AB
Institut
de Physique
CNRS

Université Claude Bernard

IN2P3 -

Nucléaire
de Lyon

sw9816

LYCEN 9745
March 1998

Supersymmetry at LEP : experimental review

S. Katsanevas

*Institut de Physique Nucléaire de Lyon IN2P-CNRS/Université Claude Bernard,
F-69622 Villeurbanne Cedex*

*To appear in the Proceedings of the 35th Course of the International School
of Subnuclear Physics : « Highlights : 50 Years Later », Erice, Italy,
Aug. 26 - Sept. 4, 1997*

Supersymmetry at LEP: experimental review ‡

Stavros Katsanevas ‡

‡ Institut de Physique Nucléaire de Lyon et Université Claude Bernard Lyon I, 43 Boulevard du 11 Novembre 1918, VILLEURBANNE, cedex 69229, France

"Il n'y a science qu' à partir du moment
où on peut plonger le réel dans le virtuel"

R.Thom

Abstract. The current status of experimental searches for supersymmetry is reviewed. After a brief exposition of the assumptions determining the mass spectrum of the supersymmetric particles we review a) the indirect limits imposed by precision measurements, b) the status of higgs searches, c) the search of signatures corresponding to two supersymmetry breaking mechanisms (gravity and gauge mediated) and d) the limits obtained if one relaxes the assumption of R-Parity conservation. Particular emphasis is given to standard topological and "gauge mediated" sparticle decay signatures, as well as to the experimental effort to cover "singular" areas of the parameter space where degeneracies and/or dynamical suppression of standard topologies dominates. The complementarities of different searches is explored and the effort to obtain a model independent lower experimental limit of the neutralino mass is described.

1. Introduction

During the last years, supersymmetry (SUSY) has been used extensively to chart the map of possible physics beyond the standard model (SM). This symmetry predicts the existence of additional particles, which differ from their standard model partners by a half-integer spin. The masses and couplings of the new, supersymmetric states, are related by the symmetry to those of the SM states. The simplest model available, is the Minimal Supersymmetric Standard Model (MSSM) [1], which contains the minimal number of new particles and interactions that are consistent with the SM gauge group. In this framework, many theoretical questions of unified theories such as the hierarchy problem and the unification of couplings, may be successfully addressed [2].

However, the facts that a) no such partners, degenerate in mass with the known particles have been found to date, and b) many measurements of particle properties (e.g the proton lifetime or in general flavor properties) could be endangered by the virtual exchange of this new class of particles, imposes two major modifications to the symmetric picture. First the symmetry can not be exact, but has to be broken in a way that the supersymmetric solutions to the naturalness and hierarchy problems are still valid. In this case, the spectrum of supersymmetric partners is determined by a supersymmetry breaking mechanism that can be parameterized by a general set of "soft" parameters. The details of the theory, as well as the phenomenological signatures, depend on the assumption of the supersymmetry breaking mechanism (e.g gravity or gauge mediated supersymmetry breaking). And second, the standard particle parameters are protected by a new multiplicatively conserved quantum number, R-Parity R_p [3]. This number assures the conservation of the leptonic (L) and baryonic (B) numbers or, more specifically, the conservation of the so-called $(B - L)$ symmetry. It can be expressed in the form $R_p = (-)^{(2S+3B+L)}$ for a particle with spin S : it

‡ To appear in the Proceedings of the 35th Course of the International School of Subnuclear Physics: "Highlights: 50 Years Later", Erice, Italy, Aug. 26 - Sept. 4, 1997

is even for standard particles and higgs bosons and odd for their supersymmetric partners. The phenomenological consequences of the conservation of R-parity can be summarized in two points: a) Supersymmetric particles are produced in pairs and b) The Lightest Supersymmetric Particle (the LSP) is stable.

Let us assume at first R_p conservation[†]. One then has further to assume a SUSY breaking mechanism, determining the mass spectrum and therefore the accessible sparticles and signatures at LEP energies. Two such mechanisms have been studied experimentally in detail so far: gravity mediated supersymmetry breaking (SUGRA) [4] and gauge mediated supersymmetry breaking (GMSB) [5]. These two mechanisms suppose the supersymmetry is broken in some "hidden" sector at some scale and is then mediated to the visible sector through the normal gauge interactions in the first case and gravity in the second. The natural scale of SUSY breaking for the first case is from a few TeV to a few thousand TeV, though higher scales are still possible, while in the second, this scale is closer to the GUT scale ($\sim 10^{11-13}$ TeV). The relevant mass terms of the Lagrangian are[6]:

- gaugino masses: $M_i \lambda_i \lambda_i$ where $i = 1, 2, 3$ for $U(1), SU(2), SU(3)$ and λ_i denotes the gaugino partner of the corresponding gauge field.
- higgsino masses: $\mu \tilde{h}_1^0 \tilde{h}_2^0$ and $\mu \tilde{h}_1^\pm \tilde{h}_2^\mp$, where μ is a higgs mixing mass term and $\tilde{h}_1^0, \tilde{h}_2^0, \tilde{h}_1^\pm, \tilde{h}_2^\pm$ are the higgsino partners of the two higgs doublets necessary in the MSSM.
- scalar masses: e.g. $m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_{(\tilde{t}, \tilde{b})_L}^2 (\tilde{t}_L^* \tilde{t}_L + \tilde{b}_L^* \tilde{b}_L) + m_{\tilde{t}_R}^2 \tilde{t}_R^* \tilde{t}_R + m_{\tilde{b}_R}^2 \tilde{b}_R^* \tilde{b}_R$
- 'A' Left-Right trilinear mixing terms: e.g. $A_t \lambda_t (\tilde{t}_L H_2^0 - \tilde{b}_L H_2^+) \tilde{t}_R^*$.
- 'B' higgs potential bilinear terms: e.g. $B\mu (H_1^0 H_2^0 - H_1^+ H_2^-)$

In order to tackle this multiparametric space, the LEP searches for sparticles are usually tacitly or explicitly assuming a hierarchy of simplifying suppositions on the gaugino masses, sparticle masses and their relationships.

2. Mass spectrum

2.1. Gaugino/higgsino and gravitino masses

There are four spin 1/2 partners to the colorless neutral gauge fields and higgs bosons: $(-i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1^0, \tilde{h}_2^0)$ the two component spinor fields of the bino, wino and the two neutral higgsinos, respectively. In the above basis the mass matrix is;

$$\begin{pmatrix} M_1 & 0 & -m_Z s_\theta \cos \beta & m_Z s_\theta \sin \beta \\ 0 & M_2 & m_Z c_\theta \cos \beta & -m_Z c_\theta \sin \beta \\ -m_Z s_\theta \cos \beta & m_Z c_\theta \cos \beta & 0 & -\mu \\ m_Z s_\theta \sin \beta & m_Z c_\theta \sin \beta & -\mu & 0 \end{pmatrix} \quad (1)$$

Apart from the diagonal mass terms (M_1, M_2) , there are also higgs mixing terms μ and non-diagonal terms involving the coupling of the higgsinos to gauginos, depending from the weak angle sine (s_θ) and cosine (c_θ) and $\tan \beta$ the ratio v_2/v_1 of the two higgs vev's.

Analogously for the charged "inos" the basis vectors are; $(-i\tilde{w}^-, \tilde{h}_1^-)$, $(-i\tilde{w}^+, \tilde{h}_2^+)$, for the two-component spinor fields of the wino and charged higgsinos, respectively. The mass matrix for charginos is:

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin \beta \\ \sqrt{2} m_W \cos \beta & \mu \end{pmatrix} \quad (2)$$

The diagonalization of the above two matrices gives 4 neutralino $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$ and 2 chargino $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$ physical states. The mass and the properties of these states are determined by the eigenvalues and the gaugino/higgsino content of the resulting eigenvectors. They depend from 3 parameters $(M_2, \tan \beta, \mu)$ in the case of the charginos and 4 $(M_1, M_2, \tan \beta, \mu)$ in the case of the neutralinos.

[†] The R_p studies will be studied in the last section of this report

At values $M_2, M_1 \ll \mu$ the mass of $\tilde{\chi}_1^0$ is close to M_1 , while $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are close to M_2 , the three are dominantly gauginos. When in violation of the "gaugino mass relationships" described below, $M_1 \sim M_2$ all three tend to become degenerate and their small mass differences make their detection difficult. Conversely when $M_1, M_2 \gg \mu$ all three become dominantly higgsinos. Since the mass scale is then set by $|\mu|$ they again tend to become degenerate. Another special case is when $M_2 \sim -\mu$ and $\tan\beta = 1$. The $\tilde{\chi}_1^0$ is then dominantly photino, the $\tilde{\chi}_2^0$ a pure higgsino and the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$ are degenerate and have a relatively high mass equal to $\sqrt{M_2^2 + m_W^2}$. In terms of content, $\tilde{\chi}_1^+$ is a pure higgsino and $\tilde{\chi}_1^-$ a pure wino, and the opposite happens for the second chargino state. This is a difficult region that has triggered a considerable experimental effort as will be shown below. When finally $M_1 \sim M_2 \sim \mu \sim 0$ one has almost a SUSY conserving case where $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are massless, while $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$ have the mass of the W . In this case $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production is practically indistinguishable from the SM $W^+ W^-$ production, and can be detected only as an excess of events over the SM expectation. This possibility has been excluded [7].

In order to simplify the parametric dependence, a relationship between gaugino masses is usually assumed. The simplest possible picture in the context of gravity induced supersymmetry breaking is the one where gaugino masses are equal at the grand-unified scale. The one-loop renormalization group equation then entails that at lower energies they evolve so as to remain proportional to their respective gauge couplings. Numerically one has: $M_3 : M_2 : M_1 = 7 : 2 : 1$. The above relationship obtained in the context of supergravity models, remains valid in the case of GMSB models. But, the existence of string or other models with non-universal masses [8] at the GUT scale, induces some skepticism on its general validity. A truly model independent search should avoid its use.

The parameter M_3 is the only contribution to the mass of the gluino, if one disregards the theoretical problems of the definition of the mass of a colored particle. The gaugino mass relationship makes thus the gluino much heavier than the SU(2) and U(1) gauginos. Nevertheless, the possibility of two effective SUSY breaking scales: one for a color-singlet and one for a color non-singlet sector has been proposed [9] creating the possibility of a light or possibly LSP gluino.

Finally, in GMSB models spontaneous SUSY breaking leads to a goldstone fermion, the goldstino $\tilde{G}$; (in local SUSY $\tilde{G}$ is the longitudinal component of the gravitino) with very low mass. The $\tilde{G}$ mass is determined by F , the characteristic scale of SUSY breaking and it is given by:

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_{Plank}} = 2.5 \times \left(\frac{\sqrt{F}}{100\text{TeV}} \right)^2 eV \quad (3)$$

For $\sqrt{F} \sim 10^8$ TeV, characteristic scale of the string-motivated/supergravity models the $\tilde{G}$ is fairly massive and has no consequences to LEP phenomenology, while for the gauge mediated models $\sqrt{F} \sim 100 - 2000$ TeV implies that the $\tilde{G}$ is the LSP. This fact is the source of the main differences in the phenomenology of the two SUSY breaking mechanisms.

2.2. Sfermion masses

In third family notation, and disregarding intergenerational mixing, the squark mass eigenstates are obtained by diagonalizing the following two 2×2 matrices in the $\tilde{q}_L, \tilde{q}_R$ basis. The top, bottom-squark squared-masses are eigenvalues of

$$\begin{pmatrix} m_{\tilde{q}}^2 + m_{t,b}^2 + m_D^2 & m_{t,b} X_{t,b} \\ m_{t,b} X_{t,b} & m_{\tilde{u},\tilde{d}}^2 + m_{t,b}^2 + m_D^2 \end{pmatrix} \quad (4)$$

where $X_t \equiv A_t - \mu \cot\beta$, $X_b \equiv A_b - \mu \tan\beta$ are the mixing terms, $m_D^2 \equiv (I^3 - Q \sin^2 \theta_W) |\cos 2\beta| m_Z^2$ are the so-called "D-terms", and $m_{\tilde{q}}$, $m_{\tilde{u}}$, $m_{\tilde{d}}$, A_t , and A_b are soft-supersymmetry-breaking parameters.

The first 2 generations, where $m_q \sim 0$ do not have any left-right mixing while one of the third generation squarks (depending on $\tan\beta$) can be the lighter than the others, due to the

strong Yukawa running of the diagonal elements $m_{\tilde{q}}, m_{\tilde{u}}, m_{\tilde{d}}$ to low values and the effect of the mixing terms $X_{t,b}$ [10]. Exactly analogous formulas determine the slepton masses. E.g for the stau one has:

$$\begin{pmatrix} m_L^2 + m_\tau^2 + m_D^2 & m_\tau X_\tau \\ m_\tau X_\tau & m_R^2 + m_\tau^2 + m_D^2 \end{pmatrix} \quad (5)$$

In SUGRA like theories, one usually makes the simplifying assumption that the scalar masses are equal to a common mass m_0 at the GUT scale. The renormalization of these masses gives then at the weak scale for the first 2 generations[†]:

$$(m_R^2 - m_0^2) : (m_L^2 - m_0^2) : (m_{\tilde{q}}^2 - m_0^2) : M_2 = 0.22 : 0.75 : 6.40 : 1 \quad (6)$$

where m_R and m_L are the right and left slepton masses, giving for e.g $\tan\beta = 1$, which puts "D terms" to zero, a clear hierarchy. The right slepton is the lightest followed by a degenerate left slepton doublet, and the squarks at higher masses.

In GMSB models the mass relationships become [6]:

$$m_{\tilde{q}}^2 : m_L^2 : m_R^2 : M_1 = 11.6 : 2.5 : 1.1 : \sqrt{N_{5,10}} \quad (7)$$

Where $N_{5,10}$ is a number characterizing the number of representations in the messenger sector. Since the $\tilde{G}$ is the LSP, the bino $\tilde{b}$ is the NLSP for $N_{5,10} = 1$ and $\tilde{l}_R$ for $N_{5,10} \geq 2$. In GMSB models the first and second generation squarks have high masses.

2.3. Higgs masses

Two higgs doublets are required in the MSSM, one (H_u) to give mass to the up-type quarks and leptons, and one ($H - d$) to give mass to the down type fermions. These two doublets after the symmetry breaking give 5 higgses 2 CP-even neutrals h, H , one neutral CP-odd A and 2 charged $H^\pm$. The higgs masses at tree level depend only on 2 parameters m_A the mass of the CP-odd higgs and $\tan\beta$. One has $m_{H^\pm}^2 = m_{A^0}^2 + m_W^2$ and the tree-level neutral CP-even mass matrix is given by

$$\mathcal{M}_0^2 = \begin{pmatrix} m_{A^0}^2 \sin^2 \beta + m_Z^2 \cos^2 \beta & -(m_{A^0}^2 + m_Z^2) \sin \beta \cos \beta \\ -(m_{A^0}^2 + m_Z^2) \sin \beta \cos \beta & m_{A^0}^2 \cos^2 \beta + m_Z^2 \sin^2 \beta \end{pmatrix}. \quad (8)$$

The eigenvalues of $\mathcal{M}_0^2$ are the squared masses of the two CP-even higgs scalars

$$m_{H^0, h^0}^2 = \frac{1}{2} \left(m_{A^0}^2 + m_Z^2 \pm \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{A^0}^2 \cos^2 2\beta} \right). \quad (9)$$

and the diagonalizing angle is α , with

$$\cos 2\alpha = -\cos 2\beta \left(\frac{m_{A^0}^2 - m_Z^2}{m_{H^0}^2 - m_{h^0}^2} \right), \quad \sin 2\alpha = -\sin 2\beta \left(\frac{m_{H^0}^2 + m_{h^0}^2}{m_{H^0}^2 - m_{h^0}^2} \right). \quad (10)$$

From these results, it is easy to obtain:

$$\cos^2(\beta - \alpha) = \frac{m_{h^0}^2(m_Z^2 - m_{h^0}^2)}{m_{A^0}^2(m_{H^0}^2 - m_{h^0}^2)}. \quad (11)$$

It is trivial to show that at tree level the mass of the lightest higgs has an upper limit $m_h \leq m_Z |\cos 2\beta|$. One therefore expects at tree level a) a higgs with mass below the Z and b) an upper limit decreasing for $\tan\beta \rightarrow 1$. The radiative corrections [12], modify these predictions introducing a dependence from the rest of the supersymmetric spectrum. In the one-loop leading logarithmic approximation one roughly has:

$$m_{h^0}^2 \sim m_Z^2 \cos^2 \beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \ln \left(\frac{M_{\tilde{t}_1} M_{\tilde{t}_2}}{m_t^2} \right), \quad (12)$$

[†] Disregarding the "D terms", both for SUGRA and the GMSB relationships. These terms are the same in the two models examined here, though more general D-terms have been proposed [11].

where $M_{\tilde{t}_1}$, $M_{\tilde{t}_2}$ are the masses of the two top-squark mass eigenstates. Although eq. (12) provides a rough guide to the higgs mass upper bound, it is not sufficiently precise for LEP-2 phenomenology.

Renormalization group (RG) techniques are used for the resummation of one-loop leading logarithms, and the effects of heavy squark mixing are taken into account [12]. Symbolically one has for e.g the CP-even higgses, $\mathcal{M}^2 = \mathcal{M}_{1LL}^2 + \Delta\mathcal{M}_{\text{mix}}^2$ where the subscript *1LL* refers to the tree-level plus the one-loop leading logarithmic approximation to the full one-loop calculation, and the subscript *mix* refers to the contributions arising from $\tilde{q}_L$ - $\tilde{q}_R$ mixing effects of the third generation squarks. The CP-even higgs mass-squared eigenvalues are then obtained diagonalizing these new matrices. In the simplest approximation, squark mixing effects are neglected and the supersymmetric spectrum is characterized by one scale, called M_{SUSY} . The effects of third generation squark mixing, constitute the largest potential source of non-logarithmic one-loop corrections, and depend on the third generation squark mixing parameters: A_t , A_b and μ . Finally a more comprehensive set of formulae can be obtained by including the third generation soft-supersymmetry-breaking diagonal squark mass parameters, M_Q , M_U , and M_D .

These corrections, show a strong dependence on the mass and the mixing of the stop. The higgs upper limit is higher for high X_t . The relative dependence of the upper limit on the value of $\tan\beta$ is not modified. Both effects are shown in figure 1 taken from [12]. The LEP results are conventionally [13] shown for 3 values of the ratio X_t/M_{SUSY} : 0 (no mixing), 1.(typical mixing) and 2.44 (maximal mixing). One sees clearly in figure 1 that they correspond to progressively higher maximal values for m_h .

Figure 1. The radiatively corrected, RG-improved light CP-even higgs mass is plotted as a function of X_t/M_{SUSY} , where $X_t \equiv A_t - \mu \cot\beta$, for $M_{\text{SUSY}} = m_{A^0} = 1$ TeV and two choices of $\tan\beta = 1.5$ and 20. Three values of μ are plotted in each case: -1 TeV [dashed], 0 [solid] and 1 TeV [dotted]. Here, we have assumed that the diagonal squark squared-masses are degenerate: $M_Q = M_U = M_D = M_{\text{SUSY}}$.

One can therefore distinguish a clear twofold complementarity between higgs and SUSY searches which already has started to be exploited by LEP experiments. Low values of $\tan\beta$ give a low lying higgs, while create difficulties for the SUSY searches, as will be shown below. High values of $\tan\beta$ give upper limits for m_h inaccessible to LEP, but lower the neutralino/chargino spectrum. Then high X_t mixing, again increases the radiative corrections to m_h but creates the hope of detecting a low lying $\tilde{t}$ and vice versa. The extent to which these complementarities can become "no-loose" statements remains to be explored. One can certainly state that a fruitless higgs search at the end of LEP, will already be setting limits on the lowest value of $\tan\beta$ possible ($\gtrsim 2$), and this would exclude a region particularly complicated for sparticle studies.

Recently, the authors of [14] have shown that in the context of universal scalar and gaugino masses at the GUT scale and moderate $\tan\beta$ in the infrared fixed point scenario†, for M_{SUSY} less than 1 TeV/ c^2 , the lightest higgs mass $m_h \leq 97 \pm 2$ GeV/ c^2 . This scenario will definitively put to test by LEP at its highest energy.

3. Precision measurement constraints

In view of the impressive success of the SM, one of the most attractive features of the MSSM is that it reduces to a SM with a light higgs ($m_h \leq 130\text{GeV}/c^2$) at the decoupling limit of a high mass sparticle sector. In fact, the most recent analysis [15] of the LEP1, SLD and FNAL(M_W) observables, combined with atomic parity violation ($Q_W(^{205}\text{Tl})$, $Q_W(^{133}\text{Cs})$), neutrino DIS (CCFR,CDHS,CHARM) precision measurements and $R_b \rightarrow s\gamma$ measurements including new precise experimental [16] and theoretical [17] determinations of the hadronic contribution to the vacuum polarization $\Delta\alpha_{had}^5(M_Z)$, and new $O(\alpha^2 m_t^2)$ corrections, gives $M_H = 93_{-46}^{+73}\text{GeV}/c^2$ as best fit value for the SM higgs. The 90% upper limit on M_H is $224-236\text{GeV}/c^2$. This upper limit clearly consistent with a MSSM higgs, is not entirely due to the high A_{LR} value measured in SLD. One obtains a best fit value $M_H = 154_{-82}^{+140}$ when the A_{LR} value is removed from the fit.

Not more than two years ago, the 3σ discrepancies found in e.g the R_b value gave a margin of hope of an imminent SUSY discovery, since the MSSM was able to fit better the precision data than the SM. The classification of the indirect effects of low lying sparticles gave the following cases[18]:

- a contribution $\Delta\rho$ to the ρ parameter from the virtual exchange of split multiplets of the stop and sbottom analogous to the top-bottom left-handed doublet,
- a threshold effect in the Z wave function renormalization mostly due to the vector coupling of charginos and (off-diagonal) neutralinos to the Z itself, affecting the Z widths,
- a negative contribution to Γ_b from $H^\pm - t$ loops proportional to $m_t^2/\tan\beta$ and an opposite positive contribution from $\tilde{\chi}_1^\pm - \tilde{t}$ loops proportional to $m_{\tilde{t}}^2/\sin^2\beta$. These effects were of course important for not very high $\tan\beta$.
- Finally for large $\tan\beta$, shifts could be obtained by loops containing bottom quarks and light neutral higgs and to a lesser extent neutralino/sbottom loops.

The recent [19] LEP results bringing R_b closer to the SM and in parallel the new direct limits on higgs, chargino and stop, reported below, make the last three contributions almost negligible.

The analysis of LEP data [18] in terms of the "epsilon" parameters $\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_b$ incorporating the oblique corrections to the propagators plus some vertex corrections, shows that the experimental values are at most $1-1.5\sigma$ away from the SM predictions, and that the MSSM stands on equal footing with the SM with respect to the agreement with the experimental values. An almost insignificant amelioration of the χ^2 of the fit, by 1 unit, occurs for a region of MSSM, with $m_{\tilde{\chi}_1^\pm} = 90 - 105\text{GeV}/c^2$, $m_{\tilde{t}} = 100\text{GeV}/c^2$, $\tan\beta = 1$ and $m_{\tilde{g}} = 1\text{TeV}$.

† Where the top quark mass and other physical quantities of the low energy theory are insensitive to the values of the theory at some high scale

On the other hand, considerable theoretical effort has been spent on calculating full one-loop corrections [20]. Full one-loop calculations are available for the quantity Δr , entering the M_W - M_Z relationship, and the Z boson observables. They have recently been improved by the sizeable supersymmetric QCD corrections to the ρ -parameter at the two-loop level. As mentioned above the mass splitting between $\tilde{b}_L$ and $\tilde{t}_L$ yields a contribution to the ρ -parameter $\rho = 1 + \Delta\rho$. As a universal loop contribution, $\Delta\rho_{\tilde{t}\tilde{b}}$ enters the quantity Δr (see 13) and the Z boson couplings affecting the overall normalization and the effective mixing angles for the corresponding fermions. It is thus significantly constrained by the data on M_W and the Z widths and asymmetries.

The correlation between the masses M_W, M_Z of the vector bosons in terms of the Fermi constant G_μ is given by

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2s_W^2 M_W^2} \cdot \frac{1}{1 - \Delta r} = \frac{\pi\alpha}{2s_W^2 M_W^2} \cdot \frac{1}{(1 - \Delta\alpha) \cdot (1 + \frac{c_W^2}{s_W^2} \Delta\rho) - (\Delta r)_{\text{rem}}} \quad (13)$$

Where, $s_W^2 = 1 - \frac{m_W^2}{m_Z^2}$, $\Delta\alpha = 0.0595 \pm 0.0007$ is the QED vacuum polarization of the photon from the light fermions, $\Delta\rho$ is the irreducible quantum contribution to the ρ -parameter, and $(\Delta r)_{\text{rem}}$ contains the residual loop terms. The SUSY QCD corrections to Δr are well approximated by the SUSY QCD corrections to $\Delta\rho$. The 2-loop terms correspond to a shift in the W mass of 10-20 MeV for not too heavy SUSY partners of the quarks and are thus of phenomenological importance. Figure 2 (from [21]) shows the relationship between M_W and m_t in the SM and the MSSM, for the full range of supersymmetric parameters respecting present experimental limits in higgs and SUSY searches. Both indirect (named LEP1-SLD) and indirect determinations named (LEP2-TEVATRON) are shown. The MSSM prefers a slightly higher value for M_W and it is presently corroborated by the direct data. The increase of precision by LEP can become decisive for the separation between the models. This is a potential source of future excitement.

A global fit to all the electroweak precision data, including the top mass measurement, and the measurement of the branching ratio $R_{b \rightarrow s\gamma}$ by CLEO and ALEPH [24], has been applied in [22], recently updated by [23]. Apart from the simplifying assumptions on gaugino unification, no strong constraints have been imposed on the parameters, leaving the fit to find the optimum values. Two $\tan\beta$ scenarii have been tested (low and high). Both scenarii give as good fit of the data as the SM, a result consistent with the analysis of [18]. The low $\tan\beta$ (1.5) scenario has an optimum point with an $m_{\tilde{\chi}_1^0} = 38 \text{ GeV}/c^2$, $m_{\tilde{\chi}_1^\pm} = 89 \text{ GeV}/c^2$ and $m_h = 98 \text{ GeV}/c^2$. The χ^2 , however, in the region of the best low $\tan\beta$ fit, increases only slowly for increasing chargino masses. While the high $\tan\beta$ scenario has $m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_1^\pm} \sim 90 \text{ GeV}/c^2$ and $m_h = 60 \text{ GeV}/c^2$. Within this scenario both neutral h^0, A bosons are light and have practically the same mass. This scenario has the largest chance to be excluded at LEP2 if no higgs is found.

The authors of [25] used full one loop calculations to fit the same 31 observables, used for the SM fit. They follow the opposite strategy from the previous authors. They determine which areas of the parameter space are excluded by the present situation of agreement †. In order to minimize the input parameters, they assumed unification conditions at the GUT scale for the masses and evolution according to the renormalization group down to the EW scale. They further assumed that one of the higgs terms evolves down to a negative mass giving rise to Electroweak Symmetry Breaking (EWSB). In this case the measured EW masses give further constraints on the SUSY parameters (e.g. the parameters $\tan\beta$ and B). This strategy permitted them to study 3 constrained but generic enough models using a small set of input parameters. They study a SUGRA type model with input parameters: $m_0, M_{1/2}, A_0, \tan\beta, \text{sgn}(\mu)$ where $M_{1/2}$ is the common gaugino mass at the GUT scale and A_0 a common trilinear coupling at the GUT scale. They also study two GMSB models with

† Only A_{FB}^b shows a 2σ deviation between data and Standard Model prediction [19], a situation which could permit the existence of tau sneutrino resonance close to the Z and R-Parity violating couplings [26].

Figure 2. Measured t and W masses with error ellipses. In the MSM (grey region) light higgs boson masses are favored. The hatched area shows the prediction in the MSSM.

input parameters: $M, F, \tan\beta, \text{sgn}(\mu)$ where M is the messenger scale. The first(second) GMSB model has a messenger sector comprised of a $5 + \bar{5}(10 + \bar{10})$ pair of fields. They find regions of the parameter space where the oblique corrections are not sufficient and one needs the full set of one-loop corrections. They then fit the electroweak data and obtain regions of the parameter space excluded by the present precision measurements. They obtain, in all 3 models, a lower limit on m_h of $78 \text{ GeV}/c^2$ and a lower limit on $\tilde{\chi}_1^0$ of $45 \text{ GeV}/c^2$. They also obtain a lower limit on $\tilde{\chi}_1^\pm$ of $90(80) \text{ GeV}/c^2$ for $\mu > 0(\mu < 0)$, in the SUGRA model and $100(89)$ and $120(82)$ respectively in the GMSB models. They further obtain lower limits on m_A : $320(115) \text{ GeV}/c^2$ for $\mu > 0(\mu < 0)$, in the SUGRA model and $255(220)$ and $230(185)$ respectively in the GMSB models. They finally obtain lower limits on $m_{H^\pm}$: $330(140) \text{ GeV}/c^2$ for $\mu > 0(\mu < 0)$, in the SUGRA model and $265(235)$ and $240(205)$ respectively in the GMSB models. This study shows clearly that the precision measurements can become a strong complementary tool in the exclusion/discovery of SUSY. Particular exclusion power in the two previous analyses and strong complementarity to supersymmetric searches is obtained by the flavor changing neutral current process $b \rightarrow s\gamma$, where the MSSM contribution is a function of $\tilde{\chi}_1^\pm, H^\pm$ and $\tilde{t}$ masses and mixings.

One step further down the super-constrained path can be taken by requiring a bottom-tau Yukawa coupling unification [27]. For $m_t = 175.6 \pm 5.5 \text{ GeV}/c^2$ only two regions of $\tan\beta$ give then an acceptable χ^2 fit: $1 \leq \tan\beta \leq 3$ and $20 \leq \tan\beta \leq 40$. Since the $b \rightarrow s\gamma$ rate is then too large for most of the parameter region, it is effectively ruled out while for the low $\tan\beta$ solution one has a real hope that LEP2 will discover the light higgs. To these constraints one can finally add cosmological constraints (regions where the LSP does not overclose the universe, or is simply cosmologically relevant[28]), or more specific model choices (e.g the "no-scale" model of [29]) to obtain the class of Constrained MSSM models. These models will be conclusively, put to test by LEP, if they are not already [28], since their high predictivity, allows very few "lanes of escape".

4. Higgs searches

The higgs search is the most important search for LEP2, since it is the area where LEP2 has the largest chances, as explained above, to make a significant discovery. Nevertheless, since the subject has been reviewed many times in the past [31], we only mention here a few salient aspects complementary to the search of "genuine" (that is R_p -odd) SUSY particles. The lightest MSSM higgs is produced either through the "higgstrahlung" process in association with a Z or in association with the CP-odd A higgs ($e^+e^- \rightarrow hZ(hA)$). The first process is suppressed by $\sin^2(\alpha - \beta)$ with respect to standard model higgs production, while the second by $\cos^2(\alpha - \beta)$ with respect to neutrino pair production. Luckily these suppressions are complementary, so one hopes to exploit this complementarity to obtain model-independent limits. The higgs $h(A)$ and Z decay modes determine the event signatures in the detector. The LEP accessible neutral higgses, for large $\tan\beta$, decay into $b\bar{b}$ ($\sim 90\%$), and $\tau^+\tau^-$ ($\sim 10\%$). This simple rule is modified when light higgs approaches its maximal value. The BR's then become closer to the SM BR's; that is $b\bar{b}$ is around $\sim 86\%$ and some decays to charm and gluons $\sim 5\%$ become possible. The present limits on charginos and neutralinos exclude the possibility of a higgs decaying into gauginos other than the LSP ($h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$).

Searches have been performed in

- a) 4 jet events ($hZ, hA \rightarrow b\bar{b}q\bar{q}, b\bar{b}b\bar{b}$)
- b) 2 jets and missing energy ($hZ \rightarrow b\bar{b}\nu\bar{\nu}$)
- c) a pair of $e^+e^- (\mu^+\mu^-)$ and 2 jets ($hZ \rightarrow b\bar{b}l^+l^-$)
- d) a pair of $\tau^+\tau^-$ and 2 jets ($hZ, hA \rightarrow b\bar{b}\tau^+\tau^-, q\bar{q}\tau^+\tau^-$)
- e) 2 non-b jets and missing energy (the $hZ \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 q\bar{q}$).

In cases a) and b) the tagging of the b-decays is a decisive tool to reduce the background. In case a) b-tagging and a full kinematical reconstruction using a 4 or 5C fit is used, to reject the 4jet decays of WW or multijet QCD events. In case b) the hermeticity of the detector is of utmost importance, together with b-tagging, to fight badly reconstructed radiative returns to the Z , single W production ($W\nu\nu$) and to some extent WW production with one W decaying to an unidentified lepton. Case e) is similar to case a) but one does not have anymore the help of b-tagging to reduce the background.

The four LEP experiments have chosen different event selection strategies with respect to the number of expected background events. From very tight event selection (ALEPH) to very loose (L3) through an intermediate case (DELPHI, OPAL). No significant signal has been found.

The combination of the 4 experiment data at 172 GeV E_{CM} , gives a limit of 77 GeV for the SM higgs, while very preliminary results from the $\sim 50 \text{ pb}^{-1}$ of 1997 data-taking at 183 GeV give a new limit of 82-83.6 GeV/ c^2 for OPAL, L3 and DELPHI in good agreement with what is expected from the luminosities analyzed, while ALEPH gives a higher limit 88.6 corresponding to a 83 GeV/ c^2 limit expected. This last upward fluctuation is mostly due to the fact that fewer candidates than expected were observed. Sensitivities are expected to increase by optimization for the new data.

In the case of hA production one has the spectacular 4b signature, used by the LEP experiments to complement the hZ channel. The cross section at 172 GeV for $m_A = 73$ GeV/ c^2 and $\tan\beta = 10$, that is when $m_A \sim m_h$ and $\cos^2(\beta - \alpha) \sim 1$, is $\sim 0.1 \text{ pb}$. A typical plot is shown (figure 3) for DELPHI results. Three regions are shown: the excluded region at 95% CL from the $e^+e^- \rightarrow hZ$ and hA searches combined, the theoretically disallowed region and the unexcluded region where a discovery is possible. For the low $\tan\beta$ region the hZ searches, and for the large $\tan\beta$ region the hA searches determine the exclusion boundary. Figure 3 gives a preliminary bound $\tan\beta > 1.7$ independent of m_h for the no-mixing case. Both ALEPH and DELPHI report preliminary results of $m_h > 73 \text{ GeV}$ at 95% [34] for the 3 mixing scenarii.

The charged higgs boson production and decay processes are $e^+e^- \rightarrow H^+H^- \rightarrow cscs, cst\nu, \nu\nu\nu\nu$. The resulting signatures are events with four jets, two jets, a τ lepton and

Figure 3. DELPHI MSSM exclusion for 161 to 172 GeV data. The dark region is theoretically not allowed, and the grey region is excluded. Preliminary results from 183 GeV data are included.

missing energy, and two τ leptons with large missing energy. No signal has been observed. A lower limit of 52-54.5 GeV/c^2 has been set by ALEPH, DELPHI and OPAL. On the other hand it is very difficult, in the context of the MSSM studied here, to have a charged higgs below the mass of W. And the indirect limits are already giving very high values for the charged higgs.

In the case e) of the decay to neutralinos the search signature is very similar to that for the $H\nu\nu$ channel and the four LEP experiments have set mass limits. For example, L3 gives a mass limit of $m_h \geq 70 \text{ GeV}/c^2$ under the assumption that the higgs boson is produced with the SM rate and the decay is completely invisible. This limit degrades to $\sim 65 \text{ GeV}/c^2$ when the production rate times the branching ratio is divided by 4. No consistently supersymmetric experimental study has been done yet to establish the regions of the parameter space where this decay process might dominate; but given the lower mass limits for the neutralino presented below ($\sim 23 \text{ GeV}/c^2$) one suspects that at least for standard scenarios this decay is effectively excluded. The final sensitivity for the MSSM higgs $\sim 90 - 100 \text{ GeV}/c^2$ will anyway most probably be accompanied with equivalent limits for the neutralino $\sim 45 - 50 \text{ GeV}/c^2$, leaving no room for this decay.

5. Gaugino/higgsino, slepton and gravitino production in R_p conserving models

The production of neutralinos and charginos would occur through the diagrams of fig 4, formally identical to the ones of SM double gauge boson production, once the replacement rules or R_p conservation† and those of spin-statistics are followed. The ν_e and e exchanged in the SM t channel are replaced by the corresponding $\tilde{\nu}_e$ and $\tilde{e}$. The t channel exchange, which cannot be conservatively ignored far from the Z^0 pole, introduces extra parameters in the cross section: the mass of $\tilde{\nu}_e$ in chargino production and this of $\tilde{e}$ for neutralino. In the case of GMSB hypothesis for the scalar masses, there is no new parameter involved. In GMSB models, the single or double gravitino production becomes accessible to LEP. The feynman diagrams are given by those of the neutralino pair production of fig. 4 when one or both neutralinos are replaced by a gravitino [32].

The sfermions are produced in pairs, through s channel exchange, for second and third generation sfermions. The $\tilde{\nu}_e$ and $\tilde{e}$ are produced also through chargino and neutralino exchange in the t channel and they can be significantly enhanced. Figure 5 shows the relevant diagrams. For the third generation sfermions, the cross section depends also on the mixing angle θ_q parameterizing the left-right mixing [10].

Figure 4. Chargino/neutralino production

Figure 5. Sfermion production

6. Searches in the context of gravity mediated supersymmetry breaking

In SUGRA inspired models since the $\tilde{G}$ is heavy, the two possible neutral supersymmetric particles LSP candidates are the $\tilde{\chi}_1^0$ and the $\tilde{\nu}$. The $\tilde{\nu}$ as LSP has become quite improbable after the LEP1 limits ($m_{\tilde{\nu}} \geq 41.8 \text{ GeV}/c^2$) if one assumes the SUGRA relationship given in (6), so most studies consider only the $\tilde{\chi}_1^0$ as the LSP‡. We therefore, following existing experimental studies, examine only the case of the $\tilde{\chi}_1^0$ as the LSP.

† Replace a pair number of sparticles per vertex

‡ A more general approach should take the possibility of the $\tilde{\nu}$ as the LSP into consideration

The pair production of $\tilde{\chi}_1^0$ gives 2 invisible products that can be tagged only through the initial state radiation (ISR) photon emitted. This signature competes with the copiously produced SM background $\nu\bar{\nu}\gamma$, and it has been shown [33] that the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production cannot be distinguished from the background for realistic luminosities.

The next possibility to detect a supersymmetric signal is the detection of the Next Lightest Supersymmetric Particle (NLSP). The NLSP can be either a gaugino/higgsino ($\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$) or a slepton ($\tilde{e}, \tilde{\mu}, \tilde{\tau}$ or $\tilde{\nu}$). As shown above the $\tilde{t}$ or $\tilde{b}$ can be the lightest squarks through mixing, and they can also be accessible at LEP. For the same reasons the $\tilde{\tau}$ could be the lightest slepton.

The $\tilde{\chi}_1^\pm(\tilde{\chi}_2^0)$ typically decay through the s channel to a $W^*(Z^*)$ and the $\tilde{\chi}_1^0$. The signatures are then determined by the branching ratios (BR) of the $W^*(Z^*)$ bosons. The $\tilde{\chi}_1^0\tilde{\chi}_2^0$ decay to $jets + \cancel{E}$ ($Z^* \rightarrow q\bar{q}$, 70%) or $l^+l^- + \cancel{E}$ ($Z^* \rightarrow l^+l^-$, 10%) or undetectable particles ($Z^* \rightarrow \nu\bar{\nu}$, 20%). The $\tilde{\chi}_1^+\tilde{\chi}_1^-$ decay to $jets + \cancel{E}$ (49%) or $jets + l^\pm + \cancel{E}$ (42%) or $l^+l^- + \cancel{E}$ (9%). These are the standard "topological" signatures. When the sleptons have masses close to the $\tilde{\chi}_1^\pm(\tilde{\chi}_2^0)$, these decay through the u and t channel to $\tilde{l}^*\nu(\tilde{l}^*l)$ and $\tilde{\nu}^*l(\tilde{\nu}^*\nu)$ respectively, giving enhanced leptonic signatures. Analogous things can happen for low lying squarks. The sfermions generally decay to the corresponding fermion and the $\tilde{\chi}_1^0$ or when this is possible to their doublet partner and the $\tilde{\chi}_1^\pm$. Cascade decays complicate somewhat the picture but are naturally taken into account in the generation of expected signals. The second neutralino can also decay to higgs plus the LSP, but the current limits on the mass of $m_h, m_A \geq 73\text{GeV}/c^2$ make this decay very improbable. Besides, since the higgs decay to the easily tagged b-quarks, neglecting the process gives a conservative limit. Another possibility is the decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma$ giving characteristic single ($\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$) and double ($\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma\gamma$) photon signatures.

The main backgrounds to the topological signatures are pair and single W production, the radiative return to the Z ($Z\gamma$), pair and single Z production, $\gamma\gamma$ interactions, four-fermion and Bhabha events for the multilepton studies and $\nu\bar{\nu} + \gamma's$ for $\gamma + \cancel{E}$ signatures. There are two extreme situations where a specific background dominates: a) when the mass difference ΔM between the NLSP and the LSP is very small the signal has to be distinguished from the abundant low mass and low track multiplicity $\gamma\gamma$ events and b) when ΔM becomes too high, or the mass of the $\tilde{\chi}_1^0$ tends to be very small the signal has to be distinguished from W^+W^- production, since then the $\tilde{\chi}_1^0$ starts to resemble a missing ν .

6.1. The $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$ as the NLSP

For the production and decay of the gauginos/higgsinos one can in general distinguish two cases, depending on the relative spectrum of the sfermion masses.

In the first case, the relevant scalar mass is much larger than the corresponding gaugino/higgsino mass. The t channel exchange in the production process can be neglected, and the decay branching ratios are mostly determined from the decays of the off-shell Z and W . The search for these standard "topological" signatures has shown no significant excess so far [34]. This translates to chargino mass limits close to the kinematical limits (the current preliminary limits are $\sim 90 - 91 \text{ GeV}/c^2$, [34]), since one has a significant chargino cross section (a few pb) on most of the parameter space.

Figure 6 shows a typical published exclusion plot in the μ versus M_2 plane by the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\chi}_1^0\tilde{\chi}_2^0$ searches. It is evident that the first search is more sensitive than the second in large portions of the parameter space. The only region where the neutralino search is clearly more sensitive is the special region $M_2 \sim -\mu \leq 100 - 200 \text{ GeV}$ for $\tan\beta \sim 1$. For this range of parameters the main signature of $\tilde{\chi}_1^0\tilde{\chi}_2^0$ is the radiative decay to $\tilde{\chi}_1^0\tilde{\chi}_1^0 + \gamma$. All 4 experiments have used this process to gain some extra parameter coverage, needed in order to set a significant lower limit to the $\tilde{\chi}_1^0$ mass. And indeed since the exclusion areas in the μ vs M_2 plane can be effectively translated to excluded masses of the $\tilde{\chi}_1^0$, each of the 4 experiments has given a lower limit of $\sim 25 \text{ GeV}/c^2$ † for the mass of the LSP in the high

† ALEPH and OPAL have shown preliminary results raising this limit to $30 \text{ GeV}/c^2$ [34]

$m_{\tilde{\nu}}$ limit, assuming the gaugino mass relationship $M_2 : M_1 = 2 : 1$. This limit is not valid in regions here the NLSP $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are quasi-degenerate ($\Delta M \leq 3 - 5$) GeV/c^2 with the LSP (e.g the "deep higgsino" regions, see section 2.1).

Figure 6. Exclusion plot in the M_2 vs μ plane for chargino and neutralino searches at $E_{CM} = 172$ GeV. The dark grey area is the contribution of neutralino searches while the light grey area is the contribution of chargino searches. The region excluded by LEP1 is also shown.

The "special" region above ($M_2 \sim -\mu$ and $\tan\beta \sim 1$) is also compatible with the CDF $e^+e^- \gamma\gamma$ event [36], when the gaugino mass relationship is violated ($M_2 : M_1 = 1 : 1$). The $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ production would then give a signature of $2 \gamma + \cancel{E}$. The combination of the 4 experiments has been reported in [37]: 7 candidates have been found against 6 expected from the MC. The MC predictions have a rather large spread $\sim 30\%$ [38] which has to be studied further, but the MC uncertainty does not seem to give room to a possible excess in this channel. The recoiling mass of the combined data is shown in figure 7.

In the second case the sleptons have low masses and therefore a) the t channel exchange introduces a negative interference, lowering substantially the chargino production cross-section, b) the leptonic BR are enhanced. When the sleptons are below the $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$, they become the NLSP themselves (see next subsection), and the charged slepton searches play a complementary role.

The ALEPH, L3 and OPAL, used this complementarity with their respective slepton searches. They also used the SUGRA relationship (6) giving an interrelated spectrum of charged and neutral sleptons depending on $M_2, \tan\beta, m_0, \mu$ and found the minimum limit obtained after the variation of these parameters. Care must be taken for a particularly difficult region when the $\tilde{\nu}$ is below and close in mass to the $\tilde{\chi}_1^\pm$. Not only the cross section is lowered but also the $\tilde{\chi}_1^\pm$ decays to $\tilde{\nu} l^\pm$ where the $\tilde{\nu}$ has invisible decays to $\nu \tilde{\chi}_1^0$ and the $l^\pm$ is very soft making its detection very difficult. The strongest limit is the one by ALEPH, excluding a $\tilde{\chi}_1^0$ below 14 GeV/c^2 at 95% CL for all possible values of the above parameters, assuming the gaugino and scalar mass relationships stated above. The ALEPH search also used the complementarity of the higgs search mentioned in section 2.3. to gain

Figure 7. Recoil mass opposite the 2γ for events $\gamma\gamma + \cancel{E}$. The plot includes the combined candidates of the 4 experiments and 2 energies.

some sensitivity in the low $\tan\beta$ region as can be seen in figure 8.

Figure 8. Limits on the lowest neutralino mass versus $\tan\beta$ for different values of the common scalar mass at the GUT scale m_0 . The limits coming from the unfruitful higgs searches at LEP are also reported as a dashed line. The minimum value is at $\tan\beta \sim 2.4$

Further, OPAL compared the excluded parameter space in the above searches, with the one excluded at FNAL, when the gluino and squarks are related to the gauginos and sleptons through the SUGRA gaugino and scalar mass relationships, and has found that presently the parameter space covered by LEP searches is larger than the one covered by FNAL [39], as can be seen in figure 9

Figure 9. A typical exclusion region for CDF in the $m_{\tilde{g}}$ vs $m_{\tilde{q}}$ plane compared to the excluded region by OPAL, provided one assumes GUT gaugino and scalar mass unification. The area below the dashed line gives negative slepton masses.

6.2. Sfermions as the NLSP

There is no significant excess in sfermion searches. The charged slepton limits have been combined by the LEP SUSY working group [40] obtaining a net improvement over published individual limits. The selectron limits are the best since they are helped by the neutralino exchange in the t channel. They are obtained under the assumption of a right handed slepton at $\mu = -200$ GeV and $\tan \beta = 2$. Figure 10 shows the exclusion curves, extending to excluded masses of ~ 77 GeV/ c^2 . The corresponding limit for the $\tilde{\mu}$ extends to ~ 70 GeV/ c^2 , while no combination of the $\tilde{\tau}$ limits has yet been reported. Individual experiment $\tilde{\tau}_R$ limits are of the order of ~ 62 GeV/ c^2 . The degenerate cases ($\Delta m_{\tilde{e}-\tilde{\chi}_1^0} \leq 10$ GeV) here also cannot be excluded as can be seen in figure 10. Only in the extreme case of $\Delta m_{\tilde{e}-\tilde{\chi}_1^0} \leq \sim 10 - 20$ MeV/ c^2 the charged slepton decays outside the detector and the signature becomes 2 charged heavy highly ionizing particles in the TPC's or the RICH detectors. The combined results by ALEPH, DELPHI and OPAL exclude a left(right) $\tilde{\mu}$ or $\tilde{\tau}$ of 76.5(75.6) GeV/ c^2 . The preliminary results by OPAL, ALEPH and DELPHI at 183 GeV CM energy raise these limits to 81(80) GeV/ c^2 . A search for kinks, charged particles changing direction inside the detector, or displaced impact parameters has also been performed in DELPHI extending the accessible Δm to 100-200 MeV/ c^2 . This analysis will be examined in the next section.

The $\tilde{t}$ and $\tilde{b}$ searches did not show any significant excess. The $\tilde{t}$ decays at LEP are dominated by the decay to $c\tilde{\chi}_1^0$ through CKM mixing, though also the decay $\tilde{t} \rightarrow b\tilde{\nu}$ could dominate for a low mass $\tilde{\nu}$. The combination of the 4 experiment stop searches in the first channel, for 2 mixing angles, is presented in figure 11, compared to the results of D0. A limit on the mass of $\tilde{t}_1$ of 72(65) GeV/ c^2 is obtained for $\Delta m_{\tilde{t}_1-\tilde{\chi}_1^0} \leq 10(5)$ GeV/ c^2 independently of the mixing angle, for the first channel, while a mass limit of 65 GeV/ c^2 is obtained for

Figure 10. Combined limit for the selectron search in the $M_{\tilde{\chi}_1^0}$ vs $M_{\tilde{e}}$ plane, at $E_{CM}=161+172$ GeV. The expected and actual limits are shown.

$\Delta m_{\tilde{t}_1 - \tilde{\chi}_1^0} \leq 7$ GeV/c² for the second channel. OPAL and L3 presented preliminary results [34] raising this limit to 82-83 GeV/c² for optimum coupling ($\tilde{t}_1 = \tilde{t}_L$). The lower charge of the $\tilde{b}$ results to a very low production cross-section at the mixing angle $\theta_{\tilde{b}}$ where the $\tilde{b}$ decouples from the Z. The present luminosities permit therefore only the extraction of a limit on the mass of $\tilde{b}_L$ (high coupling to the Z) of 70 GeV/c² for $\Delta m_{\tilde{b}_L - \tilde{\chi}_1^0} \leq 7$ GeV/c² for the decay to $b\tilde{\chi}_1^0$.

Figure 11. Combined limit for the stop search in the $M_{\tilde{\chi}_1^0}$ vs $M_{\tilde{t}}$ plane, at $E_{CM}=161+172$ GeV, for 2 mixing angles. The D0 exclusion plot is also shown.

6.3. Closing the "degeneration gap"

All searches above present a blind spot for $\Delta m_{NLSP-LSP} \leq 3-5 \text{ GeV}/c^2$ (standard topologies) and $\Delta m_{NLSP-LSP} \geq$ a few tens or hundred MeV/c^2 (search for kinks and heavy ionizing particles). When $10 - 20 \text{ MeV} \leq \Delta m \leq 3 \text{ GeV}/c^2$ one has a few visible tracks in the detector, practically indistinguishable from the $\gamma\gamma$ background. Dedicated searches [41] use an extra ISR γ to tag the event. These searches were able to close the gap for the $\tilde{\chi}_1^\pm$ and give a limit of $53.5 \text{ GeV}/c^2$ only for the case where the $\tilde{\chi}_1^\pm$ is a pure gaugino and the mass of the $\tilde{\nu}$ is high (see figure 12). More luminosity is needed for these studies penalized by the extra $\sim 10\%$ reduction of the radiative cross-section. These searches could be extended to charged sleptons and possibly close some part of the gaps of the above searches.

Figure 12. Exclusion limits for the chargino search in the $\Delta M_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0}$ vs $M_{\tilde{\chi}_1^\pm}$ plane. The light grey region shows the reach of standard topological searches. The long lived particle searches cover the lower area. The medium dark area denoted "ISR" shows the exclusion obtained using the ISR-photon tagged search.

7. Searches in the context of gauge mediated supersymmetry breaking

In the context of GMSB the LSP is the gravitino. The change of the signatures is quite radical since e.g now the $\tilde{\chi}_1^0$ becoming possibly a NLSP can decay to a gravitino and a photon, and the $\cancel{E}$ signature becomes $\cancel{E} + \gamma$. These photons can be either prompt or displaced, depending on the gravitino mass. The gravitino mass is setting the scale of the coupling of the gravitino to the gaugino and can be so small as to force the decay outside the detector. In this last case one obtains the gravity mediated supersymmetry breaking signatures.

Further, since charged sleptons also become candidate NLSP's, one has the decays $\tilde{l} \rightarrow \tilde{G}l$ giving a prompt lepton + $\cancel{E}$ or a track with a kink or a heavy ionizing particle decaying outside the detector, depending again on the gravitino mass.

The relationship between the gaugino spectrum and the scalar masses is given in section 2.2 and can give according to the number of messenger families two possibilities for the NLSP. The NLSP can be either the $\tilde{\chi}_1^0$ or a $\tilde{l}_R$. One then has depending on the relative position of the two NLSP candidates the following signatures (the case where the signature is the same as in gravity mediated models is not shown):

- The neutralino NLSP
 - $\tilde{\chi}_1^0 \tilde{G} \rightarrow \gamma + \cancel{E}$ prompt or displaced
 - $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma + \cancel{E}$ prompt or displaced
 - $\tilde{l}_R^+ \tilde{l}_R^- \rightarrow l^+ l^- \gamma\gamma + \cancel{E}$ prompt or displaced
- The right slepton NLSP
 - $\tilde{l}_R^+ \tilde{l}_R^- \rightarrow l^+ l^-$ presenting decay kinks or heavy ionizing particles
 - $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow l^+ l^- l'^+ l'^- \cancel{E}$

When $\tan\beta$ is large and the right slepton is the NLSP, the $\tilde{\tau}$ through mixing may be the lightest slepton. In fact this possibility is favored by some minimal gauge mediated models [42]. A multi-tau signature is quite striking, and it is the subject of current activity.

The LEP experiments have searched for single photons end missing energy, the " ν counting" signature. No signal above the SM $\nu\bar{\nu}\gamma$ has been found. L3 has e.g set a limit on the mass of the $\tilde{\chi}_1^0$ of $\sim 120 \text{ GeV}/c^2$ for a specific gravitino mass ($m_{\tilde{G}} = 10^{-5} \text{ eV}$), using the constrained "LNZ" model of [32]. The exclusion plot as a function of the gravitino mass is shown in figure 13.

In the search for two photons end $\cancel{E}$ the data shown in figure 7 can be used to give limits on the the pair production of neutralinos. Figure figure 14 compares the ALEPH-DELPHI-L3-OPAL combined exclusion limit to the region compatible with the CDF event. The gauge mediated supersymmetry breaking interpretation of this event will be seriously put to test by the end of the LEP2 program.

Depending on the gravitino mass the slepton decay to the corresponding l and the $\tilde{G}$ has the following possibilities:

- prompt decay, giving 2 charged leptons and $\cancel{E}$. The GMSB signature is the same as the gravity mediated signature for a $\tilde{\chi}_1^0$ of zero mass.
- decay close to the vertex, giving a signature of 2 tracks with displaced vertices and $\cancel{E}$.
- decay inside the central body of the tracking device, giving a particle presenting a kink or displaced vertices
- decay outside the detector, giving two heavily ionizing particles.

DELPHI has combined all the above signatures and has excluded a $\tilde{\tau}$ of mass 55(65)[73] GeV/c^2 for $m_{\tilde{G}} \leq 1(40)[200] \text{ eV}$. See figure 15. The small corner at high gravitino masses not excluded, is due to the fact that previous studies of this kind were only made at very early phases of LEP. A search at LEP1, using all the available data will certainly cover this area.

Figure 13. Excluded region by L3 in the $m_{\tilde{\chi}_1^0}$ vs m_G plane in the LNZ scenario

Figure 14. Excluded region in the $m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{\chi}_1^0}$ plane by the combination of 4 experiments compared to the region compatible with the CDF event according to the the authors of [18].

Figure 15. Exclusion limits on the stau mass as a function of the gravitino mass, by the combination of the 4 experimental signatures mentioned in the text.

8. Searches in the context of R_p models

8.1. R_p couplings

The supersymmetric Lagrangian derived within the MSSM, possesses a more general expression when one includes the following supersymmetric invariant terms [3]:

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \quad (14)$$

where L and E (Q and U, D) denote the left-handed component of lepton doublet and anti-lepton singlet (quark doublet and anti-quark singlet) chiral superfields respectively. The λ_{ijk} , λ'_{ijk} and λ''_{ijk} are new Yukawa couplings, where i, j and k are family indices going from 1 to 3. The terms proportional to λ and λ' violate L explicitly, whereas the term with a λ'' coupling, violates B explicitly. In order to avoid an unacceptably large amplitude for proton decay through squark exchange, it is sufficient to assume that certain “dangerous” lepton and baryon number violating couplings that would generate such a process, are not simultaneously present in the low energy Lagrangian. The simplest (and most conservative) assumption that one can make, is that one R-parity violating coupling is dominant.

Due to $SU(2)$ invariance, there are only 9 allowed λ terms i.e. all combinations of i, j and k going from 1 to 3 with $i \neq j$. There are 27 allowed λ' terms i.e. all combinations of i, j and k going from 1 to 3. Finally, from $SU(3)$ invariance, there are only 9 λ'' allowed terms i.e. all combinations of i, j and k going from 1 to 3 with $j \neq k$. One of the main phenomenological consequence of the R-Parity violating models (R_p) is the decay of the LSP.

We can distinguish the R_p decays in direct and indirect. In direct R_p decays the sparticle decays directly or via a virtual exchange to standard particles through an R_p vertex. If e.g the $\tilde{\nu}$ is the LSP, it can decay directly to a pair of fermions $f^+ f^-$. If on the other hand the lightest neutralino $\tilde{\chi}_1^0$ is the LSP, then it can decay into a fermion+virtual-sfermion pair $f^+ \tilde{f}^{*-}$ with the subsequent decay of the sfermion to standard fermions via the R-parity violating terms (see figures 16 and 17). In the indirect R_p (or cascade) decays the sparticle first decays through an R_p -conserving vertex to an on-shell sparticle which then decays through a R_p vertex. This mode usually dominates when there is enough phase space between the “mother” and the “daughter” sparticle. An exception to this can be the light stop decay, whose R_p decay is naturally suppressed. A typical example of indirect decay is the R_p decay $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + W^{*+}$ and the subsequent decay of $\tilde{\chi}_1^0$ through the R_p couplings. In the case of λ'' dominance, the direct $\tilde{\chi}_1^+$ decay has a signature of 3 jets, while the indirect would give either 5 jets or 3 jets + 1 lepton + missing energy, depending on the decay modes of W^* .

The requirement that the sparticle decays through direct decay within the detector (typically within 1 m) translates for the energies and masses of present interest, for a sfermion to $\lambda \geq 10^{-8}$ and for a gaugino into $\lambda \geq 3 \times 10^{-6}$. Where λ is any of the 45 R_p couplings. For weaker values of λ the R_p signatures become indistinguishable from the R_p ones. Very low mass neutralinos decay outside the detector even for relatively high λ values. Measurements on different processes at low energies provide strong constraints on R_p interactions [43].

8.2. Pair production of gauginos/higgsinos, squarks and sleptons

The pair production of gauginos and sfermions is described by the standard MSSM processes and couplings. The new couplings λ only affect the decay. As long as they are strong enough to permit a sparticle decay close to the vertex, they play a minor role in the sensitivity of detection. Under the assumption that only one operator is responsible for the R_p decay one has the following classification:

The λ dominance case has been studied by all 4 collaborations. The different channels can be classified as follows:

The neutralinos decay directly to 2 charged leptons and a neutrino ($\tilde{\chi}_1^0 \rightarrow \nu l^+ l^-$), while the chargino can either decay to one charged lepton and 2 neutrinos or 3 charged leptons

Figure 16. R_p decays of sfermions

Figure 17. R_p decays of charginos and neutralinos

($\tilde{\chi}_1^+ \rightarrow \nu l^+ \nu$ or $\tilde{\chi}_1^+ \rightarrow l^+ l^- l^+$). The combinatorics give the following signatures: $\tilde{\chi}_i^0 \tilde{\chi}_i^0 \rightarrow 4 l + \cancel{E}$, $\tilde{\chi}_i^+ \tilde{\chi}_i^- \rightarrow 2$ or $4 l + \cancel{E}$ or $6 l$ and no $\cancel{E}$. The neutralino being the LSP in most of the parameter space will decay directly, while the chargino will decay mostly indirectly. The indirect decays of the chargino passing through the virtual W will add to the above signatures the leptonic and hadronic decays of the W so one will have 2 extra leptons, 1 extra lepton and 2 jets, or extra 4jets. The signatures from purely leptonic become thus "semi-leptonic". Similar arguments hold for the second neutralino indirect decay (through the Z^*). See table 1 for a detailed and hopefully exhaustive description of the different signatures for the direct and indirect decays through the λ operators. The LEP experiments [44] have searched for the above signatures. Generally the selection efficiencies are high (typically in the range 50-90%) for the "best case scenarios" where one has a maximum number of muons or electrons (e.g λ_{122}) and 30-50% for final states which contain a maximum number of taus (e.g λ_{133} , "worst case scenario"). Searches have been conducted in both scenari and the most conservative limits are reported. Figure 18 from ALEPH shows that the R_p searches have no difficulty to attain the R_p conserving limits, when one combines direct and indirect searches. ALEPH has shown that the excluded area, excludes effectively a neutralino of mass smaller than $23\text{GeV}/c^2$ and this for all possible values of $\tan\beta$ and m_0 , assuming the usual SUGRA relationships.

Charged slepton pairs decay directly to 2 charged leptons and missing energy ($\tilde{l} \rightarrow l\nu$). This analysis is then similar to the R_p conserving analysis, where the slepton decays to the corresponding lepton and a neutralino, at the kinematical limit of zero neutralino mass. The corresponding results can be transposed. The indirect decays ($\tilde{l}^\pm \rightarrow l^\pm \tilde{\chi}_0, \nu \tilde{\chi}^\pm$) give the same signatures as the neutralino and chargino analyses, with the bonus of 2 extra leptons or missing energy. The predominance of indirect over direct decays depends off course on the the value of λ and the mass difference between the slepton and the neutralino. The present mass limits for the direct decays are $\sim 54(49)\text{GeV}/c^2$ for the best(worst) case, for $\tilde{\mu}$ and $\tilde{\tau}$ production. Where best case from the detector point of view is a multimuon and worst is a multitau event. The $\tilde{e}$ limits depend on the MSSM parameters taken. The indirect decays for a neutralino with mass above $23\text{ GeV}/c^2$, already excluded by the gaugino search give worst case limits of $\sim 62(56)\text{GeV}/c^2$ for $\tilde{\mu}$ ($\tilde{\tau}$).

Sneutrino pair production leads to a topology of 4 leptons and no missing energy, when direct decays are dominant, since each sneutrino decays directly to 2 leptons ($\tilde{\nu} \rightarrow l^+l^-$) giving a resonant signature. The indirect decay $\tilde{\nu} \rightarrow \nu \tilde{\chi}_1^0 \rightarrow \nu l^+l^- \nu$ dominates when kinematically available and λ is below presently constrained limits. The pair production of the indirect decay gives a signal similar to the one studied above for the neutralino search. The 'CC' decay $\tilde{\nu} \rightarrow l^\pm \tilde{\chi}_1^\mp$ is equally possible in the "deep higgsino" region of low μ and high M_2 giving multilepton or lepton and jet signatures similar to the ones above. For the direct decays an indicative mass limit for $\tilde{\nu}_\mu$ is $65(60)\text{ GeV}/c^2$ for $\lambda_{122}(\lambda_{233})$. The indirect case limits depend on the magnitude of the coupling λ_{ijk} . The worst case limits are $\sim 50\text{ GeV}/c^2$ for a $m_{\tilde{\chi}_1^0}$ larger than $23\text{ GeV}/c^2$.

Finally the squark indirect decays where the neutralino decays through the λ operator give "semileptonic" signatures. For the λ_{122} case and $\tilde{t}, \tilde{b}$ production at the "minimum coupling" mixing angle $\theta_{\tilde{t}(\tilde{b})} = 56(40)^\circ$, ALEPH obtains limits of the order of $\sim 60(56)\text{ GeV}/c^2$ for $\tilde{t}(\tilde{b})$, and $m_{\tilde{\chi}_1^0}$ greater than $23\text{ GeV}/c^2$ while one cannot improve over the LEP1 limits for the λ_{133} case.

OPAL has published also in cross-section lower limits. They are of the order of 0.4-0.5 pb for gauginos and sleptons in the multimuon case, and of the order of 1.3 pb for sleptons in the multitau case.

In the λ' dominance case the chargino/neutralino direct and indirect signatures fall in the categories multijets+charged leptons+ E , or multijets+ E . Here too, limits comparable to the R_p conserving case have been obtained (see figure 18). Upper limits of the order of 0.5-0.7 pb for high mass neutralinos and charginos have been set by OPAL. From the squark semileptonic decays the $\tilde{b}\tilde{b}$ pairs decay directly to 2 jets plus 2 charged leptons or 2 jets plus missing energy, while the $\tilde{t}\tilde{t}$ pairs decay directly only to 2 charged leptons + 2 jets. The specificity of this last channel is that due to the very low width of $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ the indirect decay is not dominant down to $\lambda' \sim 10^{-4}$. This channel has been studied by DELPHI and the results are shown below together with the single R_p sparticle production and the indirect limits to R_p 21. The R_p decays through this operator have attracted a lot of interest recently since they could be an explanation of the "High Q^2 " HERA excess[46]. A comparison is shown in the next subsection. Charged sleptons and sneutrinos decay to 4 jet topologies through the operator corresponding to λ'_{ijk} . A typical "4 jet" analysis can be used to set an upper limit on the production of charged sleptons and neutrinos. The corresponding ALEPH mass limits are: $M_{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L} \geq 51\text{ GeV}/c^2$ where for the selectron the limit is evaluated for a point in the deep higgsino region, assuming gauge unification conditions. OPAL has the same limits. DELPHI has studied in particular the λ'_{333} operator controlling the decay of $\tilde{\nu}_\tau$ to a pair of b quarks, giving a striking 4 b signature through its pair production. They obtained a 95% CL limit of $59.3\text{ GeV}/c^2$ on the mass of the $\tilde{\nu}_\tau$.

Finally charginos, neutralino and squarks can decay through the λ'' operator.

The charginos and neutralinos decay to multijet topologies through the operators corresponding to λ''_{ijk} . The neutralino will decay directly to 3 jets ($\tilde{\chi}_1^0 \rightarrow \bar{u}\bar{d}\bar{d}$). Its pair production will give a 6 jet topology. DELPHI has looked for peaks in "forced" 6-jet

signatures	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	$\tilde{\chi}^\mp \tilde{\chi}^\pm$	$\tilde{l} \tilde{l}$	$\tilde{\nu} \tilde{\nu}$	$\tilde{q} \tilde{q}$	similar R_p channels
2l + $\cancel{E}$			λ^D	λ^D			$\tilde{\chi}^\mp \tilde{\chi}^\pm, \tilde{l} \tilde{l}$
4l			λ^D		λ^D		
6l			λ^D		λ^I		
8l					λ^I		
4l + $\cancel{E}$	λ^D	λ^D	λ^D	λ^I	λ^I		
6l + $\cancel{E}$		λ^I	λ^I	λ^I	λ^I		
8l + $\cancel{E}$					λ^I		
3l+2jets + $\cancel{E}$		λ'^I	λ^I	λ^I			
4l+2-4jets + $\cancel{E}$		λ^I	λ^I, λ'^I	λ^I	λ'^I	λ'^I	λ^I
5l+2jets + $\cancel{E}$			λ^I	λ^I	λ^I		
6l-7l+2jets + $\cancel{E}$					λ^I		
4jets				λ'^D	λ'^D	λ'^D	hZ, hA
2l+2jets	λ'^D	λ'^D	λ'^D	λ'^I		λ'^D	hZ
2l+4jets	λ'^D	λ'^D	λ'^D	λ'^I		λ'^I	hZ
2l+6jets		λ'^I, λ''^I				λ'^I	hZ
2l+8jets			λ^I				hZ
4l+4jets		λ'^I		λ'^I			
1l+2jets+ $\cancel{E}$	λ'^D	λ'^D				λ'^D	$\tilde{\chi}^\mp \tilde{\chi}^\pm$
1l+4jets+ $\cancel{E}$		λ'^I	λ'^D	λ'^I	λ'^I	λ'^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm$
1l+6jets+ $\cancel{E}$			λ'^D, λ''^I			λ'^I, λ''^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm$
1l+8jets+ $\cancel{E}$			λ''^I			λ'^I, λ''^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm$
1l+10jets+ $\cancel{E}$						λ'^I, λ''^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm$
2l+4jets+ $\cancel{E}$		λ'^I	λ'^I	λ'^I	λ'^I	λ'^I	
2l+6jets+ $\cancel{E}$			λ'^I, λ''^I			λ'^I	
2l+8jets+ $\cancel{E}$						λ'^I	
2l+10jets+ $\cancel{E}$						λ'^I, λ''^I	
3l+4jets+ $\cancel{E}$			λ^I	λ^I	λ^I	λ'^I	
3l+6jets+ $\cancel{E}$						λ'^I	
3l+8jets+ $\cancel{E}$						λ'^I	
2jets + $\cancel{E}$	λ'^D	λ'^D	λ'^D			λ'^D	$\tilde{\chi}^\mp \tilde{\chi}^\pm, \tilde{q} \tilde{q}, hZ$
4jets + $\cancel{E}$	λ'^D	λ'^D	λ'^D		λ'^I	λ'^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm, \tilde{q} \tilde{q}, hZ$
6jets + $\cancel{E}$		λ'^I, λ''^I				λ'^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm, \tilde{q} \tilde{q}, hZ$
8jets + $\cancel{E}$			λ^I			λ'^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm, \tilde{q} \tilde{q}, hZ$
10jets + $\cancel{E}$						λ'^I	$\tilde{\chi}^\mp \tilde{\chi}^\pm, \tilde{q} \tilde{q}, hZ$
6jets	λ''^D	λ''^D	λ''^D			λ''^I	
8jets		λ''^I	λ''^I			λ''^I	
10jets		λ''^I	λ''^I			λ''^I	
12jets						λ''^I	

Table 1. List of R_p signatures. The entries λ show the operator responsible for the decay, and the superscript D or I, indicates whether one has a direct or indirect decay

events and found no candidates. They were able to set an upper limit of 1.4 pb^{-1} on 6 jet production processes. The indirect decay of the chargino to the neutralino plus an off-shell W is dominant in practically all the phase space, apart from cases of extreme degeneracy of the chargino and the neutralino. The indirect decays give thus a 10 jet topology, 6 jets and 2 charged leptons and $\cancel{E}$ or 8 jets and 1 charged lepton and $\cancel{E}$, depending on the BR of W^* . ALEPH has used the semileptonic signatures and extracted the limits shown in figure 18. These semileptonic signatures are sufficient to extend the limits close to kinematical limit for large sfermion masses.

The squarks decay to 4 jet topologies through the operator corresponding to λ''_{ijk} . The stop would decay to 2 down quarks ($\tilde{t} \rightarrow dd$) and the sbottom to an up and a down quark ($\tilde{b} \rightarrow ud$). For the case of the light stop where the R_p decays are going through C.K.M suppressed matrix elements the direct decay dominates for a large region of values of λ'' . On the contrary the decay of a sbottom to $b\tilde{\chi}_1^0$ dominates whenever it is kinematically possible giving 8 jet topologies. OPAL and DELPHI give a limit of 61(47) GeV/ c^2 on the mass of the $\tilde{t}_L(\tilde{t}_{56^\circ})$ using the process $\tilde{t}\tilde{t}^* \rightarrow 4 \text{ jets}$.

Figure 18. Excluded regions in the μ vs M_2 plane from chargino and neutralino with R_p signatures, for 3 types of R_p operators

8.3. Single production of squarks and sleptons and indirect effects.

The search for manifestations of R-Parity violation can be extended to masses $\sim E_{CM}$, provided we introduce at least one R_p vertex in the production. The single production processes are of 2 types:

a) *single squark and slepton production*: through the interaction of a quark or lepton (contained in a radiated "resolved" gamma from one of the incoming particles (e^+ or e^-) [45] (see fig. 19)

Figure 19. Single squark production

In this case as well, the direct and indirect decays respectively give: a) a striking signature eq of a single lepton opposite a hadronic jet, with a resonant mass, or νq missing energy and a hadronic jet, equally resonant. b) a R_p decay to $q\tilde{\chi}_1^0$ or $q'\tilde{\chi}_1^+$, giving a final topology where a jet is opposite 2 jets and a lepton or 2 jets and missing energy. The "leptoquark" searches, plus specific searches for the indirect decays can be used to set limits. The results of a search of this type for DELPHI are shown in figure 21 and commented below.

b) $\tilde{\nu}_\mu$ or $\tilde{\nu}_\tau$ resonant production in the s channel through the operators λ_{121} and λ_{131} . [3] (see fig 20). The $\tilde{\nu}$ decays through R_p conserving decays to $\nu\tilde{\chi}_1^0$ and/or $l^\pm\tilde{\chi}_1^\pm$ and they decay in their turn through the same R_p operator giving a final signature of 2 or 4 leptons with or without missing energy. DELPHI has set limits $\lambda_{121} \geq 0.003 - 0.007$ for a $\tilde{\nu}$ between 130 and 173 GeV/c^2 . When the $\tilde{\chi}_1^0$ and/or $\tilde{\chi}_1^\pm$ have a mass equal or larger than the mass of the $\tilde{\nu}$, the $\tilde{\nu}$ can decay either through the dominant operators responsible for its production ($\lambda_{121}, \lambda_{131}$), or some other. The R-Parity violation will manifest itself through anomalous $R_{q,e}$ values and asymmetries, anomalous "radiation return" events, and/or generational lepton number violating processes. DELPHI has searched in the $b\bar{b}$ channel for λ'_{333} manifestations, and found limits comparable to the λ_{121} case; while L3 has studied the possibility of anomalous e^+e^- and $\mu^+\mu^-$ distributions setting limits to $\lambda_{121}, \lambda_{232}$ of the order of 0.025 to 0.004 for $m_{\tilde{\nu}_\tau}$ between 125 and 175 GeV/c^2 .

Finally the t channel exchange of a squark (or slepton) can in principle give access to squarks (slepton) masses well beyond the E_{CM} energies. Deviations of the SM cross-sections and asymmetries are studied as a means of setting new limits to R_p couplings, for high sfermion masses beyond the kinematical limits of double or single sfermion production [47].

8.4. LEP R_p searches and HERA

Figure 21 presents a synopsis of the complementary searches and measurements that can be performed in an e^+e^- collider, using as an example DELPHI. In this figure 2

Figure 20. R_p sneutrino resonance production, and decay to R_p permitted channels

possible interpretations of the HERA anomalous events as squark production through the R-Parity violating operator λ' are compared to the DELPHI exclusion plots. The 2 possible interpretations are:

- Production of a left up squark from a valence d

$$e^+ d \rightarrow \tilde{c}_L, \tilde{t}_L(\lambda'_{121}, \lambda'_{131}) \quad (15)$$

- Production of a left up squark from a sea s, or right down quark from a sea anti-up quark.

$$e^+ s \rightarrow \tilde{c}_L, \tilde{t}_L(\lambda'_{122}, \lambda'_{132}), e^+ \bar{u} \rightarrow \tilde{s}_R, \tilde{b}_R(\lambda'_{121}, \lambda'_{131}) \quad (16)$$

The DELPHI exclusion plots are obtained using:

- a) Pair production. The λ' operators do not affect the production cross-section, since it is a R-Parity conserving one. They only determine the decay properties. Depending on the strength of λ' the direct R-Parity violating decays can dominate or not over the cascade decays. The stop case is a particular one, since its R-Parity conserving decay is naturally suppressed when the stop is below the top, and it occurs mostly through a Cabibo-Kobayashi-Maskawa transition to charm and the neutralino. The direct R-Parity violating decays dominate down to a strength of 10^{-4} . The search of the stop described in the previous section in the 2 lepton + 2 jets channel provides the limit extending down to very low λ' . This corresponds to the dark area in the upper plot.
- b) Single production. The squarks can be produced singly as also mentioned above through an emitted gamma "resolved" to a quark-antiquark pair. Here the study looking for a leptoquark decaying in a charged lepton + jet in DELPHI can be transposed in a supersymmetric context. Since for the stop the direct decays dominate for the λ' above 10^{-4} and the only possible decay is $\tilde{t} \rightarrow eq$, the leptoquark limits for a production of a charge 2/3 scalar, with branching ratio 1, are reported in light grey in the same plot. For the sbottom case, two direct possible decays are open $\tilde{b} \rightarrow eq$ or $\tilde{b} \rightarrow \nu q$, since their search was only in the lepton + jet channel, they take the branching ratio 50% limits of their leptoquark paper.
- c) Exchange of a squark in the t channel. Further the indirect decays are reported on the same plot in medium dark color. The indirect search barely touches the s interpretation of the anomalous events, while completely excludes the $\bar{u}$ interpretation. The H1 stop exclusion (in blue) while it seems to exclude the s interpretation, it had assumed a valence quark, so it is not immediately applicable.

Figure 21. Exclusion domain in the λ' versus $m_{\tilde{q}}$ plane.

9. Conclusions

The experimental searches have moved during recent years from a "classicist" approach, where super-constrained models were tested according to a few canonical $\cancel{E}$ signatures to a more varied approach where many signatures and an exhaustive search of the parametric space down to the most "singular" possibilities are examined. The proliferation of models of SUSY breaking, was not been seen as a source of despair for experimentalists but on the contrary as a chance to extend the range of things searched for. The recent addition of $\mathcal{R}_p$ model searches has completed the list which currently includes: a) $\cancel{E}$ signatures, b) prompt or displaced leptons and γ 's, c) kinks, d) heavy ionizing particles and e) resonances in multijet or jet and lepton mass distributions. Supersymmetry gives a disciplined framework for all these searches, and this constitutes its pragmatic justification. Further, complementarities span different types of processes from the higgs, to SUSY and precision measurements of

EW parameters. One can tentatively claim that at LEP relatively "assumption free" limits on e.g the mass of the neutralino will be obtained given enough luminosity and provided one is willing to search for alternative signatures and map carefully the parameter space leaving no unexplored gaps behind.

Bibliography

- [1] H.P. Nilles, *Phys. Rep.* **110** (1984) 1; H.E. Haber and G.L. Kane, *Phys. Rep.* **117** (1985) 75.
- [2] For a recent review see e.g S. Dawson hep-ph/9712464 and references therein.
- [3] For a recent review see e.g H. Dreiner hep-ph/9707435 and references therein.
- [4] For a recent review see e.g P. Nath hep-ph/9708221 and references therein.
- [5] For a recent review see e.g G.F Giudice and R. Rattazzi hep-ph/9801271 and references therein.
- [6] For a recent review see e.g J.F. Gunion hep-ph/9704349.
- [7] For a recent review see e.g P. Janot plenary talk in EPS97, Jerusalem.
- [8] For a recent review see e.g G. Anderson et al. hep-ph/9609457.
- [9] For a recent review see e.g S. Raby hep-ph/9702299.
- [10] For a recent review see e.g A. Bartl et al hep-ph/9604221.
- [11] For a recent review see e.g M. Peskin hep-ph/9604339.
- [12] For a recent review see e.g H.E. Haber hep-ph/9707213.
- [13] E. Accomando et al., "Higgs Physics" in *Physics at LEP2*, CERN 96-01 (1996) p. 351.
- [14] J. A. Casas et al. hep-ph/9801365.
- [15] J. Erler and Paul Langacker hep-ph/9801422
- [16] Davier, M. and Hocker, A, hep-ph/9711308
- [17] Martin A.D and Zeppenfeld, D. *Phys. Lett.* **345B**, 558 (1995).
- [18] For a recent review see G. Altarelli et al. hep-ph/9712368
- [19] The LEP Electroweak Working Group and the SLD Heavy Flavor Working Group, CERN-PPE/96-183 (1996); and CERN-PPE/97-154, 2 December 1997.
- [20] For a recent review see W. Hollik, hep-ph/9711489.
- [21] D. Ward talk at the HEP'97 Conference, Jerusalem, Aug. 19-26, 1997, J. Erler and P. Langacker, *The 1997 off-year partial update for the 1998 edition of Particles Data*, available on the PDG Web-pages (URL: <http://pdg.lbl.gov/>).
- [22] W.de Boer, et al. *Z. Phys. C* **75** (1997) 627.
- [23] U. Schwickerath, WIN97, Capri 1997.
- [24] R. Ammar et al. *Phys. Rev. Lett.* **74** (1995) 2885; M. Feindt, EPS97, Jerusalem, August 1997.
- [25] J. Erler and P. Langacker hep-ph 9801422
- [26] J. Erler et al. *Phys. Rev. Lett.* **78**, 3063 (1997)
- [27] W. De Boer et al. hep-ph/9712376.
- [28] See e.g J. Ellis et al. hep-ph/9705444.
- [29] See e.g J. Lopez D. Nanopoulos hep-ph/9701264
- [30] ALEPH, DELPHI, L3, and OPAL Coll., and the LEP Working Group for higgs Boson Searches, CERN/LEPC 97-11, Nov 3, 1997.
- [31] For a recent review see e.g A. Sopczak hep-ph/9712283.
- [32] J. Lopez et al hep-ph/9611437
- [33] S. Ambrosanio et al. *Phys. Lett. B* **373** (1996) 107-116
- [34] Talks by M. Pohl (L3), P.J. Dornan (ALEPH), P. Charpentier (DELPHI), A. Honma (OPAL) during the LEPC open session 11 November 1997.
- [35] M. Felcini parallel session talk in EPS97, Jerusalem.
- [36] G. Kane hep-ph/9705382
- [37] M. Chemarin parallel session talk in EPS97, Jerusalem
- [38] R. Pain et al. DELPHI paper no528 contributed to EPS97, Jerusalem.
- [39] OPAL Coll. CERN-PPE 97-083
- [40] S. Asai parallel session talk in EPS97, Jerusalem
- [41] DELPHI paper no427 submitted to EPS97, Jerusalem
- [42] See e.g F. Borzumati hep-ph/9702307
- [43] G. Bhattacharyya hep-ph/9709395.
- [44] ALEPH CERN-PPE/97-151, DELPHI HEP'97 n0 589, L3 CERN-PPE/97-99, OPAL Physics Note PN-307 submitted to EPS97 Jerusalem. See also older publications: OPAL *Phys. Lett. B* **313** (1993) 333, ALEPH *Phys. Lett. B* **349** (1995) 238, ALEPH *Phys. Lett. B* **384** (1996) 461.
- [45] M. Donchenski, S. Godfrey *Phys. Rev. D* **49** (1994) 6220.
- [46] H1 and ZEUS Collaboration DESY 97-024 and DESY-025, or hep-ex/9702012 and hep-ex/9702015.
- [47] For a recent review see e.g Jan Kalinowski hep-ph/9712550.