chi$ of the lightest neutralino is smaller than 31 GeV/$c^2$, for $\tan\beta = 1.41$ and assuming heavy sfermions ($m_0 = 200$ GeV/$c^2$). It is worth noticing that, in this particular example, the LEP 1 exclusion still plays some role, due to the fact that the neutralino search is limited, in the region near the point where the $\chi$ mass limit is set, by the value of the couplings to the Z rather than by kinematics. (In a general fashion, the LEP 1 constraints remain useful for low values of $\tan\beta$.) The lower limit obtained [11] for $m_\chi$ as a function of $\tan\beta$ and for heavy sfermions ($m_0 = 200$ GeV/$c^2$) is displayed in Fig. 7(left).

For lower sfermion masses, as already discussed, the assumption of a universal scalar mass $m_0$ is needed to render the analysis manageable. Since, as has been seen above, the constraints in the chargino/neutralino sector are weaker in that case, it is not surprising that the limits on $m_\chi$ also degrade. For $m_0 = 75$ GeV/$c^2$ and $\tan\beta = 1.41$, the $\chi$ mass lower limit is 21 GeV/$c^2$ (instead of 31 GeV/$c^2$ for $m_0 = 200$ GeV/$c^2$). At the time of writing, a complete analysis, letting both $m_0$ and $\tan\beta$ vary freely, is not available at LEP 2. The results obtained [12] at LEP 1.5 will therefore be used in the following for the purpose of illustration of the methods.

In Fig. 7(right), the limit obtained for $m_\chi$ is displayed, for various values of $\tan\beta$, as a function of $m_0$. For large values of $m_0$, they reflect the equivalent of Fig. 7(left) at LEP 1.5. As $m_0$ decreases, the limit degrades slowly, due to the destructive interference in the chargino production cross section for light sneutrinos. As $m_0$ decreases further, the sneutrino mass becomes smaller than the chargino mass and the detection efficiency vanishes abruptly, as mentioned previously. However, for very low values of $m_0$, the results from slepton searches, such as the LEP 1.5 counterpart of Fig. 3(right), can be used (including the sneutrino mass limit from LEP 1 which is most relevant for large values of $\tan\beta$). In general, the exclusions from sleptons and from charginos overlap,
and a massless neutralino is excluded irrespective of \( m_0 \). This is however not the case for \( \tan \beta = 1.41 \) and \( m_0 \sim 60 \text{ GeV}/c^2 \), as can be seen in Fig. 7(right). Preliminary results \[1\] from LEP 2 indicate that this small region is now excluded, with a neutralino LSP mass limit of 14 GeV/c\(^2\), independent of \( m_0 \) and of \( \tan \beta \).

More constraining results can be derived by imposing further constraints on the model. If minimal SUGRA is assumed, the \( \mu \) value, up to now a free parameter, can be calculated up to its sign from \( m_0, m_{1/2} \) and \( \tan \beta \). Moreover, the results from the searches for Higgs bosons can also be used, particularly relevant for low values of \( \tan \beta \) and for negative \( \mu \). Examples of exclusion domains \[12\] in the \((m_0, m_{1/2})\) plane are shown in Fig. 8. A \( \chi \) mass lower limit of 22 GeV/c\(^2\) can be inferred this way from the LEP 1.5 data, independent of \( m_0 \), of \( \tan \beta \) and of the sign of \( \mu \). (Here too, this rather low value for the limit on \( m_\chi \) is entirely due to the loophole discussed earlier.)

## 4 Unconventional scenarii

### 4.1 Constraints from LEP 1 on light gluinos

In most of the analyses presented up to now, it has been assumed that gluinos are too heavy to affect the decay pattern of the supersymmetric particles considered. Indeed, stringent mass limits for gluinos have been obtained at hadron colliders, as reported elsewhere in this book. Although some simplifying assumptions had to be made when deriving these limits, for instance regarding the details of cascade decays, it is hard to see how relaxing these assumptions could invalidate the exclusion of gluinos in the mass range of interest at LEP, at least within the MSSM with GUT relations.

There remains however a small mass window for very light gluinos (approximately from 2.5 to 4 GeV/c\(^2\), for squarks in the few hundred GeV/c\(^2\) range) not officially excluded by any of the searches at hadron colliders or elsewhere (e.g. in beam dump experiments or in upsilon decays). Such light gluinos could invalidate some of the searches performed at LEP 2. For instance, the dominant chargino decay mode could well be \( \chi^+ \rightarrow q\bar{q}_g \), with subsequent hadronization of the gluino into a long-lived R-hadron. In that case, the final state from chargino pair production would not exhibit the characteristic signature of missing energy.

Such light gluinos would however modify the usual phenomenology of QCD. For instance, they would affect the topology of four-jet events, via \( g \rightarrow \tilde{g}\tilde{g} \) splitting. More importantly, they would contribute to the running of \( \alpha_s \) as three additional flavours, in leading order, up to mass effects. With the large sample of hadronic events collected at LEP 1, such detailed studies have been performed \[13\], excluding gluinos with masses smaller than 6.3 GeV/c\(^2\).
4.2 Stable charged particles

In the conventional scenario, the LSP is assumed to be neutral and colourless, based on cosmological arguments. Even in that case, it could nevertheless occur that the LCSP is hardly heavier than the LSP, which could make it long lived without conflicting with cosmology. In the MSSM, this may occur for instance if the GUT relation between \( M_1 \) and \( M_2 \) is not satisfied. In scenarii with a light gravitino LSP, of which some implications are discussed further down, a slepton could be the next to lightest supersymmetric particle; for large enough values of the supersymmetry breaking scale, this slepton would decay with a lifetime long enough to appear as stable in a LEP detector.

Searches for long-lived weakly interacting heavy charged particles have been performed up to 172 GeV centre-of-mass energy \([14]\). Pair production of such particles would resemble muon pair production, with a back to back topology but with smaller particle velocities and hence larger specific ionization loss (\( dE/dx \)). The absence of any signal excludes charginos almost up to the kinematic limit of 86 GeV/\( c^2 \), for heavy sneutrinos, and right smuons or staus up to 67 GeV/\( c^2 \). (The selectron production cross section is affected by the details of the neutralino sector.)

4.3 The light gravitino LSP scenario

A class of supersymmetric models in which the gravitino is the lightest supersymmetric particle has recently received renewed attention, as discussed elsewhere in this book. For LEP, the main feature of such models is that the lightest neutralino is expected to decay into a photon and a gravitino, \( \chi \rightarrow \gamma \tilde{G} \). For practical purposes, the neutralino lifetime is negligibly small as soon as the gravitino mass is smaller than a few eV/\( c^2 \).

Pair production of the lightest neutralinos, \( e^+ e^- \rightarrow \chi \chi \), then leads to a final state consisting of two acoplanar photons with missing energy. The background from the process \( e^+ e^- \rightarrow \nu \bar{\nu} \gamma \gamma \) is reduced by the requirement that the mass recoiling to the two photons should not be close to the Z mass; in addition, a minimum energy for both photons is required, the value of which depends on the \( \chi \) mass considered. In the absence of signal, upper limits \([15]\) are set on the production cross section of \( \chi \) pairs at the level of 0.25–0.35 pb. To turn these constraints into a \( \chi \) mass limit, further specification of the model is required (right and left selectron masses, \( \chi \) field content). Typically, values around 70 GeV/\( c^2 \) are obtained.

4.4 R-parity violation

R-parity conservation was introduced to forbid lepton number or baryon number violating terms in the superpotential, otherwise allowed by supersymmetry and by gauge invariance. These terms are of the form \( \lambda_{ijk} L_i L_j E_k \), \( \lambda'_{ijk} L_i Q_j D_k \) or \( \lambda''_{ijk} U_i D_j D_k \), where \( i, j, k \) are generation indices, \( L \) and \( Q \) are doublet superfields, and \( U, D \) and \( E \) are singlet superfields. The simultaneous presence of the last two types of term would induce unacceptably fast
proton decay. There is however no compelling theoretical justification for this prescription, and there exist alternatives, in which only some subsets of these terms are present, and which are equally viable. In particular, it is sufficient to assume that only one (or more generally only one type) of the R-parity violating terms is present to obtain an acceptable phenomenology.

The main consequence of R-parity violation is that the LSP is no longer stable. For instance, a \( \lambda_{ijk} L_i L_j \overline{E}_k \) term may induce the decay of a neutralino LSP to final states such as \( \overline{\nu}_i \ell^+_j \ell^-_k \) (via virtual slepton or sneutrino exchange) or of a sneutrino \( \tilde{\nu}_i \) to a lepton pair \( \ell^-_j \ell^+_k \). The characteristic signature of supersymmetry therefore no longer consists in missing energy, but rather in multileptonic final states. Searches for supersymmetric particles have been performed at LEP 1 [16] and LEP 2 [17] under the assumption that R-parity is violated by such a \( \lambda_{ijk} L_i L_j \overline{E}_k \) term. A large variety of final state topologies arise, depending on the type of particles produced in the \( e^+e^- \) annihilation, and on whether they decay directly via an R-parity violating interaction or first toward the LSP via a gauge interaction (with the LSP subsequently decaying as indicated above in the case of a neutralino LSP). The generation indices in the \( \lambda_{ijk} \) Yukawa coupling control the lepton flavours appearing in the final state and therefore affect the selection efficiencies; the most favourable case is obtained for \( \{ijk\} = \{122\} \), with only electrons and muons as final state leptons, and the worst case for \( \{ijk\} = \{133\} \), with taus also appearing in the final state.

No signal above the expected standard model backgrounds was detected in any of the topologies investigated, resulting into mass limits or constraints on the parameters of the MSSM at least as strong as in the case of R-parity conservation, even assuming a dominant \( \lambda_{133} \) coupling. This can be seen, for instance, in Fig. 9 for chargino and neutralino searches. Interestingly, a substantial region is excluded at LEP 1 beyond the kinematic limit for chargino searches at LEP 2. This is due to the large statistics accumulated at the \( Z \) peak and to the fact that the \( Z \to \chi\chi \) decay leads to visible final states, in contrast to the case of R-parity conservation.

The first results of searches for signals of supersymmetry at LEP under the assumption of a dominant \( \lambda'_{ijk} L_i Q_j D_k \) coupling were reported as this chapter was being completed. The final states typically involve multijets with leptons or with some missing energy. Here too, the kinematic limit for charginos is almost reached [17].

5 Outlook

As indicated in the introduction, it is foreseen that the centre of mass energy at LEP 2 will be increased beyond 172 GeV, the energy at which most of the results reported above were obtained. Based on the experience already gathered, it appears that \( \sim 10 \text{ pb}^{-1} \) are enough to reach the kinematic limit for charginos over large regions of the parameter space. Increasing the energy is therefore always beneficial compared to collecting more luminosity at a given energy. Once the ultimate LEP 2 energy is reached, it will nevertheless remain worthwhile accumulating sufficient integrated luminosity to improve the sensitivity to sleptons, stops and neutralinos. More optimistically, large statistics will be welcome
to allow the LEP experiments to determine accurately the masses and couplings of the various supersymmetric particles which they will have revealed.

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Figure 1: (top): A monojet event observed at LEP 1. This event is probably due to the process $e^+e^- \rightarrow Z\gamma^* \rightarrow \nu\bar{\nu}qq$. (bottom): An acoplanar $\tau$ pair observed at LEP 2. The visible $\tau$ decay products are a $\rho$ and an $a_1$. This event cannot be interpreted as resulting from $e^+e^- \rightarrow W^+W^-$ with two $W \rightarrow \tau\nu$ decays. It is rather due to $e^+e^- \rightarrow ZZ^*$, with $Z \rightarrow \nu\bar{\nu}$ and $Z^* \rightarrow \tau^+\tau^-$. 

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Figure 2: Upper limits on product branching ratios times $10^6$ for neutralino production: (left) $\text{BR}(Z \to \chi'\chi')\text{BR}(\chi' \to \chi Z^*)$; (right) $\text{BR}(Z \to \chi'\chi')\text{BR}(\chi' \to \chi \gamma)$.

Figure 3: (left): Excluded regions in the plane of the $\tilde{e}_R$ and $\chi$ masses, in the MSSM with $\tan \beta = 2$ and for $\mu = -200$ GeV/$c^2$ (solid) and $\mu = 1000$ GeV/$c^2$ (dashed). The dotted curve is the LEP1.5 limit. (right): Excluded regions in the $(m_0,M_2)$ plane, for $\tan \beta = 2$ and $\mu = -200$ GeV/$c^2$ (solid curve).
Figure 4: (left): Excluded regions in the plane of the $\tilde{t}$ and $\chi$ masses, for two values of the mixing angle in the stop sector, 0.0 and 0.98 rad corresponding to the most and least favourable cases, respectively. The cross hatched region has been excluded at LEP 1. The singly hatched region has been excluded by D0 at the Tevatron. (right): Cross section upper limit for chargino pair production at 172 GeV in the plane of the $\chi^+$ and $\chi$ masses.

Figure 5: Excluded regions in the $(M_2, \mu)$ plane for $\tan \beta = 1.41$ (left) and $\tan \beta = 35$ (right), assuming heavy sfermions ($m_0 = 200$ GeV/$c^2$).
Figure 6: Chargino mass limit as a function of $\mu$ (left) and of $M_2$ (right), for $\tan \beta = 1.41$. On the left, the limits from the chargino searches are given for various values of $m_0$, and the dashed curve is the limit from the neutralino searches for $m_0 = 75$ GeV/$c^2$. On the right, the limits from the chargino, neutralino and combined searches are given for $m_0 = 200$ GeV/$c^2$.

Figure 7: (left) Mass limit for the lightest neutralino as a function of $\tan \beta$ and for heavy sfermions ($m_0 = 200$ GeV/$c^2$). (right): Mass limit obtained at LEP 1.5 for the lightest neutralino as a function of $m_0$ and for various values of $\tan \beta$ ($\mu < 0$).
Figure 8: Excluded domains in the \((m_0,m_{1/2})\) plane for \(\tan \beta = 2\) (top) and for \(\tan \beta = 10\) (bottom), and for \(\mu < 0\) (left) and \(\mu > 0\) (right). The dark shaded regions are theoretically excluded. The vertical, horizontal, crossed and slanted hatched regions are excluded by charginos at LEP 1, by sneutrinos at LEP 1, by Higgs bosons at LEP 1 and by charginos at LEP 1.5, respectively.
Figure 9: Excluded regions in the $(M_2, \mu)$ plane for $\tan \beta = 1.41$ and for heavy sfermions, assuming that R-parity is violated by a $\lambda_{ijk} L_i L_j \tilde{E}_k$ term. The dashed line is the kinematic limit for $m_{\chi^+} = 86$ GeV/$c^2$. 