# 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. Many of these have been based on the canonical missing-energy signature caused by the escape of weakly-interacting LSP's ('lightest supersymmetric particles'). Other scenarios have also been investigated, widening the range of topologies and experimental signatures in which new physics might be found.

Unfortunately, no convincing evidence for the production of supersymmetric particles has been found. This review concentrates on the searches performed at LEP and the Tevatron. Some special opportunities exploited at HERA and by certain fixed-target experiments have been discussed in the 2000 edition of this Review.

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. It follows that there are always at least two LSP's per event. If $R$-parity, a hypothetical quantum number which distinguishes between SM and SUSY particles, is conserved, the LSP is stable. For most typical choices of model parameters, the lightest neutralino is the LSP. Since the neutralino is neutral and colorless, interacting only weakly with matter, it will escape detection, giving signal events the characteristic appearance of "missing energy." In $e^+e^-$ machines, the total visible energy and total visible momentum can be well measured. Since the electron beam energy has a very small spread, the missing energy ($E^{\rm miss} = \sqrt{s} - E^{\rm vis}$) and the missing momentum ($\vec{p}^{\,\rm miss} = -\vec{p}^{\,\rm vis}$) are well correlated with the net energy and momentum of the LSP's. In proton colliders, the distribution of the energy and longitudinal momentum of the partons (quarks and gluinos inside the (anti-)protons) is very broad, so in practice only the transverse momentum is useful. It is calculated from the vector sum of energy registered in the calorimetry and is called "missing transverse energy" ($\not\!\!E_T$). Collimated jets, isolated leptons or photons, and appropriate kinematic and topological cuts provide additional handles for reducing 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). For the most part, the production of superpartners is unchanged, but 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. The pair-production of LSP's, which need not be electrically neutral or free of color charge, is a significant SUSY signal.

In models assuming gauge-mediated supersymmetry breaking (GMSB) [4], the gravitino, $\widetilde{G}$, 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, $\widetilde{\chi}_1^0$, 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 neutralino lifetime is not too long, the event topologies are augmented by the presence of energetic and isolated photons. If the 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 have covered this mass range definitively. Strong indirect exclusion of light gluinos was obtained by a study of jet angular correlations in $Z$ decays [7].

***II.3. Experimental issues:*** When given no signal for supersymmetric particles, experimenters are obliged 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. 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 can all be used together to constrain the parameter space. A very similar model is called the 'constrained MSSM' (cMSSM) (see [8] for a discussion).

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. It has been possible in some instances to reduce the model-dependence of experimental results by combining several searches. When model-independent results are impossible, the underlying assumptions and their consequences are (or should be) carefully delineated.

In the analysis of data from hadron collider experiments, the experimenter considers several supersymmetric processes simultaneously. In contrast to experiments at $e^+e^-$ colliders, it does not makes sense to talk about one process at a time due to the very broad mass range spanned. This makes the appeal to some sort of organizing device, such as a constrained version of the MSSM, practically unavoidable.

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 ran at energies ranging from the $Z$ peak to $\sqrt{s} = 209$ GeV/$c^2$. Each experiment (ALEPH, DELPHI, L3, OPAL) accumulated large data sets at a series of energies, as detailed in [9]. For the limits discussed here, the most relevant data samples include 180 pb$^{-1}$ at 189 GeV/$c^2$, and 220 pb$^{-1}$ at higher energies, of which 140 pb$^{-1}$ was delivered above 206 GeV/$c^2$. While data taking has ceased, some searches at the highest energies are not yet finalized, and time will be required to complete the combination of results by the LEP SUSY working group [9].

Running at the $Z$ pole, the LEP experiments and SLD at SLAC excluded essentially all supersymmetric particles up to about half the $Z$ mass. These limits come mainly from the comparison of the measured $Z$ widths to SM expectations, and are insensitive to the details of SUSY particle decays [10]. The data taken at higher energies allow much stronger limits to be set, although the complex interplay of masses, cross sections, and branching ratios allow for a few exceptions to simple general limits.

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.

The various SUSY particles considered at LEP typically 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 $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ production, and acoplanar leptons for both $\widetilde{\ell}^+\widetilde{\ell}^-$ and $\widetilde{\chi}^+\widetilde{\chi}^-$.

Backgrounds come mainly 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 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 ($M_{\rm miss} = \{(\sqrt{s} - E_{\rm vis})^2 - \vec{p}_{\rm vis}^{\,2}\}^{1/2}$), which is small if $p_T^{\rm miss}$ is caused by a single neutrino or undetected electron or photon, and 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 ($M_{\rm LSP}$) is less than the parent particle ($M_{\rm parent}$) by at least 10 GeV/$c^2$, and greater than about 10 GeV/$c^2$. Difficulties arise when the mass difference $\Delta M = M_{\rm parent} - M_{\rm LSP}$ 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, so mass limits are not degraded very much. Also, the combination of results amounts to a factor four more data than the 'average' LEP experiment.

***Charginos and Neutralinos:*** The phenomenology of charginos and neutralinos depends on their field content: they tend to be 'gaugino-like' (for $M_2 \ll |\mu|$) or 'higgsino-like' ($|\mu| \ll M_2$), with a 'mixed' field content available only for a relatively small region of parameter space. The cross section for gauginos varies with the masses of sleptons exchanged in the $t$-channel. In particular, chargino production can be suppressed by more than an order of magnitude for particular values of $M_{\widetilde{\nu}_e}$. The gaugino branching ratios also depend on the sfermion sector. When the sfermion masses are larger than $\sim 200$ GeV/$c^2$, the chargino and neutralino branching ratios are close to those of the $W$ and $Z$ bosons. At LEP, enhancements of leptonic branching ratios are important when light sleptons are hypothesized. Light squarks are excluded by hadron collider experiments and are not considered. Cross sections and branching ratios for higgsinos are, in contrast, insensitive to the masses of the sfermions.

In the gaugino-like region, the lightest chargino mass is driven by $M_2$, and the lightest neutralino mass by $M_1$. For popular 'supergravity' models, $M_1$ and $M_2$ unify at a GUT scale, with $M_1 \approx M_2/2$ at the electroweak scale. Consequently, the mass difference $\Delta M = M_{\widetilde{\chi}^\pm} - M_{\widetilde{\chi}_1^0}$ is not very small and selection efficiencies are high. In the higgsino-like region, chargino and neutralino masses are all close to $|\mu|$, and hence, small mass differences of order 5 GeV/$c^2$ are typical. In the mixed region of moderate negative $\mu$, $\Delta M \approx M_W$, and cuts designed to reject $W$ background lead to lower efficiencies.

Chargino masses have been excluded up to 103 GeV/$c^2$ on the basis of a combination of LEP data sets [9]. However, this limit can be degraded when the sneutrino is lighter than $\sim 200$ GeV/$c^2$. Thanks to the large luminosity and the combination of four experiments, the impact for $M_{\tilde{\nu}_e} \gtrsim 100$ GeV/$c^2$ is less than a GeV/$c^2$. The limit is also weakened when the mass difference is small ($\Delta M = M_{\tilde{\chi}^\pm} - M_{\tilde{\chi}_1^0} \lesssim 3$ GeV/$c^2$), as in the higgsino region; however, in this case the associated production of neutralino pairs $\tilde{\chi}_1^0\tilde{\chi}_2^0$ is large, and the problem of small mass differences ($M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$) less severe. Experimental sensitivity now extends down to mass differences of 3 GeV/$c^2$, corresponding to $M_2$ above 2 TeV/$c^2$.

For a summary of the interplay of chargino field content and sfermion masses, see Fig. 1.

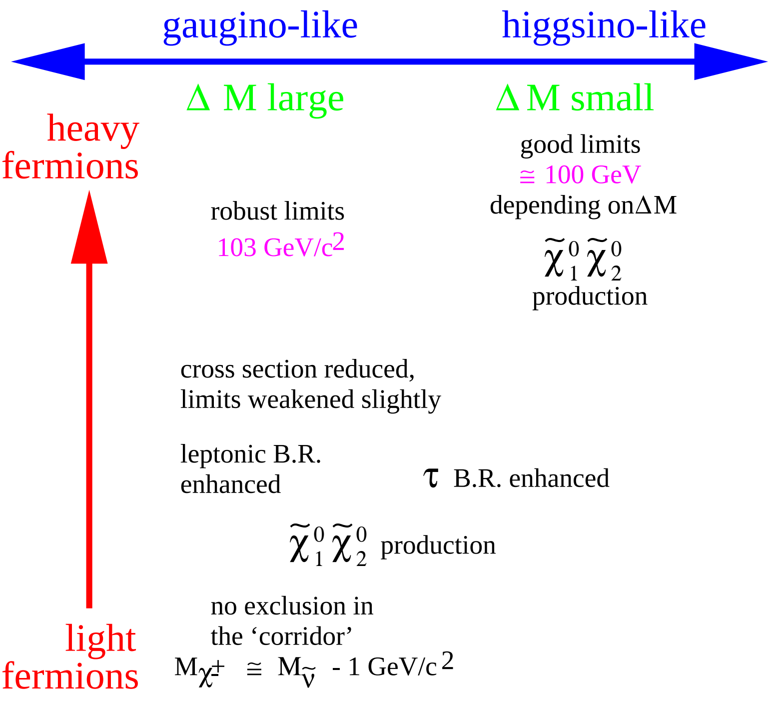

**Figure 1:** heuristic diagram of the interplay of chargino field content and sfermion masses.

The possibility of extremely small mass differences has been raised in several theoretical papers which propose models rather different from supergravity [11]. The DELPHI Collaboration was the first to engineer searches to cover this scenario [12], and other collaborations have followed suit [13]. For

$\Delta M \sim 1\ \mathrm{GeV}/c^2$, the signal can be distinguished from two-photon background on the basis of isolated photons detected at low angles: hard initial-state radiation sometimes accompanies the signal process, but is absent for the background. For $\Delta M \sim 0.4\ \mathrm{GeV}/c^2$, the chargino acquires a non-negligible lifetime, and decays at a significant distance from the interaction point, producing tracks which do not extrapolate back to the interaction point. When $\Delta M < m_\pi$, the lifetime is so long that the chargino appears as a heavily ionizing particle which exits the tracking detector before decaying. The bounds on the chargino mass are about 20 $\mathrm{GeV}/c^2$ weaker than in the canonical case [14].

The limits from chargino and neutralino production are most often used to constrain $M_2$ and $\mu$ 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, especially when electron sneutrinos are light. This is the weak point when inferring an indirect limit on the LSP mass [15].

When the sleptons are light, branching ratios to leptons are enhanced, especially to $\tau$'s via $\widetilde{\tau}$'s when there is non-negligible mixing. These effects are greatest when the chargino has a large gaugino component. The weakest bounds are found for small negative $\mu$ 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 $\Delta M$ is large. If sneutrinos are lighter than the chargino, then two-body decays $\widetilde{\chi}^+ \to \ell^+\widetilde{\nu}$ dominate, and in the 'corridor' $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3\ \mathrm{GeV}/c^2$, the acceptance is so low that no direct exclusion is possible [16]. However, in the context of the cMSSM, it is possible to cover this region with slepton and neutralino searches.

***Sleptons:*** Sleptons and squarks are produced via $\gamma^*$ and $Z^*$ exchange. For selectrons, there is an important contribution from $t$-channel neutralino exchange, which generally increases the cross section substantially. Even though the cross section is suppressed near threshold, the large luminosity at LEP has allowed mass limits to be placed close to the kinematic threshold. For equal masses, the cross section for the $R$ state is smaller than for the $L$ state, so limits are set conservatively for the production of $R$-sleptons only. In grand unified theories, the masses of the $R$ and $L$ states are linked, and usually the $R$ state is lighter, especially when $\tan\beta$ is large. For $\widetilde{\tau}$ sfermions, mixing can be important.

The simplest slepton topology results from $\tilde{\ell} \to \ell\widetilde{\chi}_1^0$, though for some particular parameter choices, branching ratios for decays to $\widetilde{\chi}_2^0$ reach a few percent. Combined mass limits have been obtained by the LEP SUSY working group [9]. For $\tilde{\mu}_R$, the limit is 94 GeV/$c^2$. The limit for $\tilde{e}_R$ is 4 GeV/$c^2$ higher due to the higher cross section coming from $\widetilde{\chi}^0$ exchange. Since the selection of $\tau$'s is relatively difficult, the limit is expected to be lower. The actual limit is 80 GeV/$c^2$, which is about 5 GeV/$c^2$ *lower than expected*, due to an excess of events taken at certain energy points. The excess does not, however, support claims of new physics.

Assuming a common scalar mass term $m_0$, as in the cMSSM, the masses of the $R$ and $L$-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 of a neutralino close in mass to the right-selectron still results in a viable signature: a single energetic electron. ALEPH has used this to close the gap $M_{\tilde{e}_R} - M_{\widetilde{\chi}} \to 0$.

***Squarks:*** Although the Tevatron experiments had placed general limits on squark masses far beyond the reach of LEP, a light top squark ('stop') could still have been found, since the flavor eigenstates can mix to give a large splitting between the mass eigenstates. While less natural theoretically, light sbottoms also have been considered. LEP limits on stop and sbottom masses vary with the mixing angle because the cross section does: for $\theta_{\widetilde{t}} = 56°$ and $\theta_{\widetilde{b}} = 67°$, the contribution from $Z$ exchange is "turned off." In fact, the variation in mass limits is only a couple of GeV/$c^2$ due to the large luminosity used for these searches [9].

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. The conservative limit is $M_{\widetilde{t}_1} > 95$ GeV/$c^2$, valid for $\Delta M > 5$ GeV/$c^2$. If sneutrinos are light, the decay $\widetilde{t}_1 \to b\ell\widetilde{\nu}$ dominates, giving two leptons in addition to jets, and the limit is 96 GeV/$c^2$. Access to very small $\Delta M$ is possible due to the visibility of the decay products of the $c$ and $b$ hadrons [17], in which case the conservative limit $M_{\widetilde{t}_1} > 59$ GeV/$c^2$ is obtained. A comparison to results from the Tevatron is given below.

The electric charge of the sbottoms is smaller than that of stops, so the cross section is considerably lower. The only decay channel considered is $\widetilde{b}_1 \to b\widetilde{\chi}_1^0$. Use of $b$-jet tagging helps retain sensitivity: the bound is $M_{\widetilde{b}} > 93$ GeV/$c^2$. It has been pointed out that very light bottoms squarks ($M_{\widetilde{b}} < 5$ GeV/$c^2$), which are decoupled from the $Z$, are not excluded by LEP searches.

The results from the search for acoplanar jets and missing energy has been interpreted as a limit on the production of generic squarks [18,9]. A comparison with Tevatron results is given below.

***The Lightest Neutralino:*** 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 [14,15,19]. 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 very high, the bound on $M_{\widetilde{\chi}_1^0}$ is derived from the results of chargino and neutralino searches, and the limit is $M_{\widetilde{\chi}} > 39$ GeV/$c^2$ [13,14,20,21].

When sleptons are lighter than $\sim 200$ 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 light neutralino. A combined limit has been obtained in the cMSSM for any

$\tan\beta$: $M_{\widetilde{\chi}_1^0} > 36$ GeV/$c^2$. The results of Higgs searches can be brought into play on the basis of mSUGRA mass relations, to very good effect. They exclude large regions at low $m_0$ and $m_{1/2}$ for low $\tan\beta$, and strengthen the neutralino bound to $M_{\widetilde{\chi}_1^0} > 59$ GeV/$c^2$ [9].

***Gauge-Mediated Scenarios:*** All of the limits above obtain in supergravity models. In models with gauge-mediated supersymmetry breaking (GMSB), however, the phenomenology is rather different, and several interesting new topologies are expected. They can be classified on the basis of the 'next-to-lightest supersymmetric particle' (NLSP), which can be either the lightest neutralino or charged sleptons. The gravitino ($\widetilde{G}$) is the LSP, with mass well below one keV.

In the case in which $\widetilde{\chi}_1^0$ is the NLSP, high energy photons are present from the decay $\widetilde{\chi}_1^0 \to \gamma\,\widetilde{G}$. They facilitate the separation of signal and background, so for gauginos and sfermions, the resulting limits are very similar to the canonical case. The pair production of $\widetilde{\chi}_1^0$'s provides an additional search channel consisting of two acollinear photons and missing energy. The mass limit derived is 93 GeV/$c^2$ using the data from all four experiments [9], valid when $M_{\tilde{e}_R} < 2\,M_{\widetilde{\chi}_1^0}$. Also, single-photon production has been used to constrain the process $e^+e^- \to \widetilde{G}\widetilde{\chi}_1^0$.

When sleptons are the NLSP, there are two possibilities: all three flavors enter more or less equally, or, due to significant mixing, the lightest stau dominates. Considering the first three flavors of sleptons, the topology depends strongly on the slepton lifetime, which is determined by the scale parameter $\sqrt{F}$. For very short lifetimes, the decay $\widetilde{\ell}_R \to \ell\widetilde{G}$ corresponds to the searches described above with a very light neutralino. When the sleptons have some lifetime, the leptons will have impact parameters which help to reject backgrounds. For even longer lifetimes, the apparatus can actually resolve the decay vertex, consisting of an incoming slepton and an outgoing lepton – a track with a 'kink' in the tracking volume. Finally, if the lifetime is long, the experimental signature is a pair of collinear, heavily ionizing tracks. By combining searches for all of these signatures, limits of approximately 80 GeV/$c^2$ for staus can be placed independent of the slepton lifetime [22].

When, due to mixing, the lightest stau is significantly lighter than the other sleptons, special topologies may result. For example, $4\tau$ final states result from neutralino pair production. No evidence for a signal was found [23].

***R-parity Violation:*** 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. At LEP, all sets of generational indices ($\lambda_{ijk}$, $\lambda'_{ijk}$, $\lambda''_{ijk}$) have been considered. Signatures of direct and also indirect RPV have been utilized. Rather exotic topologies can occur, such as six-lepton 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 [24]. 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 $\widetilde{\chi}_1^0$'s rules out some parameter space not accessible in the canonical case.

### *II.5. Supersymmetry searches at proton machines:*

While the LEP experiments can investigate a wide range of scenarios and cover corners of parameter space, they cannot match the mass reach of the Tevatron experiments (CDF and DØ). Although the full $p\overline{p}$ energy is never available for annihilation, the cross sections for supersymmetric particle production are large due to color factors and strong coupling. Each experiment has analyzed approximately 110 pb$^{-1}$ of data at $\sqrt{s}$ = 1.8 TeV during Run I, which ended in 1996. Now Run IIa is underway, with the goal of logging 2 fb$^{-1}$ by 2004.

The main source of signals for supersymmetry are squarks and gluinos, in contradistinction to LEP. Pairs of squarks or gluinos are produced in $s$, $t$ and $u$-channel processes. These particles decay directly or via cascades to at least two $\widetilde{\chi}_1^0$'s. The number of observed hadronic 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 enriches the possibilities of the search. The $u$, $d$, $s$, $c$, and (usually) $b$ 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 spread of partonic energies in hadron machines is very large, so one has to consider the presence of several SUSY signals in one data set. A search in a given topology, such as $\geq 3$ jets+$\not{E}_T$, can capture events from $\widetilde{q}$'s, $\widetilde{g}$'s and even $\widetilde{\chi}^{(\pm,0)}$, with or without cascade decays. Applying experimental bounds on one production mechanism while ignoring the rest would be invalid, so the experimenters must find a relatively simple way of organizing the full phenomenology. Traditionally, they have turned to mSUGRA, in part because the fundamental parameters $m_0$ and $m_{1/2}$ can be fairly easily related to the squark, gluino, and gaugino masses, which determine the event kinematics, and hence, the signal acceptance.

As a consequence of this reliance on mSUGRA, some topological possibilities might be overlooked when reporting exclusions. Still, it is not easy to find a way to report the results which is less model-dependent and still succinct. Both Tevatron collaborations are exploring methodologies which are not tied to specific models. A good example is the 'SLEUTH' anlaysis of DØ [25](see also [38,41]).

Backgrounds at the Tevatron are relatively much higher than at LEP. There are essentially two types. First, ordinary multijet events can appear to have missing energy due to measurement errors. While large mis-measurements are rare, there are very many di-jet and tri-jet 'QCD' events. This background must be estimated directly from control samples. Second, much rarer processes yield energetic neutrinos which produce a genuine missing energy signature. Examples include the production of $W$ and $Z$ bosons with initial-state jets, of boson pairs, and of the top quark. Estimates for these backgrounds are commonly based on theoretical cross sections, although in some analyses, direct measurements are used to reduce uncertainties.

***Squarks and Gluinos:*** The classic searches [26] 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 can be reduced by rejecting events with identified leptons. Uncertainties in the rates of these processes can be reduced 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 using simulations normalized using the data.

The bounds traditionally are derived for the $(M_{\widetilde{g}}, M_{\widetilde{q}})$ plane. A new analysis by the CDF Collaboration places significantly stronger bounds than all previous analyses [27]. The removal of instrumental backgrounds is keyed more directly to the detector, which, together with specific topological cuts against poorly reconstructed multijet backgrounds, leaves gauge boson and $t\overline{t}$ backgrounds dominant. The estimates for these are tied directly to CDF measurements, which greatly reduces systematic uncertainties. The signal region is loosely specified by demanding high $\not\!\!E_T$ and $H_T$, the scalar sum of the $\not\!\!E_T$ of the second and third jets, and $\not\!\!E_T$. The number of isolated tracks allows the experimentalist to switch between a background-dominated sample and one which could contain SUSY events. As a measure of analysis rigor, the region expected to be potentially rich in SUSY events is ignored, as the event counts in background-dominated samples are examined. No excess is observed, and the cuts on $\not\!\!E_T$ and $H_T$ are tuned to obtain the exclusion shown in Fig. 2.

If squarks are heavier than gluinos, then $M_{\widetilde{g}} \gtrsim 195$ GeV/$c^2$. If they all have the same mass, then that mass is at least 300 GeV/$c^2$. If the squarks are much lighter than the gluino (in which case they decay via $\widetilde{q} \rightarrow q\widetilde{\chi}^0_1$), the bound on the gluino mass is generally high, much more than 300 GeV/$c^2$. A small region, in which the neutralino-squark mass difference is small, is covered by the LEP experiments.

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 $\mu$ and $\tan\beta$. Direct constraints on the theoretical parameters $m_0$ and $m_{1/2} \approx 0.34\,M_3$ have been obtained for some analyses, assuming the mass relations of the mSUGRA model. These bounds do not carry significantly more information than is contained in the region above the diagonal of Fig. 2. However, if the LEP limits on chargino production are interpreted in this context as an indirect limit on gluinos, then roughly $M_{\tilde{g}} > 310$ GeV/$c^2$ obtains [8].

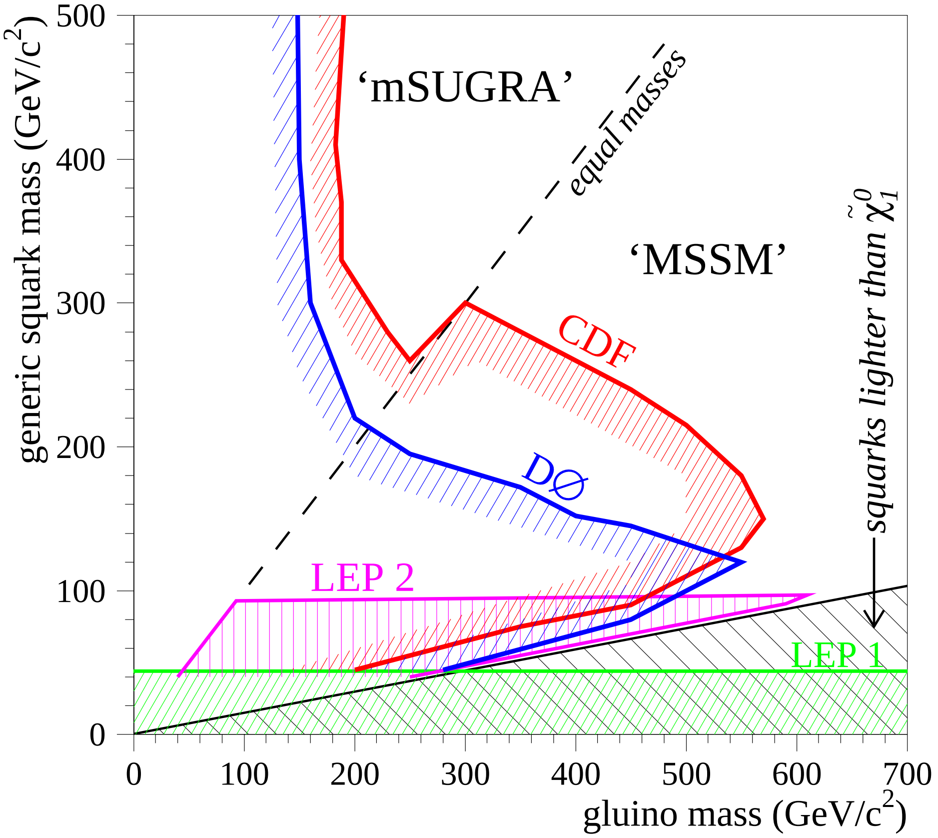

**Figure 2:** Regions in the $M_{\tilde{g}}$-$M_{\tilde{q}}$ plane excluded by searches at CDF, DØ, and LEP.

***Gauginos:*** In the context of the mSUGRA model, which fixes $|\mu|$ by the requirement of electroweak symmetry breaking, the lightest chargino and neutralinos are dominantly gaugino. They 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 ($\widetilde{\chi}^{\pm} \to \ell\nu\widetilde{\chi}_1^0$ 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 $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ [28]. The requirement of three energetic leptons, augmented by simple angular cuts against Drell-Yan production, and cosmic rays and isolation requirements against semileptonic decays of heavy mesons, reduces backgrounds to a very small level. The bounds have been derived in the context of mSUGRA models, which generically predicts modest leptonic branching ratios for charginos and neutralinos. Consequently, in this framework, the results are not competitive with the LEP bounds. Nonetheless, the search is completely independent of the jet+$\not\!\!E_T$ search, and could be more effective in particular models.

The dilepton signal is geared more for the production of gauginos in gluino and squark cascades [29]. 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 angle of the leptons and their transverse momentum. The Majorana nature of the gluino can be exploited by requiring two leptons with the same charge, thereby greatly reducing the background. In this scenario, limits on squarks and gluinos are comparable to those from the jets+ $\not\!\!E_T$.

DØ tried to find squarks tagged by $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\gamma$, where the $\widetilde{\chi}_2^0$ appear in cascade decays [30]. The branching ratio can be large for a selected set of model parameters, leading to a Higgsino-like $\widetilde{\chi}_1^0$ and a gaugino-like $\widetilde{\chi}_2^0$. DØ assumed a branching ratio of 100% to place the limits $M_{\widetilde{g}} > 240$ GeV/$c^2$ for heavy squarks, and $M_{\widetilde{g}} > 310$ GeV/$c^2$ for squarks of the same mass.

***Stops and Sbottoms:*** The top squark is unique among the squarks because its SM partner is so massive: large off-diagonal terms in the squared-mass matrix lead to large mixing effects, and a mass eigenstate possibly much lighter than all the others. This can also happen for bottom squarks for rather special parameter choices. Hence, special analyses have been developed for $\widetilde{t}_1$'s and $\widetilde{b}_1$'s among all the squarks.

Top squarks are pair-produced with no dependence on the mixing angle, in contrast to LEP. The searches are based on two final states: $c\not\!\!E_T$ and $b\ell\not\!\!E_T$, and it is assumed that one or the other dominates. Theoretical calculations show that if chargino and slepton masses are well above $M_{\widetilde{t}_1}$, then the loop-induced FCNC decay $\widetilde{t}_1 \to c\widetilde{\chi}^0$ does dominate. If $M_{\widetilde{\chi}^\pm} < M_{\widetilde{t}_1}$, then $\widetilde{t}_1 \to b\widetilde{\chi}^\pm$ is the main decay mode, and the experimenters assume $\mathrm{BR}(\widetilde{\chi}^\pm \to \ell\nu\widetilde{\chi}^0) = \mathrm{BR}(W \to \ell\nu)$, which is appropriate for a gaugino-like $\widetilde{\chi}^\pm$. When charginos are heavy but $M_{\widetilde{\nu}} < M_{\widetilde{t}_1}$, leptonic final states again are favored via $\widetilde{t}_1 \to b\ell\widetilde{\nu}$. In this case, the branching ratio is assumed to be 1/3 for each lepton flavor. In fact, all these channels compete, and the assumption of a 100% branching ratio is not general. Furthermore, four-body decays to $b\ell\nu\widetilde{\chi}$ should not be neglected, for which limits would be reported in the $(M_{\widetilde{t}}, M_{\widetilde{\chi}})$ plane [31].

CDF has obtained a new result for the $c\not\!\!E_T$ final state [32]. They employed their vertex detector to select charm jets. After a lepton veto and $\not\!\!E_T$ requirement, this result surpasses the older result from DØ [33]. The vertex detector was also used to tag $b$-quark jets for the final state $b\ell\not\!\!E_T$. In this case, CDF went beyond simple event counting, and applied a likelihood test to the shapes of kinematic distributions. Like the earlier DØ result, however, this search did not exclude any signal in the channel $\widetilde{t}_1 \to b\widetilde{\chi}^\pm$, and covered a small region for $\widetilde{t}_1 \to b\ell\widetilde{\nu}$. Finally, CDF considered the possibility $t \to \widetilde{t}_1\widetilde{\chi}$ followed by $\widetilde{t}_1 \to b\widetilde{\chi}^+$ [34]. Such events would remain in the top event sample, and could be discriminated using a multivariate technique. No events were found compatible with the kinematics of SUSY decays, and limits on $\mathrm{BR}(t \to \widetilde{t}_1\widetilde{\chi})$ were derived in a fairly limited range of stop and chargino masses.

The search for light $\widetilde{b}_1 \to b\widetilde{\chi}$ follows the $\widetilde{t}_1$ search in the charm channel. The CDF search tightens the requirements for a jet with heavy flavor to good effect. An earlier DØ result tagged $b$-jets through semileptonic decays to muons [35].

A summary of the searches for stops and sbottoms is shown in Fig. 3. Given the modest luminosity and small detection efficiencies, the mass reach of the Tevatron searches is impressive. New data will extend this reach (as would the combination of results from the two experiments). Unfortunately, the region with $M_{\widetilde{\chi}^0} > M_{\widetilde{t}_1} + 20$ GeV/$c^2$ will remain inaccessible in Run 2, due to the necessity of a minimum required missing energy in the experimental trigger. The LEP results do not suffer this limitation, and the dependence on the mixing angles is reduced thanks to the large luminosities delivered.

It should be noted that there is a 'hole' in the exclusion of light sbottoms, on the order of 5 GeV/$c^2$. Such a particle can escape detection in standard searches at LEP when it is decoupled from the $Z$ boson. If it decays, for example, to $q\ell\widetilde{\nu}_R$ or $q\widetilde{G}$, the resulting jets will not be very acollinear, and the $\not{E}_T$ at the Tevatron will be small. Such events are relatively difficult to pick out from SM backgrounds.

***R-Parity Violation:*** The CDF and DØ collaborations have searched for supersymmetry in certain RPV scenarios [36], in which the lightest neutralino decays to a lepton and two quarks. DØ considered all possible production processes as a function of mSUGRA parameters. Their trilepton search amounted to strong bounds on these parameters, stronger than the limits from their search for two electrons and jets. CDF used their same-sign dielectron and jets topology to look for gluino and squark (including stop) production, and obtained some specific upper limits on cross sections corresponding to $M_{\widetilde{q}} > 200$ GeV/$c^2$ and $M_{\widetilde{t}_1} > 120$ GeV/$c^2$.

***Gauge-Mediated Models:*** Interest in GMSB models was spurred by an anomalous '$ee\gamma\gamma\not{E}_T$' event found by the CDF Collaboration [37]. Some of 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 photons arise from

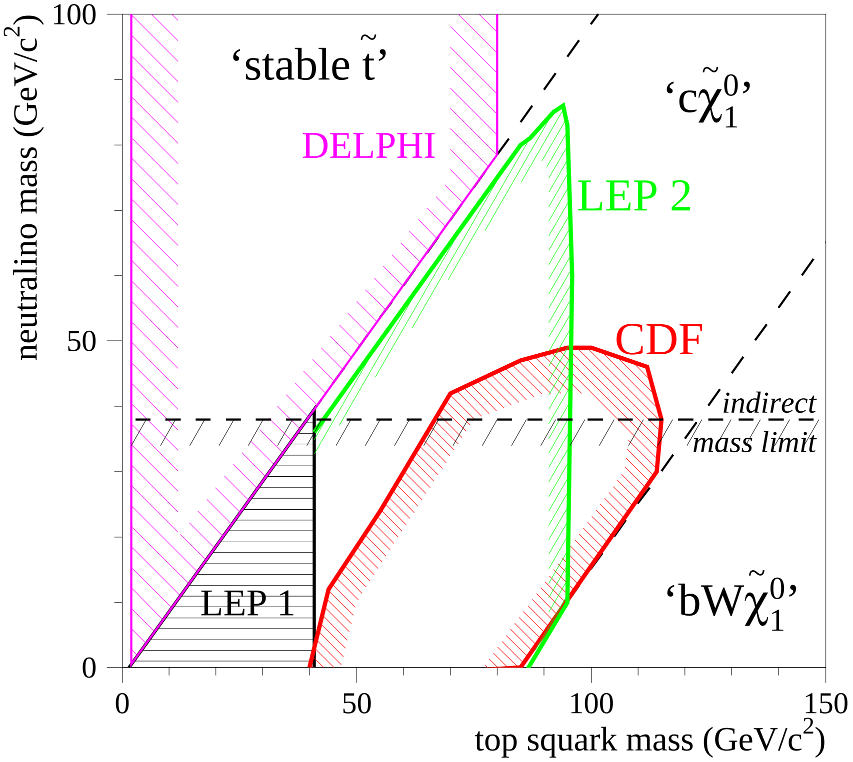

**Figure 3:** Regions excluded in the $(M_{\widetilde{t}_1}, M_{\widetilde{\chi}})$ plane. The results for the $c\widetilde{\chi}_1^0$ decay mode are displayed from LEP and CDF. A DELPHI result for stable stops is indicated for $M_{\widetilde{t}_1} < M_{\widetilde{\chi}}$. Finally, the indirect limit on $M_{\widetilde{\chi}}$ is also shown. There is effectively no exclusion in the region where $\widetilde{t}_1 \to bW\widetilde{\chi}_1^0$.

the decay $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$, and the 'superlight' gravitino has a mass much smaller than the charged fermions. DØ examined their sample of $\gamma\gamma\not{E}_T$ events and reported limits on neutralino and chargino production corresponding to $M_{\widetilde{\chi}_1^0} > 75$ GeV/$c^2$ [30]. CDF experimenters carried out a systematic survey of events with photons and SM particles (leptons, jets, missing energy), and found no signal confirming the interpretation of the original anomalous event [37,38]. They also looked for evidence of light gravitino pairs without additional SUSY particles. The invisible gravitinos are tagged by a high-$E_T$ jet from the initial state; this is the so-called 'monojet' signature [39]. The limit $\sqrt{F} >$

215 GeV/$c^2$ is placed on the fundamental parameter of this model.

In GMSB models, a heavy 'sGoldstino' is possible, which may have sizable branching ratios to photon pairs. CDF looked for narrow diphoton resonances and placed a limit $\sqrt{F} >$ 1 TeV/$c^2$, depending on assumed mass of the sGoldstino [40].

***Hints?*** There are two searches, both from CDF, which hint at the possible presence of new physics. The first of these comes from the systematic survey of events with leptons, photons and missing energy [41]. Although the collaboration cautiously avoids making any claims of discovery, there is a modest 2.7 $\sigma$ excess of 'multibody' $\mu\gamma\not{E}_T$ events. Furthermore, the kinematic distributions for this sample do not match the predictions based on SM processes well, although no quantitative analysis of these discrepancies is offered.

Stronger claims are made of anomalous events culled from the top quark event sample. Events have been found with an unusual rate of leptons in jets with secondary vertices, and the kinematics of these jets deviates significantly from SM expectations and from control samples [42]. No specific model to explain the properties of these events is described, but in Ref. 43, the hypothesis of a light scalar quark ($M \approx 3.6$ GeV/$c^2$) is proposed. This is possible, since, as noted above, a light $\widetilde{b}_1$ has not definitively been ruled out by direct searches.

The analysis of new Tevatron data will decide whether these two anomalies are reproducible, or one-time statistical fluctuations.

***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 inarguable 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 have analyzed all their data, so prospects for the immediate future pass to the Tevatron collaborations. If still no sign of supersymmetry is found, 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 | $M_{\widetilde{\nu}} > 200$ GeV/$c^2$ | 103 | LEP 2 |
| | | $M_{\widetilde{\nu}} > M_{\widetilde{\chi}^\pm}$ | 85 | LEP 2 |
| | | any $M_{\widetilde{\nu}}$ | 45 | $Z$ width |
| | Higgsino | $M_2 < 1$ TeV/$c^2$ | 99 | 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/$c^2$ | 39 | LEP 2 |
| | | any $\tan\beta$, any $m_0$ | 36 | LEP 2 |
| | | any $\tan\beta$, any $m_0$, SUGRA Higgs | 59 | LEP 2 combined |
| | GMSB | | 93 | LEP 2 combined |
| | RPV | $LL\overline{E}$ worst case | 23 | LEP 2 |
| $\widetilde{e}_R$ | $e\widetilde{\chi}_1^0$ | $\Delta M > 10$ GeV/$c^2$ | 99 | LEP 2 combined |
| $\widetilde{\mu}_R$ | $\mu\widetilde{\chi}_1^0$ | $\Delta M > 10$ GeV/$c^2$ | 95 | LEP 2 combined |
| $\widetilde{\tau}_R$ | $\tau\widetilde{\chi}_1^0$ | $M_{\widetilde{\chi}_1^0} < 20$ GeV/$c^2$ | 80 | LEP 2 combined |
| $\widetilde{\nu}$ | | | 43 | $Z$ width |
| $\widetilde{\mu}_R$, $\widetilde{\tau}_R$ | | stable | 86 | LEP 2 combined |
| $\widetilde{t}_1$ | $c\widetilde{\chi}_1^0$ | any $\theta_{\rm mix}$, $\Delta M > 10$ GeV/$c^2$ | 95 | LEP 2 combined |
| | | any $\theta_{\rm mix}$, $M_{\widetilde{\chi}_1^0} \sim \frac{1}{2} M_{\widetilde{t}}$ | 115 | CDF |
| | | any $\theta_{\rm mix}$ and any $\Delta M$ | 59 | ALEPH |
| | $b\ell\widetilde{\nu}$ | any $\theta_{\rm mix}$, $\Delta M > 7$ GeV/$c^2$ | 96 | LEP 2 combined |
| $\widetilde{g}$ | any $M_{\widetilde{q}}$ | | 195 | CDF jets+$\not\!\!E_T$ |
| $\widetilde{q}$ | $M_{\widetilde{q}} = M_{\widetilde{g}}$ | | 300 | CDF jets+$\not\!\!E_T$ |

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