SUPERSYMMETRY, PART II (EXPERIMENT)

(by M. Schmitt)

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.

In order to keep this review as current as possible, the most recent results have been used, including selected preliminary results reported at the High Energy Conference of the European Physical Society, held in Jerusalem during August 1997.

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. Conservation of R-parity is assumed, so the LSP's do not decay and escape detection, causing an apparent transverse momentum imbalance, $p_T^{\rm miss}$ (also referred to as missing transverse energy, $\not\!\!E_T$), and missing energy, $E^{\rm miss}$. There are always two LSP's per event. The searches demand significant $p_T^{\rm miss}$ as the main discriminant against Standard Model (SM) processes; 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 excess leptons or hadronic jets, and in many cases it is relatively easy to suppress SM backgrounds [3]. In this scenario 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. For the most part 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 very light ($M_{\widetilde{g}} < 5$ GeV/c^2) [5]. It is a color-octet fermion which can saturate the decays of charginos and neutralinos. In this scenario the decay of the gluino to the lightest neutralino is kinematically suppressed, so long-lived supersymmetric hadrons ($\widetilde{g} + g$ bound states called R^0's) are formed [6]. These will produce hadronic showers in the calorimeters, thus spoiling the canonical missing-energy signature on which most SUSY searches rely. The exclusion of a light gluino is not settled (see the Listings), however, given recent experimental and theoretical developments, this issue may well be settled in the near future.

II.3. Experimental issues: Before describing the results of the searches, a few words about the issues facing the experimenters 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 theoretical assumptions which are highly specific, 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 recently. 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 expected backgrounds b, and the acceptance ϵ for a given signal. The upper limit on the number of signal events for a given confidence level $N^{\rm upper}$ is computed from N and b (see review of Statistics). The experimental bound is simply

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

This information is nearly always reported, but some care is needed to understand how the acceptance was estimated, since it is often sensitive to assumptions about masses and branching ratios. Also, in the more complicated analyses, $N^{\rm upper}$ 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 $N^{\rm upper}/\mathcal{L}$ 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.

Judgement 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 center-of-mass energy of the large electron-positron collider (LEP) at CERN has been raised well above the Z peak in recent years. After collecting approximately 150 pb^{-1} at LEP 1, each experiment (ALEPH, DELPHI, L3, OPAL) has accumulated the first data at LEP 2: about 5.7 pb^{-1} at $\sqrt{s} \sim 133$ GeV (1995) [7], 10 pb^{-1} at 161 GeV and 11 pb^{-1} at 172 GeV (1996). This review emphasizes the most recent LEP 2 results.

At LEP experiments and SLD at SLAC excluded 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 the SM expectations, and depend less on the details of the SUSY particle decays than do the results of direct searches [8]. The new 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 usually decay directly to SM particles and LSP's, so signatures commonly 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 $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ 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, $p_T^{\rm miss}$ is low. Second, there is difermion production, usually accompanied by a 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 $E^{\rm miss}$ and $p_T^{\rm miss}$ due to neutrinos and electrons lost down the beam pipe.

In the canonical case, $E^{\rm miss}$ and $p_T^{\rm miss}$ 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 ($M_{\rm miss} = \{(\sqrt{s} - E_{\rm vis})^2 - \vec{p}^{\,2}_{\rm vis}\}^{1/2}$) which is small if $p_T^{\rm miss}$ 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 80 GeV/c^2 is difficult to distinguish from the production of W^+W^- pairs.

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 86 GeV/c^2 [9] except in cases of low acceptance ($\Delta M = M_{\widetilde{\chi}^\pm} - M_{\widetilde{\chi}^0_1} \lesssim 5$ GeV/c^2) or low cross section ($M_{\widetilde{\nu}_e} \lesssim M_W$). When $|\mu| \ll M_2$, the Higgsino components are large for charginos and neutralinos. In this case the associated production of neutralino pairs $\widetilde{\chi}^0_1\widetilde{\chi}^0_2$ is large and the problem of small mass differences ($M_{\widetilde{\chi}^0_2} - M_{\widetilde{\chi}^0_1}$) less severe. Experimental sensitivity now extends down to mass differences of 4 GeV/c^2, corresponding to M_2 well above 1 TeV/c^2. The strong variation of the efficiency with ΔM makes it difficult to derive absolute bounds on the masses of charginos and neutralinos. The problem of low cross sections will be less severe after higher integrated luminosities have been delivered.

The limits from chargino and neutralino production are most often used to constrain M_2 and μ for fixed $\tan\beta$. An example from the OPAL Collaboration is shown in Fig. 1, where excluded regions in the (μ, M_2) plane are shown for $\tan\beta = 1.5$ and 35 for $\sqrt{s} = 172$ GeV. The case of heavy sneutrinos is illustrated by the plots with $m_0 = 1$ TeV/c^2. The plots also provide a gluino mass scale, valid assuming gaugino mass unification, which implies that the mass of gluinos hypothetically produced in proton machines is proportional to the mass of charginos with a large gaugino component.

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 $\mu \sim -70$ GeV/c^2 and $\tan\beta < 2$, 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. The erosion in the bounds when sneutrinos are light is illustrated clearly by the so-called 'minimal m_0' case (Fig. 1). Here m_0 is a universal mass for sleptons and sneutrinos at the GUT scale; for this analysis the smallest value of m_0 consistent with OPAL slepton limits has been taken.

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 [10]. An example of this is shown in Fig. 2, from the ALEPH Collaboration. Since the chargino cross-section and field content varies with μ, two values were tested: in both cases the corridor $M_{\widetilde{\chi}^\pm} \lesssim M_{\widetilde{\nu}}$ persists, and strictly speaking the lower limit on $M_{\widetilde{\chi}^\pm}$ is the one from LEP 1. Searches for charged sleptons can be used to cover this corridor, as shown in the figure, but this coverage is effective only for low $\tan\beta$. The searches for neutralinos alleviate the problem in some regions of parameter space, but they cannot close the corridor.

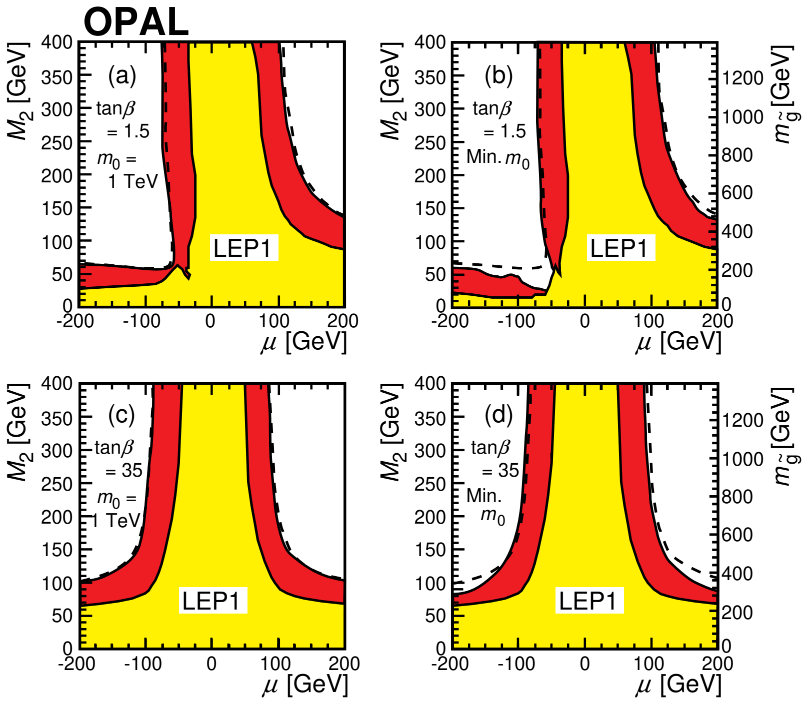

Figure 1: Regions in the (μ, M_2) plane excluded by chargino and neutralino searches performed by the OPAL Collaboration, for two values of $\tan\beta$ [9]. The light shaded region shows the limits derived from the Z width, while the dark region shows the additional exclusion obtained by the direct searches at LEP 2. The dashed line shows the kinematic bound for charginos; exclusions beyond this come from the searches for neutralinos. m_0 is the universal mass parameter for sleptons and sneutrinos, so when $m_0 = 1$ TeV$/c^2$ the sneutrino is very heavy and cross sections are as large as possible. The curves labeled 'minimal m_0' give an indication of how much the exclusions weaken when light sneutrinos are considered. The gluino scale is shown for comparison to Tevatron results; it is valid assuming the unification of gaugino masses.

The limits on slepton masses [11] are well below the kinematic limit due to a strong p-wave phase space suppression

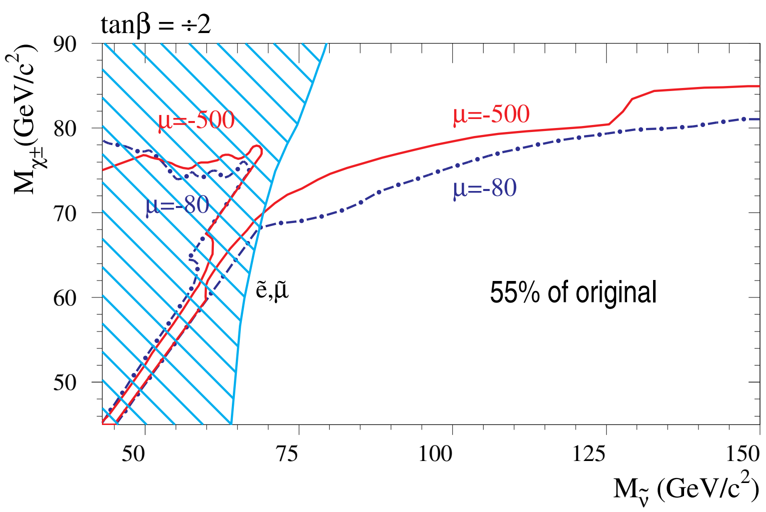

Figure 2: Limit on a gaugino-like chargino as a function of the sneutrino mass, from the ALEPH Collaboration [9]. The open corridor $0 < M_{\tilde{\chi}^{\pm}} - M_{\tilde{\nu}} \lesssim 3$ GeV$/c^2$ i s evident. $\tan\beta = \sqrt{2}$ is fixed and two values of μ are shown. The hatched region is excluded by slepton searches, but at higher $\tan\beta$ this exclusion is much weaker.

near threshold. A variety of limits have been derived, considering right-sleptons only (which is conservative), or degenerate right/left-sleptons (which is optimistic), or relying on a universal slepton mass m_0 (which is model-dependent). For individual experiments, the limits on selectrons reach 80 GeV$/c^2$ due to contributions from t-channel neutralino exchange; they depend slightly on μ and $\tan\beta$. For the extreme case $M_{\tilde{\chi}_1^0} \to 0$, the AMY Collaboration at TRISTAN obtained a result which reaches 79 GeV$/c^2$ for degenerate selectrons at 90% CL [12]. Limits on smuons reach approximately 60 GeV$/c^2$, and staus, 55 GeV$/c^2$. For selectrons and smuons the dependence on $\Delta M = M_{\tilde{\ell}} - M_{\tilde{\chi}_1^0}$ is weak for $\Delta M \gtrsim 10$ GeV$/c^2$ unless parameters are chosen which lead to a large branching ratio for $\widetilde{\ell}_R \to \ell\widetilde{\chi}^0_2$, possible when $M_{\widetilde{\chi}^0_1}$ is very small. Preliminary results from the combination of the four LEP experiments have been derived, leading to significantly stronger bounds [13]: $M_{\widetilde{e}_R} > 80\ \mathrm{GeV}/c^2$ and $M_{\widetilde{\mu}_R} > 74\ \mathrm{GeV}/c^2$ for $M_{\widetilde{\chi}^0_1} = 45\ \mathrm{GeV}/c^2$. Bounds on the parameters M_2 and m_0 also have been derived.

In some GMSB models, sleptons may decay to $\ell^\pm \widetilde{g}_{3/2}$ outside the detector, so the experimental signature is a pair of colinear, heavily ionizing tracks. Searches for such events [14] have placed mass limits of 66 GeV/c^2 (combined: 68 GeV/c^2 [13]) for $\widetilde{\mu}_R$ and $\widetilde{\tau}_R$.

Limits on stop and sbottom masses [15], like the slepton mass limits, do not extend to the kinematic limit. The stop decay $\widetilde{t}_1 \to c\widetilde{\chi}^0_1$ 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 very small ΔM is possible due to the visibility of the decay products of the c and b quarks. Limits vary from 75 GeV/c^2 for an unrealistic pure $\widetilde{t}_L$ state to 60 GeV/c^2 if the coupling of $\widetilde{t}_1$ to the Z vanishes. The DELPHI result is shown in Fig. 3 as an example. The combination of results from all four experiments, shown in Fig. 4, is significantly stronger: for example, $M_{\widetilde{t}} > 75\ \mathrm{GeV}/c^2$ is obtained for $\Delta M > 10\ \mathrm{GeV}/c^2$ and *any* mixing [13]. Limits on sbottoms are weaker due to their smaller electric charge.

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 $M_{\widetilde{\chi}^0_1}$ to be derived [9,10]. 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 $M_{\widetilde{\chi}^0_1}$ is derived from the results of chargino and neutralino searches and certain bounds from LEP 1, as illustrated in Fig. 5, from DELPHI. The

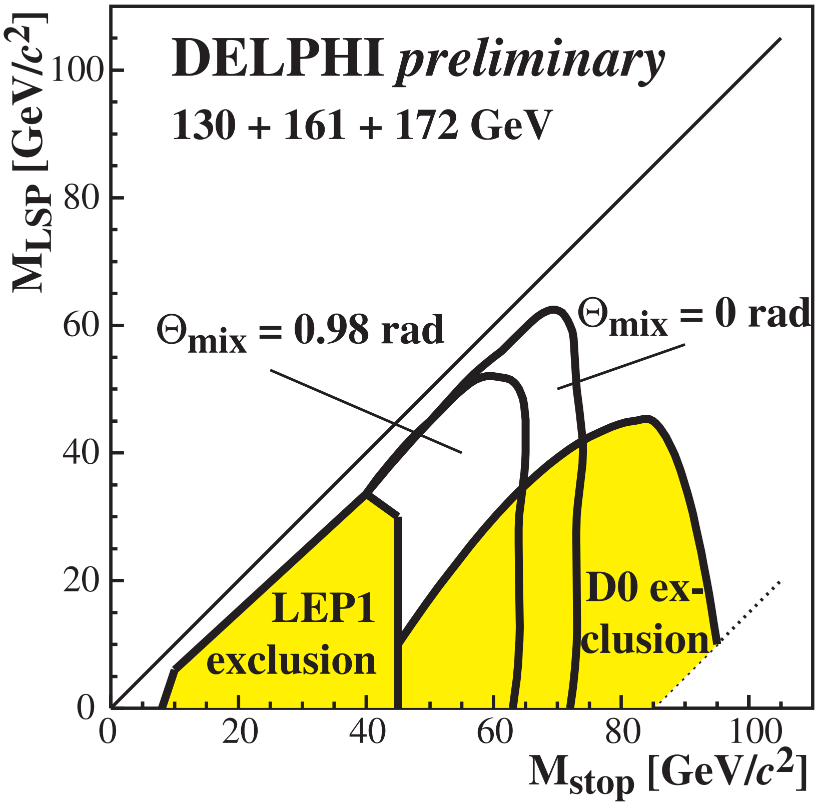

Figure 3: Ranges of excluded stop and neutralino masses reported by the DELPHI Collaboration [15]. Two values of mixing angle are shown: $\theta_{\rm mix} = 0$ gives pure $\widetilde{t}_L$ and $\theta_{\rm mix} = 0.98$ rad gives a stop with no coupling to the Z. The range excluded by DØ is also shown.

various contours change as $\tan\beta$ is increased, with the result that the lower limit on $M_{\widetilde{\chi}^0_1}$ increases also.

When sleptons are lighter than 80 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 substantially, useful additional constraints from the slepton searches rule out the possibility of a massless neutralino. The current *preliminary* limit, shown in Fig. 6, is $M_{\widetilde{\chi}^0_1} > 25$ GeV$/c^2$ for $\tan\beta > 1$ and $M_{\widetilde{\nu}} > 200$ GeV$/c^2$ (effectively, $m_0 \gtrsim 200$ GeV$/c^2$). Allowing

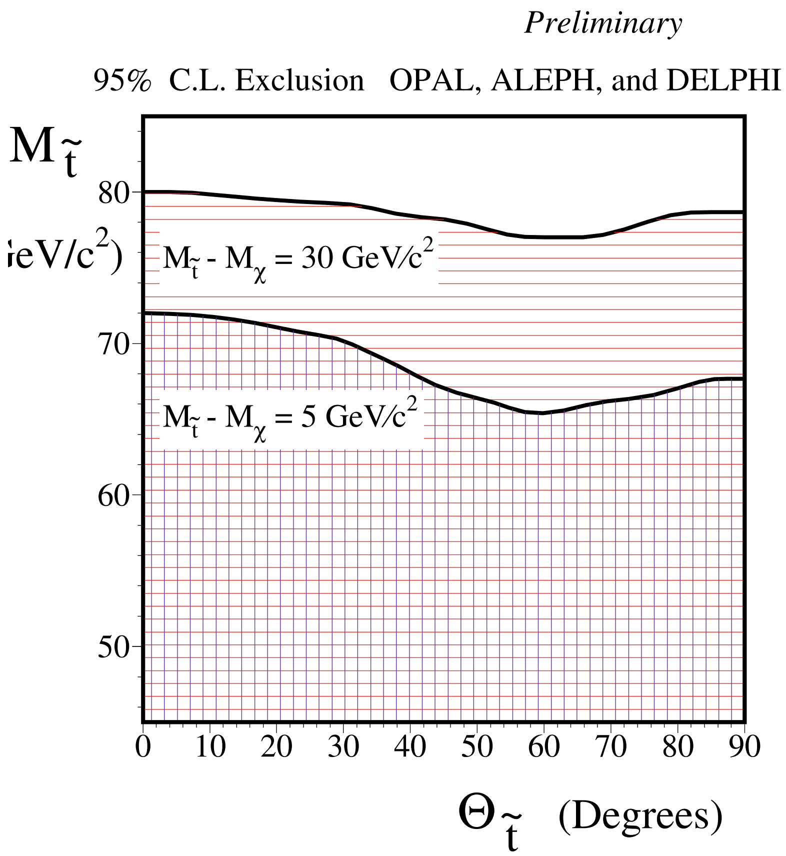

Figure 4: Lower bound on the stop mass as a function of the mixing angle for two values of $\Delta M = M_{\tilde{t}} - M_{\tilde{\chi}_1^0}$, derived from the combined results of the LEP experiments. These results are preliminary [13].

the universal slepton mass m_0 to have any value, the limit is $M_{\tilde{\chi}_1^0} > 14$ GeV$/c^2$ [10]. These bounds can be evaded by dropping gaugino mass unification or R-parity conservation, or by assuming the gluino is very light.

If R-parity is not conserved, the lightest neutralino decays to SM particles and is visible inside the detector. Searches for supersymmetry with R-parity violation [16] usually assume that one of three possible interaction terms ($LL\overline{E}$, $LQ\overline{D}$, $\overline{U}\,\overline{D}\,\overline{D}$) dominates. The relevant term can cause R-parity violation *directly* in the decay of the produced particle, or it can be

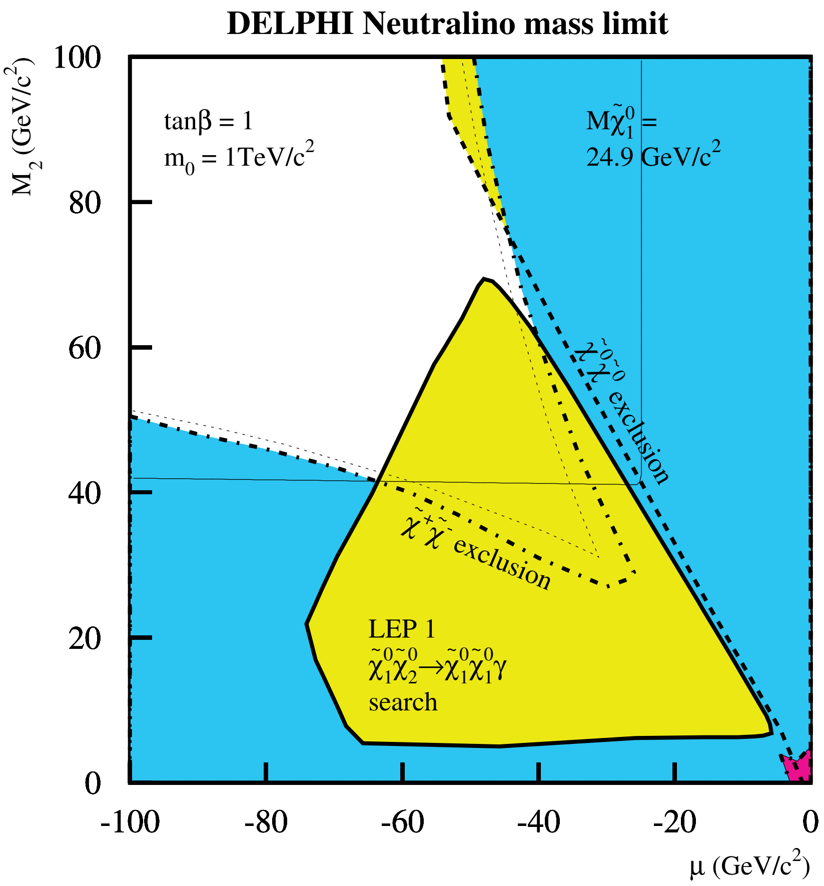

Figure 5: Excluded regions in the (μ, M_2) plane obtained by the DELPHI Collaboration, for $\tan\beta = 1$ and $m_0 = 1$ TeV/c^2 [9]. (This very high value for m_0 is tantamount to setting all slepton masses to 1 TeV/c^2.) The combination of LEP 2 chargino search (dot-dash line) and the neutralino search (dashed line) with the single-photon limits from LEP 1 (thick solid line) give the limit on $M_{\tilde{\chi}_1^0}$. The thin solid line shows the values of μ and M_2 giving $M_{\tilde{\chi}_1^0} = 24.9$ GeV/c^2, and the dotted line gives the kinematic limit for charginos at $\sqrt{s} = 172$ GeV.

manifested *indirectly* in the decay of the LSP, which need no longer be neutral or colorless. Rather exotic topologies can occur, such as six-lepton final states in slepton production with

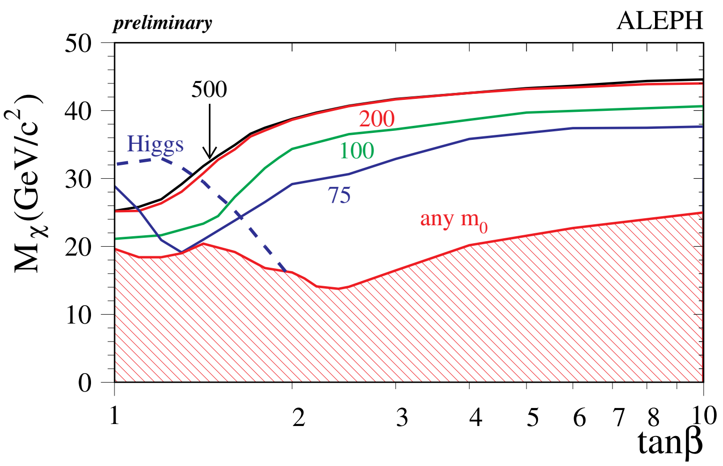

Figure 6: Lower limit on the mass of the lightest neutralino, derived by the ALEPH Collaboration using constraints from chargino, neutralino, and slepton searches [10]. The values $500, \ldots, 75$ show the bound obtained when fixing the universal scalar mass and taking slepton bounds into account; including also limits from Higgs for $m_0 = 75$ GeV/c^2 gives the dashed line. Allowing m_0 to vary freely independently of $\tan\beta$ gives the curve labelled 'any m_0.'

$LL\overline{E}$ dominating, or ten-jet final states in chargino production with $\overline{U}\,\overline{D}\,\overline{D}$ dominating; and, for the most part, entirely new search criteria keyed to an excess of leptons and/or jets must be devised. Although not all possibilities have been tested yet, searches with a wide scope have found no evidence for supersymmetry with R-parity violation, and limits are usually 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.

R-parity violation can lead to new production processes, such as s-channel sneutrino production, which also are being investigated [17].

Visible signals from the lightest neutralino are also realized in special cases of GMSB which predict $\widetilde{\chi}^0_1 \to \gamma\,\widetilde{g}_{3/2}$ with a lifetime short enough for the decay to occur inside the detector. The most promising topology consists of two energetic photons and missing energy resulting from $e^+e^- \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$. (In the canonical scenario, such events also would appear for $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_2^0$ followed by $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ which can be expected in certain regions of parameter space.) The LEP experiments have observed no excess over the expected number of background events [18], leading to a bound on the neutralino mass of about 70 GeV/c^2. As an example, the L3 upper limit on the number of signal events is plotted as a function of neutralino mass in Fig. 7. When the results are combined [13], the limit is $M_{\widetilde{\chi}_1^0} > 75$ GeV/c^2. Single-photon production has been used to constrain the process $e^+e^- \to \widetilde{g}_{3/2}\widetilde{\chi}_1^0$.

At the time of this writing, LEP was colliding beams at $\sqrt{s} = 183$ GeV. No signals for supersymmetry were reported in conferences; rather, preliminary limits $M_{\widetilde{\chi}^\pm} \gtrsim 91$ GeV/c^2 were shown [19]. In coming years the center of mass energy will be increased in steps up to a maximum of 200 GeV.

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—ten times the energy of LEP 2. 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 key distinction in the experimental signature is whether the gluino is heavier or lighter than the squarks, with the latter occurring naturally in mSUGRA models. 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 $M_{\widetilde{g}}$.

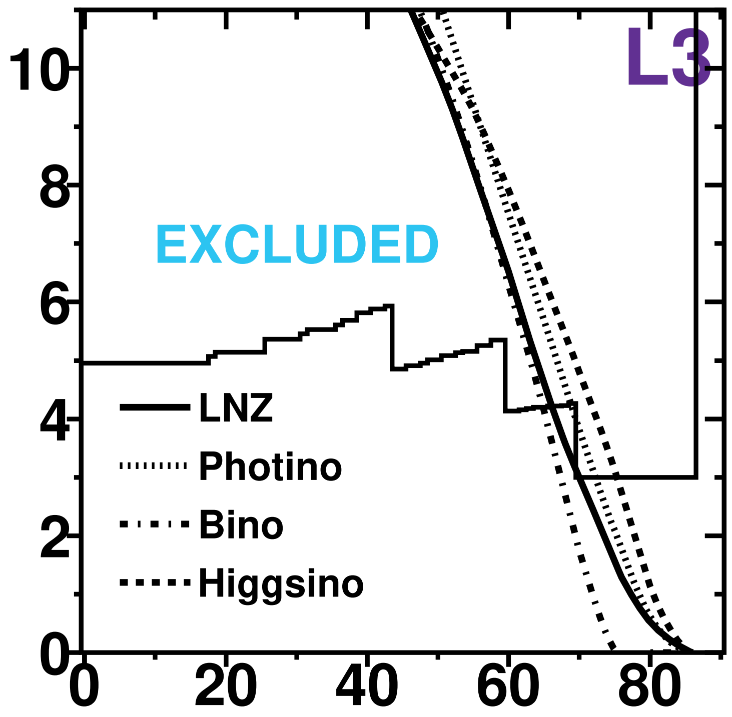

Figure 7: Upper limit on the number of acoplanar photon events as a function of the neutralino mass, from the L3 Collaboration [18]. The theoretical cross section depends on the field content of the neutralino, shown here for pure photinos, binos, and Higgsinos. 'LNZ' refers to a particular model [4].

The classic searches [20] 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 displayed in the $(M_{\widetilde{g}}, M_{\widetilde{q}})$ plane and have steadily improved with the integrated luminosity. The latest result from the CDF Collaboration is shown in Fig. 8, which also shows a recent result from DØ. 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 gluin (in which case they decay via $\widetilde{q} \to q\widetilde{\chi}_1^0$), the bounds from UA1 and UA2 [21] 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.

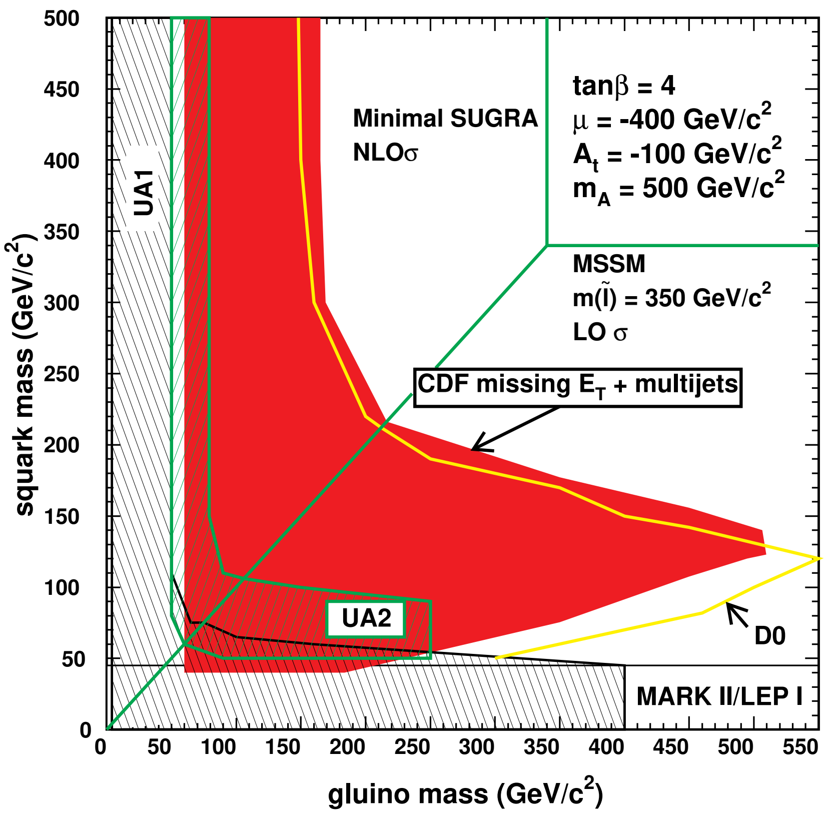

Figure 8: Excluded ranges of squark and gluino masses, derived from the jets+ $\not{E}_T$ analysis of the CDF Collaboration [20]. Also shown are recent results from DØ, and much older limits from the CERN proton experiments UA1 and UA2.

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 $m_{1/2} \approx 0.34\,M_3$, shown in Fig. 9, have been obtained by the DØ Collaboration assuming the mass relations of the mSUGRA model. 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 ($q\overline{q} \rightarrow \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^0$) or in the decays of heavier squarks ($\widetilde{q} \rightarrow q'\widetilde{\chi}_i^{\pm}$, $q\widetilde{\chi}_j^0$). They decay to energetic leptons (for example, $\widetilde{\chi}^{\pm} \rightarrow \ell\nu\widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0 \rightarrow \ell^+\ell^-\widetilde{\chi}_1^0$) 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 $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ [22]. 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 [23]. 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

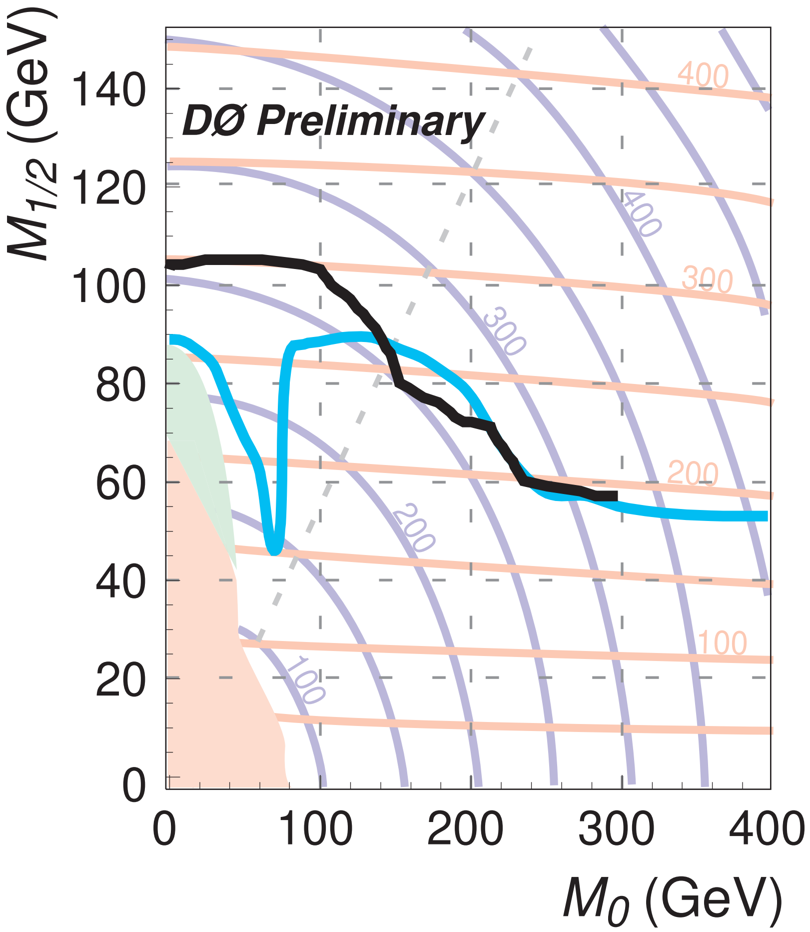

Figure 9: Bounds in the $(m_0, m_{1/2})$ plane obtained by the DØ Collaboration from their searches for squarks and gluinos [20]. The dark solid line shows the result from the jets+ $\not\!\!E_T$ selection, and the grey solid line shows the result from the dielectron selection. The radial contours give the squark mass in this plane, and the nearly horizontal lines give the gluino mass. Parameter values in the shaded region lead to unphysical conditions.

decay cascades—exactly the situation in which the dilepton signature is most effective.

A loophole in the squark-gluino bounds has recently been addressed using dijet mass distributions [24]. If gluinos are lighter than about 5 GeV/c^2, $\not\!\!E_T$ is very small and the classic jets+ $\not\!\!E_T$ searches are no longer effective. Resonant production of squarks would have a large cross section, however, and if the squarks are not very heavy, broad peaks in the dijet mass distributions are expected. Comparison of the observed spectrum with theoretical estimates rules out light gluinos if squarks are lighter than about 600 GeV/c^2.

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, $M_{\widetilde{t}_1} \ll M_{\widetilde{q}}$. Analyses designed to find light stops have been performed by DØ [25]. The first of these was based on the jets+ $\not\!\!E_T$ signature expected when the the stop is lighter than the chargino. A powerful limit $M_{\widetilde{t}} \gtrsim 90$ GeV/c^2 was obtained, provided the neutralino was at least 30 GeV/c^2 lighter than the stop as depicted in Fig. 3. (These searches are sensitive to the $c\widetilde{\chi}_1^0$ channel which does not apply below the dotted line.) More recently a search for the pair-production of light stops decaying to $b\widetilde{\chi}_1^\pm$ was performed. 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.

An anomalous event observed by the CDF Collaboration [26] sparked much theoretical speculation [27]. It contains two energetic electrons, two energetic photons, large $\not\!\!E_T$, and little else. Since it is difficult to explain this event with SM processes, theorists have turned to SUSY. While some models are based on canonical MSSM scenarios (without gaugino mass unification), others are based on GMSB models with selectron production followed by $\widetilde{e} \to e\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^0 \to \gamma\,\widetilde{g}_{3/2}$. These models predict large inclusive signals for $p\overline{p} \to \gamma\gamma + X$ given kinematic constraints derived from the properties of the CDF event. The Tevatron experiments have looked for such events, and have found none [28], aside from the one anomalous event. These results have been translated into the bound $M_{\widetilde{\chi}_1^0} > 75$ GeV/c^2, as shown in Fig. 10 from the DØ Collaboration. This bound is as good as that derived from the combination of the four LEP experiments.

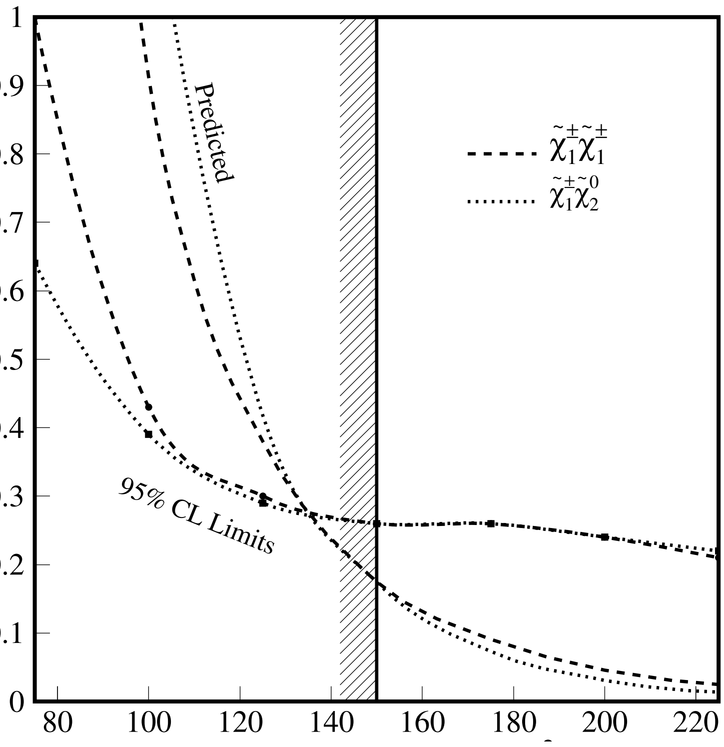

Figure 10: Comparison of the DØ upper limits on chargino and neutralino cross sections with theory in a GMSB scenario, plotted as a function of the chargino mass [28]. The vertical line shows the result obtained from the combined chargino and neutralino exclusions. It corresponds to $M_{\widetilde{\chi}_1^0} \gtrsim 75$ GeV/c^2.

II.6. Supersymmetry searches at HERA and fixed-target experiments: The electron-proton collider (HERA) at DESY runs at $\sqrt{s} = 310$ GeV and, due to its unique beam types, can be used to probe certain channels more effectively than LEP or the Tevatron.

The first of these is associated selectron-squark production [29] through t-channel neutralino exchange. Assuming the conservation of R-parity, the signal consists of an energetic isolated electron, a jet, and missing transverse momentum. No signal was observed in 20 pb^{-1} of data and limits were placed on the sum $\frac{1}{2}(M_{\widetilde{e}} + M_{\widetilde{q}})$. They are weaker than the latest ones from LEP.

A more interesting opportunity comes in SUSY models with R-parity violation, in particular, with a dominant $LQ\overline{D}$ interaction [30]. 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. Less than 3 pb^{-1} were used to look for a squark resonance above SM backgrounds. All possible topologies were considered, so model-independent bounds on the R-parity–violating parameter λ'_{111} could be 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 $M_{\widetilde{t}}$. These were improved by considering also the pair-production of stops via photon-gluon fusion (see the Listings for more information).

Limits from SUSY searches in fixed-target or beam-dump experiments were surpassed long ago by the colliders. An important exception is the search for the light gluino, materializing as a long-lived supersymmetric hadron called the R^0 [6]. These could be produced in fixed-target experiments with hadron beams and observed via their decay in flight to a low mass hadronic state: $R^0 \to \pi^+\pi^-\widetilde{\chi}^0_1$ or $\eta\widetilde{\chi}^0_1$. The KTeV Collaboration at Fermilab have searched for R^0's in their neutral-kaon data and found no evidence for this particle in the $\pi^+\pi^-\widetilde{\chi}^0_1$ channel, deriving strong limits on its mass and lifetime [31], as shown in Fig. 11. A complementary search for supersymmetric baryons was performed by the E761 Collaboration with a charged hyperon beam [32].

II.7. Conclusions: A huge variety of searches for supersymmetry have been carried out at LEP, the Tevatron, and HERA. 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_W. The LEP collaborations will analyze more data taken at higher energies, and the Tevatron collaborations will begin a high luminosity run in

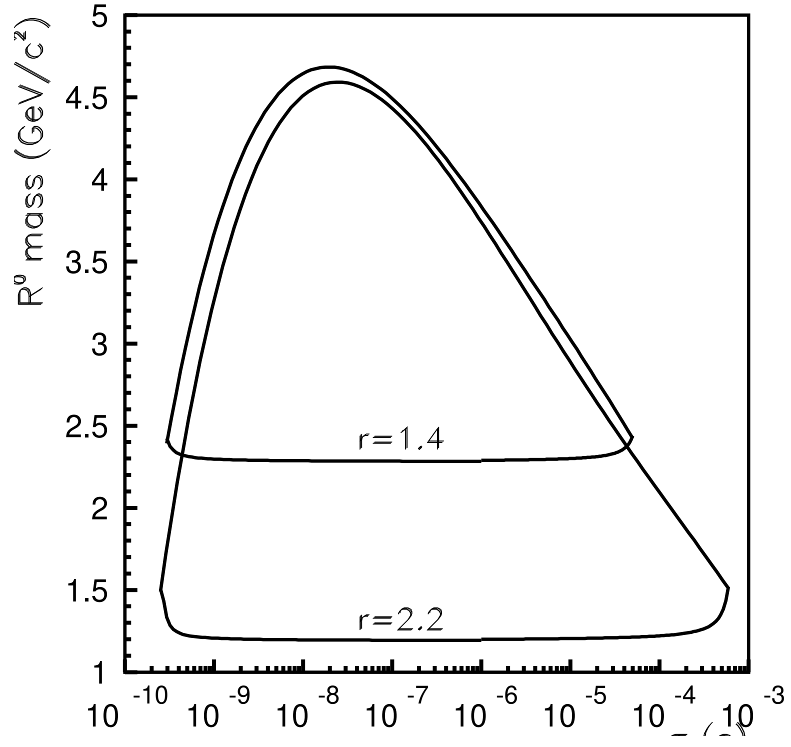

Figure 11: Ranges of R^0 mass and lifetime excluded at 90% CL by the KTeV Collaboration [31]. The ratio of the R^0 to the $\widetilde{\chi}_1^0$ mass is r.

a couple of years. If still no sign of supersymmetry appears, definitive tests will be made at the LHC.

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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	$M_{\widetilde{\nu}} > 200$ GeV/c^2	86	LEP 2
		$M_{\widetilde{\nu}} > M_{\widetilde{\chi}^{\pm}}$	67	LEP 2
		any $M_{\widetilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1$ TeV/c^2	79	LEP 2
	GMSB		150	DØ isolated photons
	RPV	$LL\overline{E}$ worst case	73	LEP 2
		$LQ\overline{D}$ $m_0 > 500$ GeV/c^2	83	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 200$ GeV/c^2	25	LEP 2
		any $\tan\beta$, any m_0	14	LEP 2
	GMSB		75	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	75	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	75	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20$ GeV/c^2	53	LEP 2
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	76	LEP 2 combined
$\widetilde{t}_1$	$c\widetilde{\chi}_1^0$	any $\theta_{\rm mix}$, $\Delta M > 10$ GeV/c^2	70	LEP 2 combined
		any $\theta_{\rm mix}$, $M_{\widetilde{\chi}_1^0} < \frac{1}{2} M_{\widetilde{t}}$	86	DØ
	$b\ell\widetilde{\nu}$	any $\theta_{\rm mix}$, $\Delta M > 7$ GeV/c^2	64	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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