SUPERSYMMETRY, PART II (EXPERIMENT)

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II.1. Introduction: The theoretical strong points of supersymmetry (SUSY) have motivated many searches for supersymmetric particles. Most of these have been guided by the MSSM and are based on the canonical missing-energy signature caused by the escape of the LSP's ('lightest supersymmetric particles'). More recently, other scenarios have received considerable attention from experimenters, widening the range of topologies in which new physics might be found.

Unfortunately, no convincing evidence for the production of supersymmetric particles has been found. The most far reaching laboratory searches have been performed at the Tevatron and at LEP, and these are the main topic of this review. In addition, there are a few special opportunities exploited by HERA and certain fixed-target experiments.

Theoretical aspects of supersymmetry have been covered in Part I of this review by H.E. Haber (see also Ref. 1, 2); we use his notations and terminology.

II.2. Common supersymmetry scenarios: In the 'canonical' scenario [1], supersymmetric particles are pair-produced and decay directly or via cascades to the LSP. For most typical choices of model parameters, the lightest neutralino is the LSP. If R-parity is conserved, the LSP is stable. Since the neutralino is neutral and colorless, interacting only weakly with matter, it can be a candidate for cold dark matter, and in fact for a wide range of theoretical parameters, an appropriate density of relic neutralinos is expected. (See the Listings for current limits and constraints.) Assuming the conservation of R-parity, the LSP's will escape detection, giving signal events the appearance of "missing energy." In proton colliders, the momentum component along the beam direction is not useful, so one works with the so-called "missing transverse energy" ($\not{E}_T$), which is the vector sum of the transverse components of all visible momenta. In e^+e^- machines, both the missing transverse momentum, $p_T^{\rm miss}$ (essentially the same quantity as $\not{E}_T$), and the missing energy, $E^{\rm miss}$, which is the difference between twice the beam energy

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and the total visible energy, are utilized. There are always at least two LSP's per event. Collimated jets, isolated leptons or photons, and appropriate kinematic cuts provide additional handles to reduce backgrounds.

The conservation of R-parity is not required in supersymmetry, however, and in some searches it is assumed that supersymmetric particles decay via interactions which violate R-parity (RPV), and hence, lepton and/or baryon number. For the most part the production of superpartners is unchanged, but in general the missing-energy signature is lost. Depending on the choice of the R-parity–breaking interaction, SUSY events are characterized by an excess of leptons or hadronic jets, and in many cases it is relatively easy to suppress SM backgrounds [3]. A distinction is made between "indirect" RPV, in which the LSP decays close to the interaction point but no other decays are modified, and "direct" RPV, in which the supersymmetric particles decay to SM particles, producing no LSP's. In either case the pair-production of LSP's, which need not be $\widetilde{\chi}_1^0$'s or $\widetilde{\nu}$'s, is a significant SUSY signal.

In models assuming gauge-mediated supersymmetry breaking (GMSB) [4], the gravitino $\widetilde{g}_{3/2}$ is a weakly-interacting fermion with a mass so small that it can be neglected when considering the event kinematics. It is the LSP, and the lightest neutralino decays to it radiatively, possibly with a very long lifetime. With few exceptions the decays and production of other superpartners are the same as in the canonical scenario, so when the $\widetilde{\chi}_1^0$ lifetime is not too long, the event topologies are augmented by the presence of photons which can be energetic and isolated. If the $\widetilde{\chi}_1^0$ lifetime is so long that it decays outside of the detector, the event topologies are the same as in the canonical scenario. In some variants of this theory the right-sleptons are lighter than the lightest neutralino, and they decay to a lepton and a gravitino. This decay might occur after the slepton exits the apparatus, depending on model parameters.

Finally, in another scenario the gluino $\widetilde{g}$ is assumed to be light ($M_{\widetilde{g}} < 5$ GeV/c^2) [5]. Its decay to the lightest neutralino is kinematically suppressed, so long-lived supersymmetric hadrons ($\widetilde{g} + g$ bound states called R^0's) are formed [6].

While the sensitivity of most searches at LEP and the Tevatron would be lost, specific searches at fixed target experiments seem to have closed this gap definitively. (See the review article by H. Murayama.)

II.3. Experimental issues: Before describing the results of the searches, a few words about experimental isues are in order.

Given no signal for supersymmetric particles, experimenters are forced to derive limits on their production. The most general formulation of supersymmetry is so flexible that few universal bounds can be obtained. Often more restricted forms of the theory are evoked for which predictions are more definite—and exclusions more constraining. The most popular of these is minimal supergravity ('mSUGRA'). As explained in the Part I of this review, parameter freedom is drastically reduced by requiring related parameters to be equal at the unification scale. Thus, the gaugino masses are equal with value $m_{1/2}$, and the slepton, squark, and Higgs masses depend on a *common* scalar mass parameter, m_0. In the individual experimental analyses, only some of these assumptions are necessary. For example, the gluon and squark searches at proton machines constrain mainly M_3 and a scalar mass parameter m_0 for the squark masses, while the chargino, neutralino, and slepton searches at e^+e^- colliders constrain M_2 and a scalar mass parameter m_0 for the slepton masses. In addition, results from the Higgs searches can be used to constrain $m_{1/2}$ and m_0 as a function of $\tan\beta$. (The full analysis involves large radiative corrections coming from squark mixing, which is where the dependence on $m_{1/2}$ and m_0 enter.) In the mSUGRA framework, all the scalar mass parameters m_0 are the same and the three gaugino mass parameters are proportional to $m_{1/2}$, so limits from squarks, sleptons, charginos, gluinos, and Higgs all can be used to constrain the parameter space.

While the mSUGRA framework is convenient, it is based on several highly specific theoretical assumptions, so limits presented in this framework cannot easily be applied to other supersymmetric models. Serious attempts to reduce the model dependence of experimental exclusions have been made. When model-independent results are impossible, the underlying assumptions and their consequences are carefully delineated. This is easier to achieve at e^+e^- colliders than at proton machines.

The least model-dependent result from any experiment is the upper limit on the cross section. It requires only the number N of candidate events, the integrated luminosity $\mathcal{L}$, the total expected background b, and the acceptance ϵ for a given signal. The upper limit on the number of signal events for a given confidence level N^{upper} is computed from N and b (see review of Statistics). The experimental bound is simply

$$\epsilon \cdot \sigma < N^{\text{upper}}/\mathcal{L}. \tag{1}$$

This information is nearly always reported, but some care is needed to understand how the acceptance was estimated, since it can be quite sensitive to assumptions about masses and branching ratios. Also, in the more complicated analyses, N^{upper} also changes as a result of the optimization for a variety of possible signals.

The theoretical parameter space is constrained by computing $\epsilon \cdot \sigma$ of Eq. (1) in terms of the relevant parameters while $N^{\text{upper}}/\mathcal{L}$ is fixed by experiment. Even after the theoretical scenario and assumptions have been specified, some choice remains about how to present the constraints. The quantity $\epsilon \cdot \sigma$ may depend on three or more parameters, yet in a printed page one usually can display limits only in a two-dimensional space. Three rather different tactics are employed by experimenters:

- Select "typical" values for the parameters not shown. These may be suggested by theory, or values giving more conservative—or more powerful—results may be selected. Although the values are usually specified, one sometimes has to work to understand the possible 'loopholes.'
- Scan the parameters not shown. The lowest value for $\epsilon \cdot \sigma$ is used in Eq. (1), thereby giving the weakest limit for the parameters shown. As a consequence, the limit applies for all values of the parameters *not* shown.

- Scan parameters to find the lowest acceptance ϵ and use it as a constant in Eq. (1). The limits are then safe from theoretical uncertainties but may be over-conservative, hiding powerful constraints existing in more typical cases.

Judgment is exercised: the second option is the most correct but may be impractical or uninteresting; most often representative cases are presented. These latter become standard, allowing a direct comparison of experiments, and also the opportunity to combine results.

Limits reported here are derived for 95% C.L. unless noted otherwise.

II.4. Supersymmetry searches in e^+e^- colliders: The large electron-positron collider (LEP) at CERN has been running at center-of-mass energies more than twice the mass of the Z boson. After collecting approximately 150 pb^{-1} at LEP 1 (collider energy at the Z peak), each experiment (ALEPH, DELPHI, L3, OPAL) has accumulated large data sets at LEP 2: about 5.7 pb^{-1} at $\sqrt{s} \sim 133$ GeV (1995), 10 pb^{-1} at 161 GeV and 11 pb^{-1} at 172 GeV (1996), 57 pb^{-1} near 183 GeV (1997), and most recently, 180 pb^{-1} at 189 GeV (1998). This review emphasizes the most recent LEP 2 results.

The LEP experiments and SLD at SLAC excluded essentially all visible supersymmetric particles up to about half the Z mass (see the Listings for details). These limits come mainly from the comparison of the measured Z widths to SM expectations, and are relatively insensitive to the details of SUSY particle decays [7]. The data taken at higher energies allow much stronger limits to be set, although the complex interplay of masses, cross sections, and branching ratios makes simple general limits impossible to specify.

The main signals come from SUSY particles with charge, weak isospin, or large Yukawa couplings. The gauge fermions (charginos and neutralinos) generally are produced with large cross sections, while the scalar particles (sleptons and squarks) are suppressed near threshold by kinematic factors.

Charginos are produced via γ^*, Z^*, and $\widetilde{\nu}_e$ exchange. Cross sections are in the 1–10 pb range, but can be an order of magnitude smaller when $M_{\widetilde{\nu}_e}$ is less than 100 GeV/c^2 due to the destructive interference between s- and t-channel amplitudes. Under the same circumstances, neutralino production is enhanced, as the t-channel $\widetilde{e}$ exchange completely dominates the s-channel Z^* exchange. When Higgsino components dominate the field content of charginos and neutralinos, cross sections are large and insensitive to slepton masses.

Sleptons and squarks are produced via γ^* and Z^* exchange; for selectrons there is an important additional contribution from t-channel neutralino exchange which generally increases the cross section substantially. Although the Tevatron experiments have placed general limits on squark masses far beyond the reach of LEP, a light top squark (stop) could still be found since the flavor eigenstates can mix to give a large splitting between the mass eigenstates. The coupling of the lightest stop to the Z^* will vary with the mixing angle, however, and for certain values, even vanish, so the limits on squarks from LEP depend on the mixing angle assumed.

The various SUSY particles considered at LEP typically would decay directly to SM particles and LSP's, so signatures consist of some combination of jets, leptons, possibly photons, and missing energy. Consequently the search criteria are geared toward a few distinct topologies. Although they may be optimized for one specific signal, they are often efficient for others. For example, acoplanar jets are expected in both $\widetilde{t}_1\overline{\widetilde{t}}_1$ and $\widetilde{\chi}^0_1\widetilde{\chi}^0_2$ production, and acoplanar leptons for both $\widetilde{\ell}^+\widetilde{\ell}^-$ and $\widetilde{\chi}^+\widetilde{\chi}^-$.

The major backgrounds come from three sources. First, there are the so-called ‘two-photon interactions,’ in which the beam electrons emit photons which combine to produce a low mass hadronic or leptonic system leaving little visible energy in the detector. Since the electrons are seldom deflected through large angles, p_T^{miss} is low. Second, there is difermion production, usually accompanied by large initial-state radiation induced by the Z pole, which gives events that are well balanced with respect to the beam direction. Finally, there is four-fermion production through states with one or two resonating bosons

(W^+W^-, ZZ, $We\nu$, Ze^+e^-, etc.) which can give events with large E^{miss} and p_T^{miss} due to neutrinos and electrons lost down the beam pipe.

In the canonical case, E^{miss} and p_T^{miss} are large enough to eliminate most of these backgrounds. The e^+e^- initial state is well defined so searches utilize both transverse and longitudinal momentum components. It is possible to measure the missing mass ($M_{\text{miss}} = \{(\sqrt{s} - E_{\text{vis}})^2 - \vec{p}\,^2_{\text{vis}}\}^{1/2}$) which is small if p_T^{miss} is caused by a single neutrino or undetected electron or photon, and can be large when there are two massive LSP's. The four-fermion processes cannot be entirely eliminated, however, and a non-negligible irreducible background is expected. Fortunately, the uncertainties for these backgrounds are not large.

High efficiencies are easily achieved when the mass of the LSP is lighter than the parent particle by at least 10 GeV/c^2 and greater than about 10 GeV/c^2. Difficulties arise when the mass difference ΔM between the produced particle and the LSP is smaller than 10 GeV/c^2 as the signal resembles background from two-photon interactions. A very light LSP is challenging also since, kinematically speaking, it plays a role similar to a neutrino, so that, for example, a signal for charginos of mass 85 GeV/c^2 is difficult to distinguish from the production of W^+W^- pairs. The lower signal efficiency obtained in these two extreme cases has been offset by the large integrated luminosities delivered over the last two years, so mass limits are not degraded very much.

Since the start of LEP 2, experimenters have made special efforts to cover a wide range of mass differences. Also, since virtual superpartners exchanged in decays can heavily influence branching ratios to SM particles, care has been taken to ensure that the search efficiencies are not strongly dependent on the final state. This ability to cover a wide range of topologies has driven the push for bounds with a minimum of model dependence.

Charginos have been excluded up to 94 GeV/c^2 [8,9] except in cases of very low acceptance ($\Delta M = M_{\widetilde{\chi}^\pm} - M_{\widetilde{\chi}_1^0} \lesssim 3$ GeV/c^2) or low cross section ($M_{\widetilde{\nu}_e} \lesssim 120$ GeV/c^2). When $|\mu| \ll M_2$, the Higgsino components are large for charginos and neutralinos.

In this case the associated production of neutralino pairs $\widetilde{\chi}_1^0 \widetilde{\chi}_2^0$ is large and the problem of small mass differences $(M_{\widetilde{\chi}_2^0} - M_{\widetilde{\chi}_1^0})$ less severe. Experimental sensitivity now extends down to mass differences of 3 GeV/c^2, corresponding to M_2 above 2 TeV/c^2.

The possibility of extremely small mass differences has been raised in several theoretical papers, and the DELPHI Collaboration has engineered several searches to cover this scenario [10]. For $\Delta M \sim 1$ GeV/c^2, they distinguish signal from two-photon background on the basis of photons radiated in the initial state, which have different kinematic characteristics. For $\Delta M \sim 0.4$ GeV/c^2, the chargino acquires a non-negligible lifetime, so they look for displaced vertices and tracks which do not originate from the interaction point. The modeling of lifetime and chargino decays required special care. When $\Delta M < m_\pi$, the lifetime is so long that the chargino appears as a heavily ionizing particle which exits the apparatus before decaying. The bounds on the chargino mass are weaker than in the canonical case with larger ΔM, but still are well above the bounds from LEP 1 (Fig. 1).

The limits from chargino and neutralino production are most often used to constrain M_2 and μ for fixed $\tan\beta$. For large $|\mu|$ (the gaugino case), chargino bounds limit M_2, and vice versa (the Higgsino case). When $\tan\beta$ is not large, the region of parameter space with $\mu < 0$ and $|\mu| \sim M_2$ corresponds to 'mixed' field content, and the limits on M_2 and $|\mu|$ are relatively modest, numerically. This is especially true when electron sneutrinos are light, leading to a degradation of the indirect limits on the LSP mass, as discussed below.

When the sleptons are light, two important effects must be considered for charginos: the cross section is significantly reduced and the branching ratio to leptons is enhanced, especially to τ's via $\widetilde{\tau}$'s which can have non-negligible mixing. These effects are greatest when the chargino has a large gaugino component. The weakest bounds are found for small negative μ and small $\tan\beta$, as the cross section is reduced with respect to larger $|\mu|$, the impact of $\widetilde{\tau}$ mixing can be large, and the efficiency is not optimal because ΔM is large.

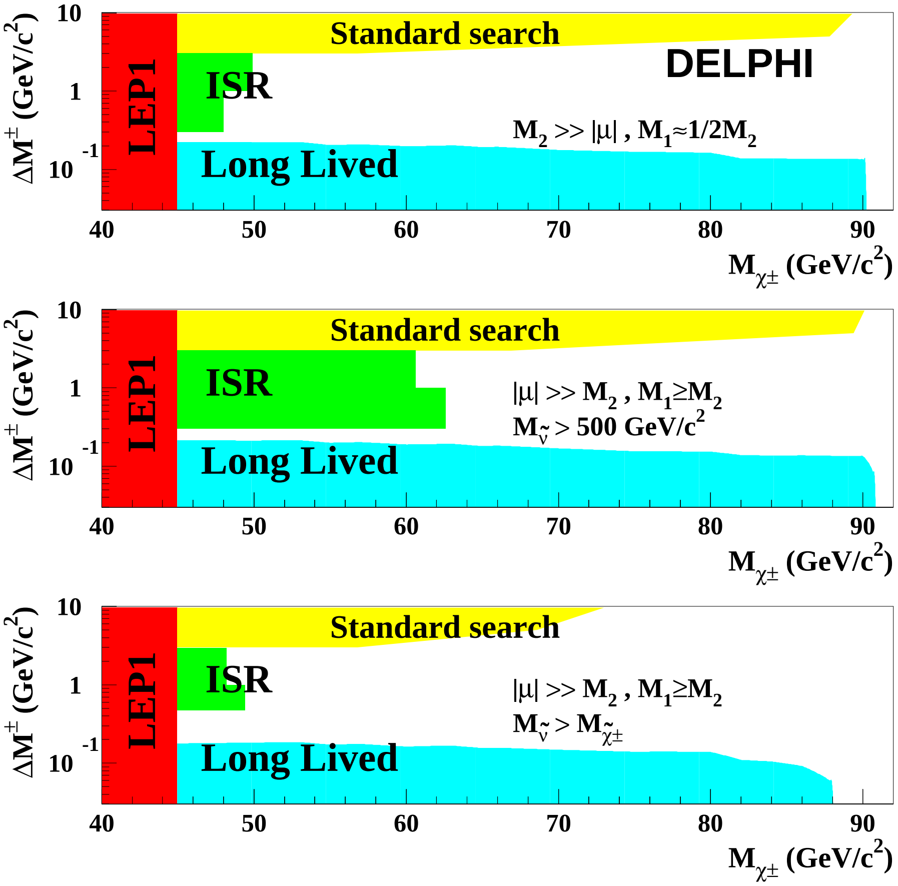

Figure 1: Ranges of excluded chargino and neutralino masses, for very small ΔM , from DELPHI [10].

If the sneutrino is lighter than the chargino, then two-body decays $\widetilde{\chi}^+ \to \ell^+\widetilde{\nu}$ dominate, and in the 'corridor' $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3$ GeV/c^2 the acceptance is so low that no exclusion is possible [11,9].

The limits on slepton masses [12] fall a bit below the kinematic limit due to a phase space suppression near threshold. The simplest topology results from $\widetilde{\ell} \to \ell\widetilde{\chi}^0_1$. Considering the production of $\widetilde{\ell}_R$ only, the 189 GeV data from OPAL gives 89 GeV/c^2 for $\tilde{e}_R$, 82 GeV/c^2 for $\tilde{\mu}_R$, and 81 GeV/c^2 for $\tilde{\tau}_1$. For selectrons and smuons there is a small improvement from the preliminary combination of the four LEP experiments [13], and one sees that the dependence on $\Delta M = M_{\widetilde{\ell}} - M_{\widetilde{\chi}_1^0}$ is weak for $\Delta M \gtrsim 5\ \mathrm{GeV}/c^2$. Assuming a common scalar mass term m_0, the masses of the left- and right-sleptons can be related as a function of $\tan\beta$, and one finds $m_{\tilde{\ell}_L} > m_{\tilde{\ell}_R}$ by a few GeV/c^2. Consequently, in associated $\tilde{e}_L\tilde{e}_R$ production, the special case $M_{\widetilde{\chi}} \lesssim M_{\tilde{e}_R}$ still results in a viable signature: a single energetic electron. ALEPH have used this to close the gap $M_{\tilde{e}_R} - M_{\widetilde{\chi}} \to 0$. In this same framework, bounds on the parameters $m_{1/2}$ and m_0 have been derived.

In some GMSB models, photons from the decay $\widetilde{\chi}_1^0 \to \gamma\, \widetilde{g}_{3/2}$ accompany the leptons. The resulting limits are similar to the canonical case. In other GMSB models, sleptons may decay to $\ell^{\pm}\, \widetilde{g}_{3/2}$ outside the detector, so the experimental signature is a pair of collinear, heavily ionizing tracks [14]. Combined search limits are 86 GeV/c^2 for $\widetilde{\mu}_R$ and $\widetilde{\tau}_R$ [15]. Shorter lifetimes are possible, however, so searches have been performed for displaced vertices, tracks with kinks, and tracks with large impact parameters. Combining these together, slepton mass limits independent of lifetime have been derived. The result from ALEPH for $\widetilde{\tau}_R$ is shown in Fig. 2 [12].

For these same GMSB models, it is possible that the lightest stau is significantly lighter than the other sleptons. If so, then special topologies may result, such as 4τ final states from neutralino pair production. DELPHI has searched in this and related channels, finding no evidence for a signal [16].

Limits on stop and sbottom masses [17,18], vary with the mixing angle because the cross section does: for $\theta_{\widetilde{t}} = 56^\circ$ and $\theta_{\widetilde{b}} = 67^\circ$ the contribution from Z exchange is “turned off.” The stop decay $\widetilde{t}_1 \to c\widetilde{\chi}_1^0$ proceeds through loops, giving a lifetime long enough to allow the top squark to form supersymmetric hadrons which provide a pair of jets and missing energy. If sneutrinos are light, the decay $\widetilde{t}_1 \to b\ell\widetilde{\nu}$ dominates, giving two leptons in addition to the jets. Access to small ΔM is possible due to the visibility of the decay products of the c and b quarks. Limits vary from 91 GeV/c^2 for an unrealistic pure $\widetilde{t}_L$ state to 89 GeV/c^2 if the coupling of $\widetilde{t}_1$ to the Z vanishes. The electric charge of the sbottoms is smaller than that of stops, leading to weaker limits, but the use of b-jet tagging helps

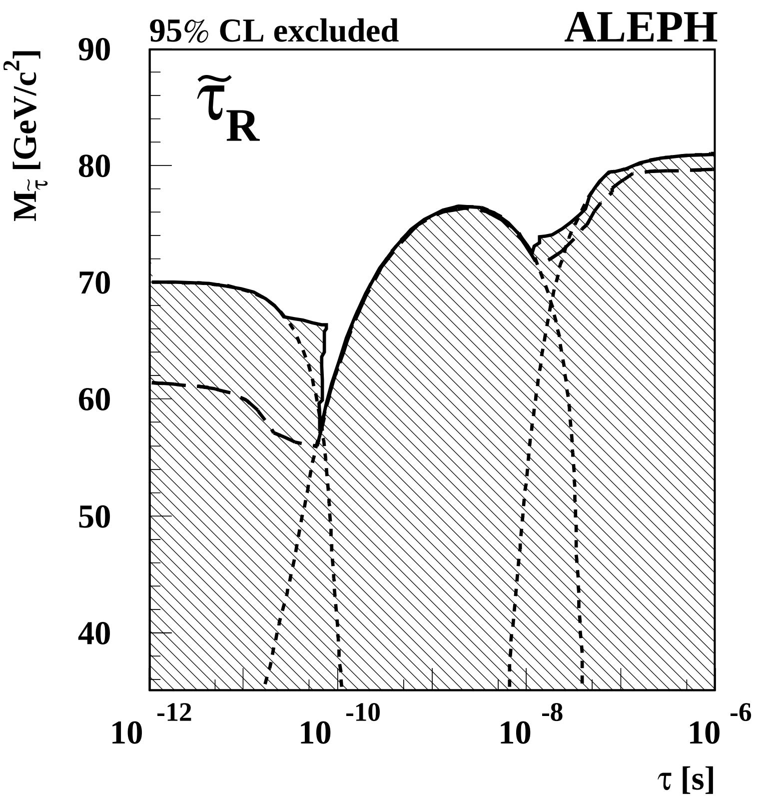

Figure 2: Lower limit on the mass of $\widetilde{\tau}_R$ as a function of its lifetime, from the ALEPH 183 GeV data [12]. The full line shows the actual mass limit obtained, while the long dashed line shows the limit expected from Monte Carlo studies. The short dashed lines indicate the limits from the three types of searches: acoplanar leptons ($\tau < 10^{-9}s$), tracks with large impact parameters and kinks ($10^{-11}s < \tau < 10^{-7}s$); and, heavily ionizing tracks ($\tau > 10^{-8}s$).

retain sensitivity: the bounds range between 75 and 90 GeV/c^2 depending on $\theta_{\widetilde{b}}$. Limits from the Tevatron reach much higher masses, but only when the neutralino is much lighter than the stop or sbottom. ALEPH has interpreted the results of their search in terms of generic squarks, excluding a rather small region not covered at the Tevatron [17].

In canonical SUSY scenarios the lightest neutralino leaves no signal in the detector. Nonetheless, the tight correspondences among the neutralino and chargino masses allow an indirect limit on $M_{\widetilde{\chi}_1^0}$ to be derived [9,11]. The key assumption is that the gaugino mass parameters M_1 and M_2 unify at the GUT scale, which leads to a definite relation between them at the electroweak scale: $M_1 = \frac{5}{3}\tan^2\theta_W M_2$. Assuming slepton masses to be at least 200 GeV/c^2, the bound on $M_{\widetilde{\chi}_1^0}$ is derived from the results of chargino and neutralino searches and certain bounds from LEP 1.

When sleptons are lighter than 120 GeV/c^2, all the effects of light sneutrinos on both the production and decay of charginos and heavier neutralinos must be taken into account. Although the bounds from charginos are weakened, useful additional constraints from slepton and higher-mass neutralino searches rule out the possibility of a massless neutralino. The current OPAL limit [8], shown in Fig. 3, is $M_{\widetilde{\chi}_1^0} > 32.8$ GeV/c^2 for $\tan\beta > 1$ and $m_0 \gtrsim 500$ GeV/c^2 (effectively, $M_{\widetilde{\nu}} > 500$ GeV/c^2). Allowing the universal scalar mass parameter m_0 to have any value, the limit is $M_{\widetilde{\chi}_1^0} > 31.6$ GeV/c^2.

The ALEPH Collaboration has explored the constraints coming from the negative results of Higgs searches [9]. These are depicted as excluded regions in the $(m_0, m_{1/2})$ plane and can be translated into bounds on $M_{\widetilde{\chi}_1^0}$; they do not, however, substantially strengthen bounds coming from less complicated analyses. This work has also been performed by the LEP SUSY Working Group [19].

If R-parity is not conserved, searches based on missing energy are not viable. The three possible RPV interaction terms ($LL\overline{E}$, $LQ\overline{D}$, $\overline{U}\,\overline{D}\,\overline{D}$) violate lepton or baryon number, consequently precisely measured SM processes constrain products of dissimilar terms. Collider searches assume only one of the many possible terms dominates; given this assumption, searches for charginos and neutralinos, sleptons and squarks have been performed. All sets of generational indices (λ_{ijk}, λ'_{ijk}, λ''_{ijk}) have been considered, allowing for both *direct* and *indirect* RPV processes. Rather exotic topologies can occur, such as six-lepton

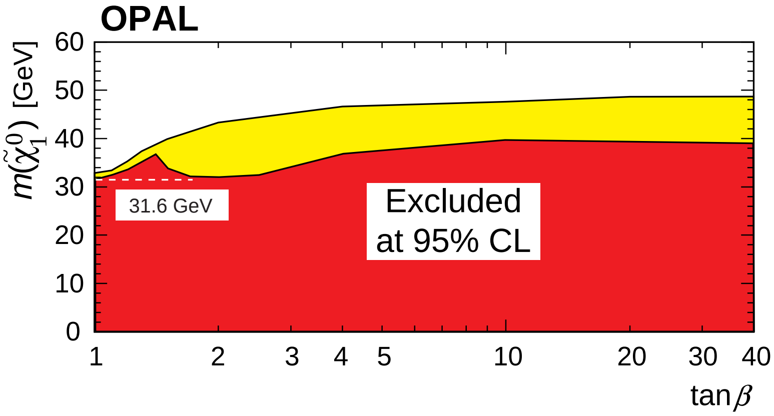

Figure 3: Lower limit on the mass of the lightest neutralino, derived by the OPAL Collaboration using constraints from chargino, neutralino, and slepton searches [8]. The light shaded region is obtained assuming $m_0 \gtrsim 500$ GeV$/c^2$; the dark region, for any m_0.

final states in slepton production with $LL\overline{E}$ dominating, or ten-jet final states in chargino production with $\overline{U}\,\overline{D}\,\overline{D}$ dominating; entirely new search criteria keyed to an excess of leptons and/or jets have been devised [20]. Searches with a wide scope have found no evidence for supersymmetry with R-parity violation, and limits are as constraining as in the canonical scenario. In fact, the direct exclusion of pair-produced $\widetilde{\chi}^0_1$'s rules out some parameter space not accessible in the canonical case.

Visible signals from the lightest neutralino are also realized in special cases of GMSB which predict $\widetilde{\chi}^0_1 \rightarrow \gamma\, \widetilde{g}_{3/2}$ with a lifetime short enough for the decay to occur inside the detector [21]. The most promising topology consists of two energetic photons and missing energy resulting from $e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$. For the DELPHI search, a technique was developed to identify photons which do not originate from the primary vertex. No excess was observed over the expected number of background events [21], leading to a bound on the neutralino mass of about 84 GeV$/c^2$. When the results are combined [22], the limit is $M_{\widetilde{\chi}_1^0} > 89$ GeV/c^2. Single-photon production has been used to constrain the process $e^+e^- \rightarrow \widetilde{g}_{3/2}\widetilde{\chi}_1^0$.

II.5. Supersymmetry searches at proton machines: Although the LEP experiments can investigate a wide range of scenarios and cover obscure corners of parameter space, they cannot match the mass reach of the Tevatron experiments (CDF and DØ). Each experiment has logged approximately 110 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV. Although the full energy is never available for annihilation, the cross sections for supersymmetric particle production are large due to color factors and the strong coupling.

The main source of signals for supersymmetry are squarks (scalar partners of quarks) and gluinos (fermionic partners of gluons), in contradistinction to LEP. Pairs of squarks or gluinos are produced in s, t and u-channel processes, which decay directly or via cascades to at least two LSP's. The number of jets depends on whether the gluino or the squark is heavier, with the latter occurring naturally in mSUGRA models. The possibility of cascade decays through charginos or heavier neutralinos also complicates the search. The u, d, s, c, and b squarks are assumed to have similar masses; the search results are reported in terms of their average mass $M_{\widetilde{q}}$ and the gluino mass $M_{\widetilde{g}}$.

The classic searches [23] rely on large missing transverse energy $\not{E}_T$ caused by the escaping neutralinos. Jets with high transverse energy are also required as evidence of a hard interaction; care is taken to distinguish genuine $\not{E}_T$ from fluctuations in the jet energy measurement. Backgrounds from W, Z and top production are reduced by rejecting events with identified leptons. Uncertainties in the rates of these processes are minimized by normalizing related samples, such as events with two jets and one or more leptons. The tails of more ordinary hard-scattering processes accompanied by multiple gluon emission are estimated directly from the data.

The bounds are derived for the $(M_{\widetilde{g}}, M_{\widetilde{q}})$ plane and have steadily improved with the integrated luminosity. If the squarks are heavier than the gluino, then $M_{\widetilde{g}} \gtrsim 180$ GeV/c^2. If they all have the same mass, then that mass is at least 260 GeV/c^2, according to the DØ analysis. If the squarks are much lighter than the gluino (in which case they decay via $\widetilde{q} \to q\widetilde{\chi}_1^0$), the bounds from UA1 and UA2 [24] play a role giving $M_{\widetilde{g}} \gtrsim 300$ GeV/c^2. All of these bounds assume there is no gluino lighter than 5 GeV/c^2.

Since these results are expressed in terms of the physical masses relevant to the production process and experimental signature, the excluded region depends primarily on the assumption of nearly equal squark masses with only a small dependence on other parameters such as μ and $\tan\beta$. Direct constraints on the theoretical parameters m_0 and $m_{1/2} \approx 0.34\, M_3$ have been obtained by the DØ Collaboration assuming the mass relations of the mSUGRA model [23]. In particular, m_0 is keyed to the squark mass and $m_{1/2}$ to the gluino mass, while for the LEP results these parameters usually relate to slepton and chargino masses.

Charginos and neutralinos may be produced directly by annihilation ($q\overline{q} \to \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^0$) or in the decays of heavier squarks ($\widetilde{q} \to q'\widetilde{\chi}_i^{\pm}$, $q\widetilde{\chi}_j^0$). They decay to energetic leptons (for example, $\widetilde{\chi}^{\pm} \to \ell\nu\widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0$) and the branching ratio can be high for some parameter choices. The presence of energetic leptons has been exploited in two ways: the 'trilepton' signature and the 'dilepton' signature.

The search for trileptons is most effective for the associated production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ [25]. The requirement of three energetic leptons reduces backgrounds to a very small level, but is efficient for the signal only in special cases. The results reported to date are not competitive with the LEP bounds.

The dilepton signal is geared more for the production of charginos in gluino and squark cascades [26]. Jets are required as expected from the rest of the decay chain; the leptons should be well separated from the jets in order to avoid backgrounds from heavy quark decays. Drell-Yan events are rejected with simple cuts on the relative azimuthal angles of the leptons and their transverse momentum. In some analyses the Majorana nature of the gluino is exploited by requiring two leptons with the same charge, thereby greatly reducing the background.

In this scenario limits on squarks and gluinos are almost as stringent as in the classic jets+ $\not\!\!E_T$ case.

It should be noted that the dilepton search complements the multijet+ $\not\!\!E_T$ search in that the acceptance for the latter is reduced when charginos and neutralinos are produced in the decay cascades—exactly the situation in which the dilepton signature is most effective.

The top squark is different from the other squarks because its SM partner is so massive: large off-diagonal terms in the squared-mass matrix lead to large mixing effects and a possible light mass eigenstate, $M_{\widetilde{t}_1} \ll M_{\widetilde{q}}$. When the parameters A, μ and $\tan\beta$ are suitably tuned, light bottom squarks can also be expected. Analyses designed to find light stops and sbottoms have been performed [27]. The first of these was based on the jets+ $\not\!\!E_T$ signature expected when the the stop is lighter than the chargino. The search was improved by employing heavy-flavor tagging, which made the selection effective for sbottoms, too. A powerful limit $M_{\widetilde{t}} \gtrsim 115$ GeV$/c^2$ was obtained for a neutralino mass around 40 GeV$/c^2$, shown in Fig. 4.

A search for the pair-production of light stops decaying to $b\widetilde{\chi}^{\pm}_1$ has been performed by DØ [27]. The presence of two energetic electrons was required; backgrounds from W's were greatly reduced. Regrettably this experimental bound does not yet improve existing bounds on stop masses.

The CDF and DØ collaborations have searched for supersymmetry in certain RPV scenarios [28]. DØ employs their search for events with two energetic electrons and jets, which is appropriate to decays $\widetilde{\chi}^0_1 \to eq\bar{q}$. Within the mSUGRA framework they sum contributions from all processes predicted as a function of m_0, $m_{1/2}$ and $\tan\beta$, thereby obtaining exclusions in parameter space. CDF uses the same-sign dielectron and jets topology to look for gluino and squark production and obtain general upper limits on cross sections. They also consider a special case of $\widetilde{g} \to c\,\widetilde{c}_L$ followed by $\widetilde{c}_L \to e\,d$, motivated by an excess of rare events reported by the HERA collaborations.

Interest in GMSB models was generated by an anomalous event observed by the CDF Collaboration [29]. These models predict large inclusive signals for $p\overline{p} \to \gamma\gamma + X$ given kinematic

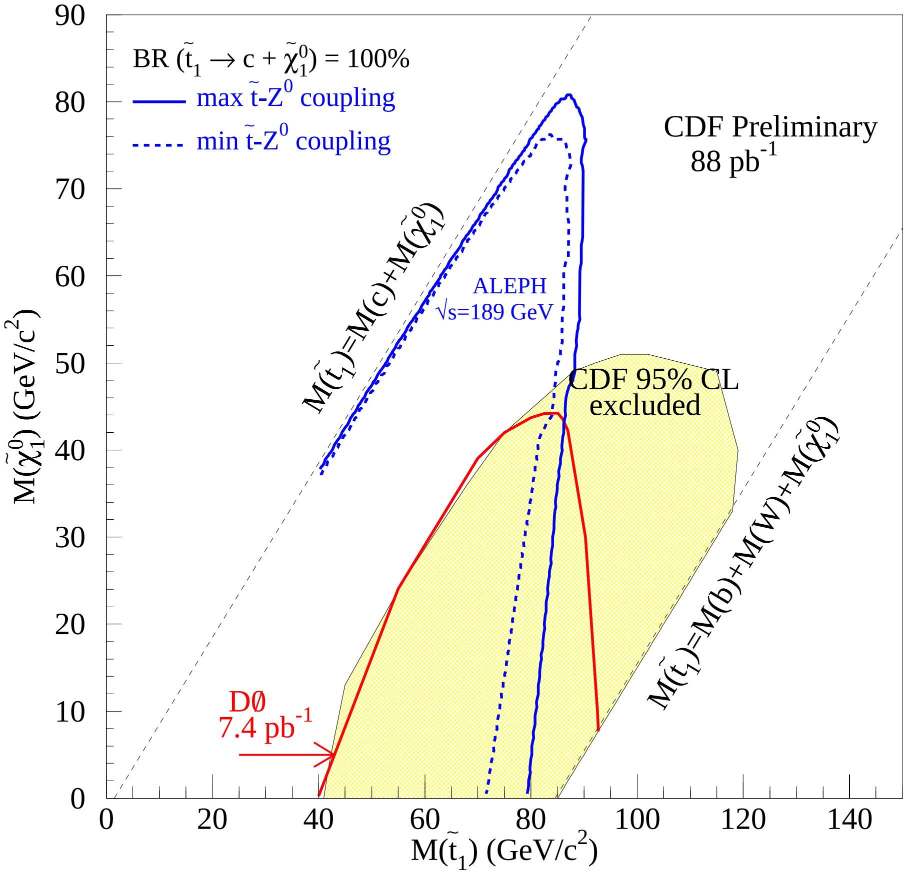

Figure 4: Excluded stop and sneutrino masses, for the $c\tilde{\chi}_1^0$ decay mode, from the CDF Collaboration [27].

constraints derived from the properties of the CDF event. DØ reported a result from events with two energetic photons and large $\not\!\!E_T$ resulting in the limit $M_{\tilde{\chi}_1^0} > 75$ GeV$/c^2$ [30]. DØ also looked specifically for squarks and gluinos in the scenario, which would give two photons and two or more jets, and obtained squark and gluino mass limits of 320 GeV$/c^2$. An analysis reported by CDF looks for virtually all thinkable topologies involving two energetic photons [30]. The neutralino mass limit is the same.

II.6. Supersymmetry searches at HERA and fixed-target experiments: The electron-proton collider (HERA) at DESY runs at a center-of-mass energy of 310 GeV and, due to its unique combination of beam types, can be used to probe certain channels effectively. Results were obtained on associated selectron-squark production with R-parity conservation [31]. An RPV search was performed assuming a dominant $LQ\overline{D}$ interaction [32]. Squarks would be produced directly in the s-channel, decaying either directly to a lepton and a quark via R-parity violation or to a pair of fermions and a chargino or neutralino, with the latter possibly decaying via R-parity violation. From less than 3 pb^{-1}, model-independent bounds on λ'_{111} were derived as a function of the squark mass. The special case of a light $\widetilde{t}_1$ was also considered, and limits derived on λ'_{131} as a function of $M_{\widetilde{t}}$.

It is difficult to conduct direct searches for light gluinos ($M_{\widetilde{g}} \lesssim 5$ GeV/c^2) at colliders because they would form light, long-lived hadrons (R^0's, a $g\widetilde{g}$ bound state) which would be difficult to identify. Certain fixed-target experiments, however, are well suited to the task. The most sensitive searches have been conducted by KTeV at Fermilab and NA48 at CERN, both designed to study very large samples of neutral kaons. KTeV looked for $R^0 \to \rho^0\tilde{\gamma}$ with $\rho^0 \to \pi^+\pi^-$ and also $R^0 \to \pi^0\tilde{\gamma}$, important below the 2π threshold [33]. NA48 searched for $R^0 \to \eta\tilde{\gamma}$ with $\eta \to 3\pi^0$ [34]. The searches required decay vertices far downstream of the target and enough missing transverse momentum to eliminate K^0_L decays. Backgrounds were estimated directly from data and fluxes measured using known K^0_L decay modes; the R^0 flux is related to the K^0_L flux theoretically. No evidence for R^0's was found, and a wide range of R^0 lifetimes was ruled out for $0.9\ \mathrm{GeV}/c^2 < M_{R^0} \lesssim 5\ \mathrm{GeV}/c^2$. These results definitively excludes the possibility of light gluinos with very light photinos (from light gluino decay) solving the cold dark matter problem.

II.7. Conclusions: A huge variety of searches for supersymmetry have been carried out at LEP, the Tevatron, and in fixed-target experiments. Despite all the effort, no signal has been found, forcing the experimenters to derive limits. We have tried to summarize the interesting cases in Table 1. At the present time there is little room for SUSY particles lighter than M_Z. The LEP collaborations will analyze more data taken at a center-of-mass energy of 200 GeV, and the Tevatron collaborations will begin a high luminosity run towards the end of the year 2000. If still no sign of supersymmetry appears, definitive tests will be made at the LHC.

Table 1: Lower limits on supersymmetric particle masses. ‘GMSB’ refers to models with gauge-mediated supersymmetry breaking, and ‘RPV’ refers to models allowing R-parity violation.

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^\pm$	gaugino	$M_{\widetilde{\nu}} > 500$ GeV/c^2	94	LEP 2
		$M_{\widetilde{\nu}} > M_{\widetilde{\chi}^\pm}$	75	LEP 2
		any $M_{\widetilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1$ TeV/c^2	89	LEP 2
	GMSB		150	DØ isolated photons
	RPV	$LL\overline{E}$ worst case	87	LEP 2
		$LQ\overline{D}$ $m_0 > 500$ GeV/c^2	88	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 500$ GeV/c^2	33	LEP 2
		any $\tan\beta$, any m_0	32	LEP 2
	GMSB		83	DØ and LEP 2
	RPV	$LL\overline{E}$ worst case	23	LEP 2
$\widetilde{e}_R$	$e\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	89	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	84	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20$ GeV/c^2	71	LEP 2
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	71	LEP 2 combined
$\widetilde{t}_1$	$c\widetilde{\chi}_1^0$	any $\theta_{\rm mix}$, $\Delta M > 10$ GeV/c^2	87	LEP 2 combined
		any $\theta_{\rm mix}$, $M_{\widetilde{\chi}_1^0} < \frac{1}{2} M_{\widetilde{t}}$	88	DØ
	$b\ell\widetilde{\nu}$	any $\theta_{\rm mix}$, $\Delta M > 7$ GeV/c^2	90	LEP 2 combined
$\widetilde{g}$	any $M_{\widetilde{q}}$		190	DØ jets+$\not\!\!E_T$
			180	CDF dileptons
$\widetilde{q}$	$M_{\widetilde{q}} = M_{\widetilde{g}}$		260	DØ jets+$\not\!\!E_T$
			230	CDF dileptons

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