SUPERSYMMETRY, PART II (EXPERIMENT)

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II.1. Introduction: Low energy supersymmetry (SUSY) is probably the most extensively studied among the theories beyond the standard model (SM). Reasons are its success in solving some of the deficiencies of the SM, such as the stabilization of the Higgs boson mass or gauge coupling unification, while not being in contradiction with the precision electroweak measurements. If unbroken, SUSY would predict the existence of partners of the SM particles, differing by half a unit of spin but otherwise sharing the same properties. Since no such particles have been observed with the same mass as their SM counterpart, SUSY is a broken symmetry. With an appropriate choice of SUSY breaking terms, denoted "soft," and with superpartner masses at the TeV scale, the good properties of SUSY, such as those mentioned above, however remain preserved.

SUSY and SM particles are distinguished by a multiplicative quantum number, R-parity, with $R = (-1)^{3(B-L)+2S}$ where B and L are the baryon and lepton numbers, and S is the spin. If R-parity is violated, the exchange of SUSY particles may lead to an unacceptably fast proton decay. It is therefore commonly assumed that R-parity is conserved. As a consequence, SUSY particles are produced in pairs, and a SUSY particle decays (possibly via a cascade) into SM particles accompanied by the lightest SUSY particle (LSP) which is stable. Cosmological constraints require that the LSP be neutral and colorless.

The first part of this review, by H.E. Haber, provides details of the theoretical aspects of supersymmetry, of the various SUSY breaking schemes, and of the structure of the minimal supersymmetric extension of the standard model (MSSM), as well as an extensive set of references. The same notations and terminology are used in the following.

As will unfortunately appear in this review, no evidence for SUSY particle production has been found up to now. The search results are therefore presented in terms of production cross section upper limits or of mass lower limits. In the following, all such limits are given at the 95% confidence level.

II.2. SUSY models: In the MSSM, every degree of freedom of the SM is balanced by a new one differing by half-a-unit of spin. There are, for instance, two scalar-quark weak eigenstates $\tilde{q}_L$ and $\tilde{q}_R$, associated with the left and right chirality states of a given quark flavor. Two Higgs doublets are, however, needed, in contrast to the minimal standard model, in order to give masses to both up-type and down-type quarks, with vacuum expectation values v_2 and v_1, the ratio of which is denoted $\tan\beta$. The SUSY partner weak eigenstates of the $W^{\pm}$ and charged Higgs bosons mix to form the two chargino mass eigenstates $\tilde{\chi}_i^{\pm}$ $(i = 1, 2)$. Similarly, there are four neutralinos $\tilde{\chi}_i^0$ $(i = 1, 4)$ associated to the B, W^0 and neutral Higgs bosons. Full details are given in H.E. Haber's review.

The main phenomenological features of SUSY models arise from the choice of mechanism for SUSY breaking mediation, and of the soft SUSY breaking terms. There are more than one hundred such terms in the MSSM, and simplifying assumptions are necessary to bring this number to a more manageable level. Requiring no additional source of flavor mixing and CP-violation than those present in the Cabibbo-Kobayashi-Maskawa matrix of the SM leaves only the gaugino mass terms M_1, M_2 and M_3 associated with the three gauge groups of the SM, mass terms for the various slepton and squark fields, *e.g.*, $m_{\tilde{t}_R}$, and trilinear Higgs-squark-squark and Higgs-slepton-slepton couplings such as A_t. The model is then fully specified with the addition of $\tan\beta$, of the supersymmetric Higgs mixing mass term μ, and of the mass of the CP-odd Higgs boson m_A.

By far the most widely studied models involve mediation by gravitational forces. In these supergravity models, the gravitino plays essentially no rôle in the phenomenology, unless it is the LSP. This possibility, which has not been addressed by experimental searches at colliders up to now except in terms of future prospects, is not considered in this review. In the minimal model of supergravity (mSUGRA), the number of free parameters is reduced to five: a universal gaugino mass $m_{1/2}$, a universal scalar mass m_0, and a universal trilinear coupling A_0, all defined at the scale of grand unification (GUT), $\tan\beta$, and the sign of μ. The low energy parameters are obtained using the renormalization group equations (RGEs), which in particular fix the absolute value of μ through the requirement of electroweak symmetry breaking at the appropriate scale. In most of the mSUGRA parameter space, the LSP, required to be neutral and colorless, turns out to be the lightest neutralino, $\tilde{\chi}_1^0$. For appropriate mSUGRA parameter choices and imposing R-parity conservation, this neutralino LSP has the right properties to form the dark matter of the universe. A slightly less constrained model has also been used, primarily at LEP, where μ and m_A are kept free. In such an approach, the mass parameters in the Higgs sector are not related to the universal sfermion mass m_0, where "sfermion" stands for squark and slepton.

In contrast, the LSP is a very light gravitino $\tilde{G}$ in models with gauge mediated SUSY breaking (GMSB). The phenomenology depends on the nature of the next-to-lightest SUSY particle (NLSP), typically the lightest neutralino or the lightest stau, and on its lifetime. Another mediation mechanism which has been considered is via the super-conformal anomaly (AMSB, for anomaly mediation SUSY breaking). In such models, the LSP is a wino $\tilde{W}^0$, with a small mass splitting with the lightest chargino, so that the lifetime of that chargino may become phenomenologically relevant, possibly long enough for the chargino to behave like a stable charged particle. More recently, a model called "split SUSY," which does not aim at solving the hierarchy problem, sets all scalar quark and lepton masses at a very high scale, such as the GUT scale, while keeping the gauginos at the TeV scale. As a result, the gluino, whose decay is mediated by squark exchange, becomes long-lived, which leads to unusual signatures.

II.3. Search strategies: Indirect constraints on SUSY particles can be obtained from cosmological considerations, primarily from the relic dark-matter density [1], from measurements of, or limits on, rare decays, mostly of B mesons [2], or from the anomalous magnetic moment of the muon [3]. These topics are not within the scope of this review. The most significant direct constraints on SUSY particles have been obtained at LEP and at the Tevatron. The large e^+e^- collider, LEP, was in operation at CERN from 1989 to 2000, first at and near the mass of the Z boson, 91.2 GeV, and progressively up to a center-of-mass energy of 209 GeV. Four detectors, ALEPH, DELPHI, L3 and OPAL, each collected a total of about 1 fb^{-1} of data. The Tevatron is a $p\bar{p}$ collider located at Fermilab. After a first run at a center-of-mass energy of 1.8 TeV, which ended in 1996, and during which the CDF and DØ detectors collected about 110 pb^{-1} of data each, both the accelerator complex and the detectors were substantially upgraded for Run II, which began in 2001. The center-of-mass energy was raised to 1.96 TeV, and the instantaneous luminosity reached the level of 2.8 $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the winter of 2007. By August 2007, about 3 fb^{-1} had been accumulated by each experiment.

The "canonical" SUSY scenario is an mSUGRA-inspired MSSM with R-parity conservation and a neutralino LSP. Since such an LSP is stable and weakly interacting, pair production of SUSY particles will lead to missing energy and momentum carried away by the LSPs resulting from the produced SUSY particle decays. In scenarios other than the canonical one, the expected SUSY signatures may exhibit some additional, or even different features. In GMSB with a neutralino NLSP, for instance, photons are expected in addition to the missing energy carried away by the gravitino LSPs, arising from $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ decays. But in GMSB again, a stau NLSP might have a lifetime long enough to appear stable in the detector and therefore not to give rise to missing energy. If R-parity is not conserved, the LSP will decay into SM particles; increased lepton or jet multiplicities are hence expected, but missing energy will arise only from possible final state neutrinos.

In e^+e^- collisions, the missing energy can be directly inferred as $\sqrt{s}-E$, from the center-of-mass energy $\sqrt{s}$, and from the total energy E of the visible final state products. Similarly, the missing momentum is the opposite of the total momentum of those products. The situation is different in $p\bar{p}$ collisions where the center-of-mass energy of the colliding partons is not known. Only its probability density can be determined, by making use of universal parton distribution functions (PDFs) obtained from fits to a large set of experimental data, most prominently the proton structure functions measured at HERA. Since most of the beam remnants escape undetected in the beam pipe, only conservation of momentum in the plane transverse to the beam direction can be used, and canonical SUSY signals will be searched for in events exhibiting large missing *transverse* energy $\not\!\!E_T$.

All SUSY particles, except for the gluino, are produced in a democratic way in e^+e^- collisions via electroweak interactions. The search is therefore naturally directed toward the lightest ones, typically the NLSP, and the results are interpreted in a fairly model-independent way. Further specifying the model, various search results can be combined to obtain constraints on the model parameters. In $p\bar{p}$ collisions, the most copiously produced SUSY particles are expected to be the colored ones, namely squarks and gluinos. The pattern of lighter SUSY particles, however, plays a rôle in the interpretation of the search results, as it has an impact on the squark and gluino decay chains. A model, typically mSUGRA, is therefore needed to translate the search results into constraints on physically relevant quantities. As will be discussed later, the searches for squarks and gluinos in the canonical scenario suffer from large backgrounds, which renders competitive the searches for electroweak gauginos, in spite of lower production cross sections, for parameter configurations such that multileptonic final states arising from the gaugino decays are enhanced. Searches in scenarios other than the canonical one call for specific strategies relying, for instance, on the observation of additional photons or stable particles.

II.4. Searches at LEP in the canonical scenario: At LEP, the production of SUSY particles via electroweak interactions is only suppressed, compared to similar SM processes, by the phase space reduction near the kinematic limit. This suppression is stronger for scalars (sleptons and squarks) than for charginos. In general, for a given process, only data collected at the highest LEP energies are relevant for the ultimate mass limits obtained, but it may happen for some specific processes that the cross section is strongly reduced by mixing effects, *e.g.*, for neutralinos with a small higgsino component, in which case the large integrated luminosity collected at lower energies provides additional sensitivity.

Sleptons: The simplest case is that of smuon pair production, which proceeds only via s-channel Z/γ^* exchange. In models with slepton and gaugino mass unification, the $\tilde{\mu}_R$ is expected to be lighter than the $\tilde{\mu}_L$. The search results are therefore interpreted under this assumption, which is conservative since the $\tilde{\mu}_R$ coupling to the Z is smaller than that of the $\tilde{\mu}_L$. Only one parameter is necessary to calculate the production cross section, the smuon mass $m_{\tilde{\mu}_R}$. If the $\tilde{\mu}_R$ is the NLSP, its only decay mode is $\tilde{\mu}_R \to \mu\tilde{\chi}_1^0$, and its pair production therefore leads to a distinct final state consisting of two acoplanar muons with missing energy. ("Acoplanar" means that the difference in azimuth between the two muons is smaller than 180°, *i.e.*, the two muons are not back-to-back when projected onto a plane perpendicular to the beam axis.) The only significant background comes from $e^+e^- \to W^+W^- \to \mu^+\nu\mu^-\bar{\nu}$, which is well under control. The selection efficiency is very high, except when the $\tilde{\mu}_R$–$\tilde{\chi}_1^0$ mass difference is small, in which case the muons carry little momentum. A second parameter, the LSP mass $m_{\tilde{\chi}_1^0}$ is therefore needed to interpret the search results, as shown in Fig. 1 for the combination of the four LEP experiments [4]. In models with gaugino mass unification, it is expected that the second lightest neutralino $\tilde{\chi}_2^0$ will have a mass roughly twice that of the LSP, in which case the $\tilde{\mu}_R \to \mu\tilde{\chi}_2^0$ decay can compete with the direct decay into $\mu\tilde{\chi}_1^0$ for small $\tilde{\chi}_1^0$ masses. The impact of this effective efficiency reduction can be seen in Fig. 1, for $\mu = -200$ GeV and $\tan\beta = 1.5$. Altogether, smuon masses below 95 to 99 GeV, depending on the $\tilde{\chi}_1^0$ mass, are excluded as long as the $\tilde{\mu}_R$–$\tilde{\chi}_1^0$ mass difference is larger than 5 GeV.

The case of staus is similar, except for the fact that the final taus further decay, and that the ultimate decay products are softer than the muons in the smuon case. The selection efficiency is therefore lower. An additional complication comes from the L–R mixing, which is expected to be non-negligible for large values of $\tan\beta$, and can reduce the coupling of the lightest stau to the Z. In the worst case where the stau does

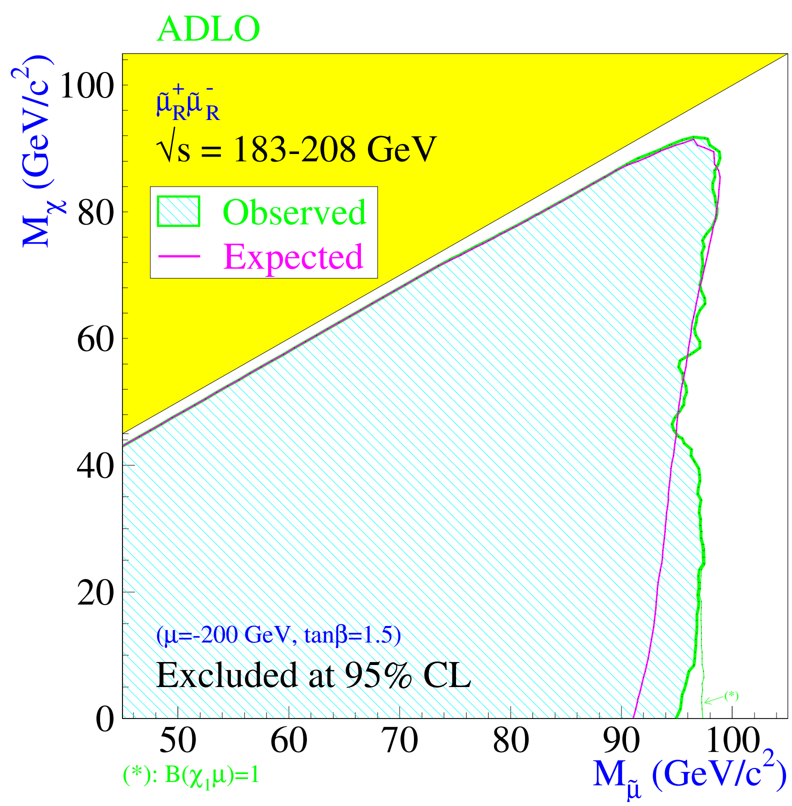

Figure 1: Region in the $(m_{\tilde{\mu}_R}, m_{\tilde{\chi}^0_1})$ plane excluded by the searches for smuons at LEP. See full-color version on color pages at end of book.

not couple to the Z, stau masses smaller than 86 to 95 GeV are excluded, depending on $m_{\tilde{\chi}^0_1}$, as long as the stau–$\tilde{\chi}^0_1$ mass difference is larger than 7 GeV [4].

For selectrons as for smuons, L–R mixing is expected to be negligible. But pair production receives an additional contribution from t-channel neutralino exchange, which tends to increase the production cross section. For $\mu = -200$ GeV and $\tan\beta = 1.5$, the $\tilde{e}_R$ mass lower limit is 100 GeV for $m_{\tilde{\chi}^0_1} < 85$ GeV [4]. Furthermore, the t-channel exchange allows for associated $\tilde{e}_L \tilde{e}_R$ production. Assuming slepton and gaugino mass unification at the GUT scale, the $\tilde{e}_L$ and $\tilde{e}_R$ masses are related, with the former heavier by a few GeV. Associated production gives the viable signal of a single energetic electron in the case where the $\tilde{e}_R$–$\tilde{\chi}_1^0$ mass difference is too small to observe $\tilde{e}_R$ pair production. This allows a lower limit of 73 GeV to be set on $m_{\tilde{e}_R}$, independent of the $\tilde{\chi}_1^0$ mass [5].

Indirect limits on the sneutrino mass can be derived from the slepton mass limits if slepton and gaugino mass unification is assumed. More generally, a $\tilde{\nu}$ LSP or NLSP mass limit of 45 GeV can be deduced from the measurement of the invisible Z width [6], for three mass degenerate sneutrinos.

Charginos and neutralinos: The masses and field content in the chargino sector depend on only three parameters: M_2, μ and $\tan\beta$. The masses and field content in the neutralino sector depend on those same parameters, and, in addition, on M_1. The latter is, however, related to M_2 assuming gaugino mass unification: $M_1 = (5/3)\tan^2\theta_W M_2 \sim 0.5 M_2$. This assumption is made for the results presented below, unless explicitly specified. Traditionally, three regions are distinguished: "gaugino" if $M_2 \ll |\mu|$, "higgsino" if $|\mu| \ll M_2$, and mixed if M_2 and $|\mu|$ have similar values. In the gaugino region, the lighter chargino and second lightest neutralino masses are close to M_2, the mass of the lightest neutralino is close to M_1, while the heavier chargino and neutralinos all have masses close to $|\mu|$; this is the typical configuration encountered in mSUGRA. In the higgsino region, all chargino and neutralino masses are close to $|\mu|$, so that the mass splitting between the lightest chargino and neutralino tends to be small. In the following, "chargino" will stand for "lighter chargino."

Chargino pair production proceeds via s-channel Z/γ^* and t-channel $\tilde{\nu}_e$ exchanges, with destructive interference. For chargino masses accessible at LEP energies, the decays are mediated by virtual W ($\tilde{\chi}^\pm \to W^{*\pm}\tilde{\chi}_1^0 \to f\bar{f}'\tilde{\chi}_1^0$) and sfermion ($\tilde{\chi}^\pm \to \tilde{f}^*\bar{f}' \to f\bar{f}'\tilde{\chi}_1^0$) exchange. Two-body decays such as $\tilde{\chi}^\pm \to \ell^\pm\tilde{\nu}$ are occasionally kinematically allowed, in which case they are dominant. Similarly, neutralino pair or associated production proceeds via s-channel Z and t-channel $\tilde{e}$ exchange, and $\tilde{\chi}_2^0$ decays are mediated by virtual Z and sfermion exchange. Here also, two-body decays such as $\tilde{\chi}_2^0 \to \nu\tilde{\nu}$ may have to be considered.

First, the case of heavy sfermions is addressed. Only s-channel exchange contributes to gaugino production, and the decays proceed via gauge boson exchange. For chargino pair production, the final states are therefore the same as those arising from W pairs, but for the addition of two LSPs. Selections have been designed for all-hadronic ($q\bar{q}'q\bar{q}'\tilde{\chi}_1^0\tilde{\chi}_1^0$), mixed ($q\bar{q}'\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$) and fully leptonic ($\ell\nu\ell\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$) topologies. No excess over SM backgrounds, of which the largest comes from W pair production, was observed. A scan over M_2, μ, and $\tan\beta$ provided a robust chargino mass lower limit of 103 GeV for sneutrino masses larger than 200 GeV [7], except for unnaturally large values of M_2 ($>\sim$ 1 TeV), in the so-called "deep higgsino" region, where the $\tilde{\chi}^{\pm}$–$\tilde{\chi}_1^0$ mass splitting is very small.

This limit is degraded for lower sneutrino masses for two reasons. First, the production cross section is reduced by the negative interference between the s- and t-channel exchanges. Second, two-body decays open up, which may reduce the selection efficiency. This is the case in particular in the so-called "corridor" where $m_{\tilde{\chi}^{\pm}} - m_{\tilde{\nu}}$ is smaller than a few GeV, so that the lepton from the $\tilde{\chi}^{\pm} \to \ell\tilde{\nu}$ decay is hardly visible. Neutralino associated production ($e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$), for which the interference tends to be positive, can be used to mitigate those effects, and searches for acoplanar jets or leptons from $\tilde{\chi}_2^0 \to f\bar{f}\tilde{\chi}_1^0$ were devised, which did not reveal any excess over SM backgrounds. Chargino and neutralino production and decays now depend, however, on the detailed sfermion spectrum. To interpret the search results, squark and slepton mass unification is therefore also assumed, so that the relevant phenomenolgy can be described with the addition of the single m_0 parameter. At this point, the results of neutralino searches can be combined with those for charginos into exclusion domains in the (M_2, μ) plane for selected values of $\tan\beta$ and m_0.

The searches for neutralinos, however, lose their sensitivity when the two-body decay $\tilde{\chi}_2^0 \to \nu\tilde{\nu}$ opens up, which leads to an invisible final state. Slepton mass lower limits can provide useful constraints in that configuration. The reason is that the slepton and gaugino masses are related by the RGEs as

$m^2_{\tilde{\ell}_R} \simeq m_0^2 + 0.22 M_2^2 - \sin^2\theta_W m_Z^2 \cos 2\beta$. For given values of $\tan\beta$ and m_0, a lower limit on $m_{\tilde{\ell}_R}$ can therefore be translated into a lower limit on M_2. In the end, the chargino mass lower limit obtained in the simple case of heavy sfermions is only moderately degraded.

As indicated above, the chargino searches lose their sensitivity in the deep-higgsino region, because of too small a $\tilde{\chi}^{\pm}$–$\tilde{\chi}^0_1$ mass difference. In the most extreme case, the chargino becomes long-lived. Dedicated searches for charged massive stable particles were designed, which take advantage of the higher ionization of such particles. In less extreme cases, the soft final state products resemble those resulting from "two-photon" interactions. In such interactions, the beam electrons radiate quasi-real photons whose collision produces a low mass system, while the incoming electrons escape undetected in the beam pipe. Chargino pair production can however be disentangled from that background when "tagged" by an energetic photon from initial state radiation ($e^+e^- \to \gamma\tilde{\chi}^+\tilde{\chi}^-$).

These various techniques allowed charginos with masses smaller than 92 GeV to be excluded in the canonical scenario with gaugino and sfermion mass unification [8].

The lightest neutralino: If the gaugino mass unification assumption is not made, there is no general mass limit from e^+e^- collisions for the lightest neutralino. A very light photino-like neutralino decouples from the Z, so that it cannot be pair produced via s-channel Z exchange, and production via t-channel selectron exchange can be rendered negligible for sufficiently heavy selectrons.

With the assumption of gaugino mass unification, on the other hand, indirect mass limits can be derived, mostly from chargino pair production. In the case of heavy sfermions, the limit is 52 GeV at large $\tan\beta$, somewhat lower otherwise. If sfermions are allowed to be light, sfermion mass unification is used and the limit at large $\tan\beta$ becomes 47 GeV. It is set by slepton searches in the corridor.

Higgs boson searches at LEP provide additional constraints at low $\tan\beta$. The analysis is rather involved, but can be summarized (and simplified) as follows. The mass of the lightest

Higgs boson in the MSSM receives radiative corrections due to the splitting between the top and stop masses. The stop mass depends on m_0 and M_3, the latter being related by unification to M_2. For given values of m_0 and $\tan\beta$, the mass lower limit on the Higgs boson translates into a lower limit on M_3, hence on M_2. These constraints are most effective at low m_0 and $\tan\beta$, where those from chargino searches are weakest.

The combination of chargino, slepton and Higgs boson searches provides the lower limit on $m_{\tilde{\chi}_1^0}$ as a function of $\tan\beta$ displayed in Fig. 2 [9]. The "absolute" lower limit is 47 GeV, obtained at large $\tan\beta$. In the more constrained mSUGRA scenario, where in particular μ is no longer a free parameter, a slightly tighter limit of 50 GeV is derived [10].

Squarks: As will be seen later, the mass reach for squarks at the Tevatron extends well beyond the masses accessible at LEP. There are, however, configurations for which the Tevatron searches are not efficient, and for which useful information is still provided by LEP. This is particularly relevant in the stop sector because the lighter of the two mass eigenstates (hereafter simply denoted "stop" or $\tilde{t}$) may be substantially less massive than all other squarks. One reason is that, if squark masses are unified at the GUT scale, $m_{\tilde{t}_R}$ is driven at the electroweak scale to lower values than the other squark mass terms by the large top Yukawa coupling. Another reason is that the off-diagonal terms of the stop squared-mass matrix, which are proportional to m_t, are much larger than for the other squark species.

At LEP energies, given the chargino mass limit which effectively forbids $\tilde{t} \to b\tilde{\chi}^+$, and as long as $m_{\tilde{t}} < m_W + m_b + m_{\tilde{\chi}_1^0}$, the main stop decay mode is expected to be $\tilde{t} \to c\tilde{\chi}_1^0$, which proceeds via flavor-changing loops. The stop lifetime may therefore be long enough to compete with the hadronization time, a feature which has been included in the simulation programs. The final state arising from stop pair production followed by $\tilde{t} \to c\tilde{\chi}_1^0$ is a pair of acoplanar jets with missing energy. The mass limit obtained depends slightly on the amount of L–R mixing. In the worst case where the stop does not couple to the Z, stop masses from 96 to 99 GeV, depending on the $\tilde{\chi}_1^0$ mass, are excluded as long as $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} - m_c > 5$ GeV [11].

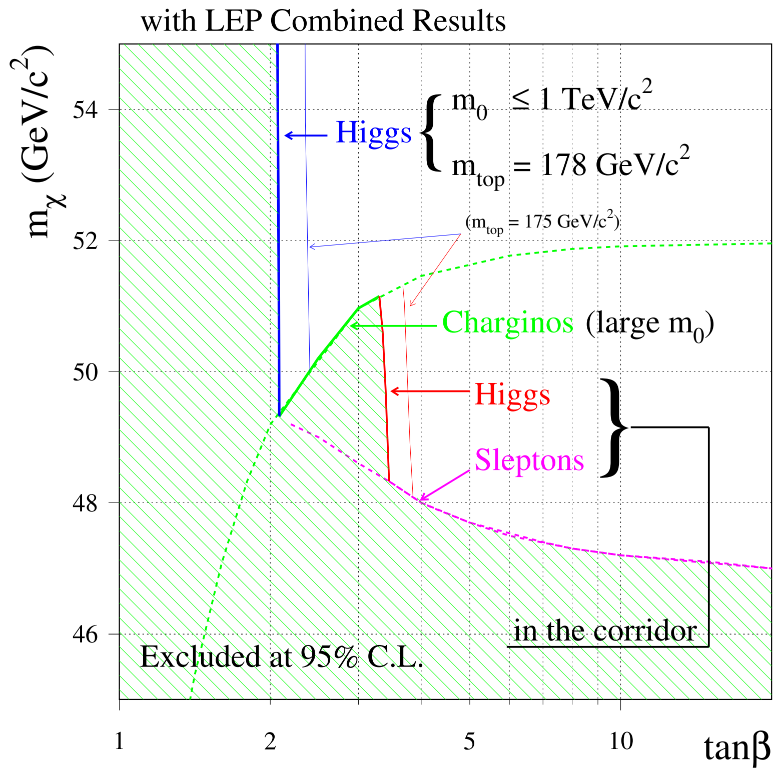

Figure 2: Lower mass limit for the lightest neutralino as a function of $\tan\beta$, inferred in the conventional scenario from searches at LEP for charginos, sleptons, and neutral Higgs bosons. See full-color version on color pages at end of book.

Dedicated searches were performed in addition to cope with smaller mass differences. In particular, the creation of long-lived R-hadrons in the stop hadronization process was taken into account, as well as the specific interactions of those R-hadrons in the detector material. (R-hadrons are color-neutral exotic bound states, *e.g.*, formed from a squark and an antiquark.) In the end, a mass lower limit of 63 GeV was set for the top squark, irrespective of $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ [12].

It has been pointed out that, for specific choices of parameters, the four-body decay mode $\tilde{t} \to bf\bar{f}'\tilde{\chi}_1^0$ could compete with $\tilde{t} \to c\tilde{\chi}_1^0$ [13]. A set of selections was designed to address this possibility, and the 63 GeV mass limit was found to hold, independent of the proportions of four-body and two-body decay modes [12]. Finally, if sneutrinos are sufficiently light for the $\tilde{t} \to b\ell\tilde{\nu}$ three-body decay mode to be kinematically allowed, in which case it will be dominant, a stop mass lower limit of 96 GeV was obtained for sneutrino masses smaller than 86 GeV [11].

The lightest sbottom mass eigenstate, $\tilde{b}$, could also be light for large values of $\tan\beta$, which enhance the off-diagonal terms of the sbottom squared-mass matrix. The situation is simpler than for the stop because the $\tilde{b} \to b\tilde{\chi}_1^0$ tree-level decay mode is expected to be dominant. Searches for acoplanar b-flavored jets were performed, leading to mass lower limits of about 95 GeV for a vanishing coupling of the sbottom to the Z [11].

II.5. Searches at LEP in non-canonical scenarios: SUSY scenarios beyond the canonical one were also extensively studied at LEP.

GMSB: The phenomenology of GMSB, with an ultra-light gravitino LSP, depends essentially on the nature of the NLSP and on its lifetime.

In the case of a neutralino NLSP, the $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decay mode is expected to be dominant in the mass range accessible at LEP. The production of a pair of $\tilde{\chi}_1^0$ with short lifetime would therefore lead to acoplanar photons with missing energy. No excess was observed above the background from $e^+e^- \to (Z^{(*)} \to \nu\bar{\nu})\gamma\gamma$ [14]. In typical GMSB models, the neutralino NLSP is bino-like. Pair production is thus mediated by t-channel selectron exchange. An exclusion domain in the $(m_{\tilde{e}_R}, m_{\tilde{\chi}_1^0})$ plane was therefore derived. The highest $\tilde{\chi}_1^0$ mass excluded is 102 GeV for light selectrons, and the interpretation of an anomalous $ee\gamma\gamma+\not{E}_T$ event observed by CDF in Run I of the Tevatron [15] in terms of pair production of selectrons with $\tilde{e} \to e\tilde{\chi}_1^0 \to e\gamma\tilde{G}$ is excluded. For non-prompt decays, searches for photons which do not point back to the primary vertex were performed, while long neutralino lifetimes lead to a phenomenology similar to that of the canonical scenario. Combinations of the results of these and a number of other searches in various topologies expected within a minimal GMSB framework were performed, leading to an absolute neutralino NLSP mass limit of 54 GeV [16].

The other generic NLSP candidate in GMSB is a scalar tau, for some parameter configurations almost mass degenerate with $\tilde{e}_R$ and $\tilde{\mu}_R$. A stau NLSP decays according to $\tilde{\tau} \to \tau\tilde{G}$. For prompt decays, this is similar to a stau NLSP with a light $\tilde{\chi}_1^0$ in the canonical scenario. For long lifetimes, the stau will appear as a highly ionizing charged particle, for which searches have been designed as discussed for charginos in the deep-higgsino region. For intermediate lifetimes, dedicated selections for in-flight decays along charged particle tracks were devised. A combination of all these searches excluded a stau NLSP with mass below 87 GeV, irrespective of its lifetime [17].

AMSB: With a wino LSP, the mass difference between the chargino and the LSP is expected to be small, leading to topologies identical to those encountered in the deep higgsino region of the canonical scenario. The chargino mass lower limit of 92 GeV [8] also holds in the AMSB framework for large sfermion masses.

A gluino LSP: The possibility that the LSP be a light gluino has also been considered. Gluinos cannot be produced directly by e^+e^- annihilation, but they could be produced by gluon splitting, for instance in $e^+e^- \to Z \to q\bar{q}g^* \to q\bar{q}\tilde{g}\tilde{g}$, or in the decays of pair-produced squarks. Such gluinos would then hadronize into long-lived R-hadrons. Dedicated searches were performed [18], leading to the exclusion of a gluino LSP with mass smaller than 27 GeV.

R-parity violation: If R-parity is allowed to be violated, new terms appear in the superpotential, that do not conserve the lepton or baryon number: $\lambda_{ijk}L_iL_j\bar{E}_k$, $\lambda'_{ijk}L_iQ_j\bar{D}_k$, $\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$, where L and Q are lepton and quark doublet superfields, E, D and U are lepton and quark singlet superfields, and i, j and k are generation indices. These terms induce new couplings such that the LSP can decay to SM particles. For instance, a neutralino LSP could decay according to $\tilde{\chi}_1^0 \to e\mu\nu$ via a λ type coupling. With a λ'' coupling, a $\tilde{\chi}_1^0$ decay would lead to three hadronic jets. Since the simultaneous presence of different coupling types is strongly constrained, for instance by the lower limit on the proton lifetime, the assumption was made that only one of the R-parity violating couplings is non-vanishing. It was also assumed that this coupling is sufficiently large for the R-parity violating decays to take place close to the e^+e^- collision point ($<\sim$ 1 cm) so that lifetime issues can be ignored.

Even with these simplifying assumptions, the number of possible final states arising from SUSY particle pair production is considerable. Nevertheless, all were considered at LEP, ranging from four leptons with missing energy for a λ coupling and $\tilde{\chi}_1^0$ pair production, now a process leaving a visible signature, to ten jets for a λ'' coupling and chargino pair production with $\tilde{\chi}^\pm \rightarrow q\bar{q}'\tilde{\chi}_1^0$. In the end, limits at least as constraining as in the canonical scenario were obtained [19].

Single production of a SUSY particle may also take place when R-parity is violated, with a production cross section now depending on the value of the λ coupling involved. The possibility of single, possibly resonant sneutrino production was investigated [20], and, in the absence of any signal, sneutrino mass lower limits extending almost to the full center-of-mass energy were established for sufficiently large values of the coupling.

II.6. Searches at HERA: The HERA $e^\pm p$ collider at DESY terminated its operation at the end of June 2007, after having delivered an integrated luminosity of ~ 0.5 fb^{-1} at a center-of-mass energy of 320 GeV to each of the H1 and ZEUS experiments. Since ep collisions do not involve annihilation processes, only R-parity violating resonant production of squarks could be investigated with good sensitivity. The production proceeds via a λ'_{1j1} or λ'_{11k} coupling, with a cross section depending on the value of the R-parity violating coupling involved. The produced squark can decay either directly with R-parity violation, or indirectly via a cascade leading to the LSP which in turn decays to SM particles (two jets and a neutrino or a charged lepton). Selections for these various topologies were combined to lead, within some mild model assumptions, to squark mass lower limits as high as 275 GeV for a λ' coupling of electromagnetic strength, *i.e.*, equal to 0.3 [21]. These results should be improved once the full HERA integrated luminosity is analyzed.

II.7. Searches at the Tevatron: Because of the much higher center-of-mass energy, the mass reach of the Tevatron for SUSY particles is expected to largely exceed the one achieved at LEP. In $p\bar{p}$ collsions, however, the effective parton-parton center-of-mass energy $\sqrt{\hat{s}}$ is only a fraction $\sqrt{x_1 x_2}$ of the total center-of-mass energy $\sqrt{s}$, where x_1 and x_2 are the fractions of the p and $\bar{p}$ momenta carried by the colliding partons. Because of the rapid decrease of the PDFs as a function of x, probing high $\sqrt{\hat{s}}$ values implies accumulating correspondingly large integrated luminosities.

Compared to the situation at LEP, the searches for SUSY in $p\bar{p}$ collisions are further complicated by the huge disparity between the cross sections of the processes of interest, currently of order 0.1 pb, and those of the SM backgrounds, *e.g.*, ~ 80 mb for the total inelastic cross section. Even for final states involving leptons, one has to cope with the $W \to \ell\nu$ and $Z \to \ell\ell$ backgrounds, with cross sections as large as ~ 2.6 nb and ~ 240 pb, respectively, per lepton flavor.

In the following, all results presented were obtained during Run II of the Tevatron collider, as they supersede those from Run I due to the higher center-of-mass energy and to integrated luminosities already up to a factor twenty larger.

Squarks and gluinos: Colored SUSY particles are expected to be the most copiously produced in $p\bar{p}$ collisions. If $m_{\tilde{q}} \ll m_{\tilde{g}}$, $\tilde{q}\bar{\tilde{q}}$ and, to a lesser extent, $\tilde{q}\tilde{q}$ pair productions are the dominant processes, and the search is performed in the $\tilde{q} \to q\tilde{\chi}_1^0$ decay channel, which leads to a final state consisting of a pair of acoplanar jets. If $m_{\tilde{g}} \ll m_{\tilde{q}}$, gluino pair production dominates, and the decay channel considered is $\tilde{g} \to \tilde{q}^*\bar{q} \to q\bar{q}\tilde{\chi}_1^0$, leading to a four-jet final state with $\not{E}_T$. Finally, if squark and gluino masses are similar, three-jet final states are expected to arise from $\tilde{q}\tilde{g}$ associated production. Soft jets from initial and final state radiation may increase these jet multiplicities. Cascade decays such as $\tilde{q} \to \tilde{\chi}^{\pm}q' \to \ell\nu q'\tilde{\chi}_1^0$, however, complicate the picture, and a specific model has to be used to assess their impact. This is why both CDF and DØ revert to the mSUGRA framework to interpret their search results, in which case the ten SUSY partners of the five light quark flavors can be considered mass degenerate for practical purposes.

Backgrounds to squark and gluino production arise from two types of sources: those with real $\not\!\!E_T$, such as $(W \to \ell\nu)$+jets, and those with fake $\not\!\!E_T$ from jet energy mismeasurements in standard multijet events produced by strong interaction. In the following, these backgrounds are denoted SM and QCD, respectively. Selection criteria were designed for each of the three relative mass configurations listed above, with at least two, at least three and at least four energetic jets, and with large $\not\!\!E_T$. Backgrounds of the SM type are largely suppressed by vetoes on isolated leptons, except for $(Z \to \nu\nu)$+jets, which is irreducible, and the remaining contribution is determined from Monte Carlo simulations. In the QCD background, the distribution of missing transverse energy from jet mismeasurements peaks strongly at low values but, because of the huge multijet production cross section, significant contributions remain even at large $\not\!\!E_T$. A substantial reduction is obtained, however, by requiring that the $\not\!\!E_T$ direction point away from the jets. While CDF estimates the remaining contribution from Monte Carlo simulations calibrated on control samples, DØ applies tighter selection criteria so that the QCD background is brought to a negligible level.

In the end, no excess was observed above expected backgrounds in the various selections, which translates into excluded domains in the $(m_{\tilde{g}}, m_{\tilde{q}})$ plane. Taking into account the large theoretical uncertainties on the signal production cross sections arising from the choice of PDFs, and of renormalization and factorization scales, lower limits of 325 and 241 GeV were published by DØ [22] for the squark and gluino masses, respectively, based on an integrated luminosity of 310 pb^{-1}. Along the $m_{\tilde{g}} = m_{\tilde{q}}$ line, the limit is 337 GeV. These results, derived for $\tan\beta = 3$, $A_0 = 0$, and $\mu < 0$, are valid for a large class of parameter sets at low $\tan\beta$. A preliminary result from DØ [23], based on an integrated luminosity of ~ 1 fb^{-1}, excludes $m_{\tilde{q}} < 375$ GeV, $m_{\tilde{g}} < 289$ GeV, and $(m_{\tilde{g}} = m_{\tilde{q}}) < 383$ GeV, as shown in Fig. 3.

Similar preliminary results were obtained by the CDF collaboration, based on an integrated luminosity of 1.4 fb^{-1} [24]. Within the mSUGRA framework, these limits can be compared with those from slepton and chargino searches in e^+e^- collisions, as shown for DØ in Fig. 3 and for CDF in Fig. 4. The domain in the parameter space excluded at LEP is extended for simultaneously low values of m_0 (below 250 GeV) and $m_{1/2}$ (below 160 GeV).

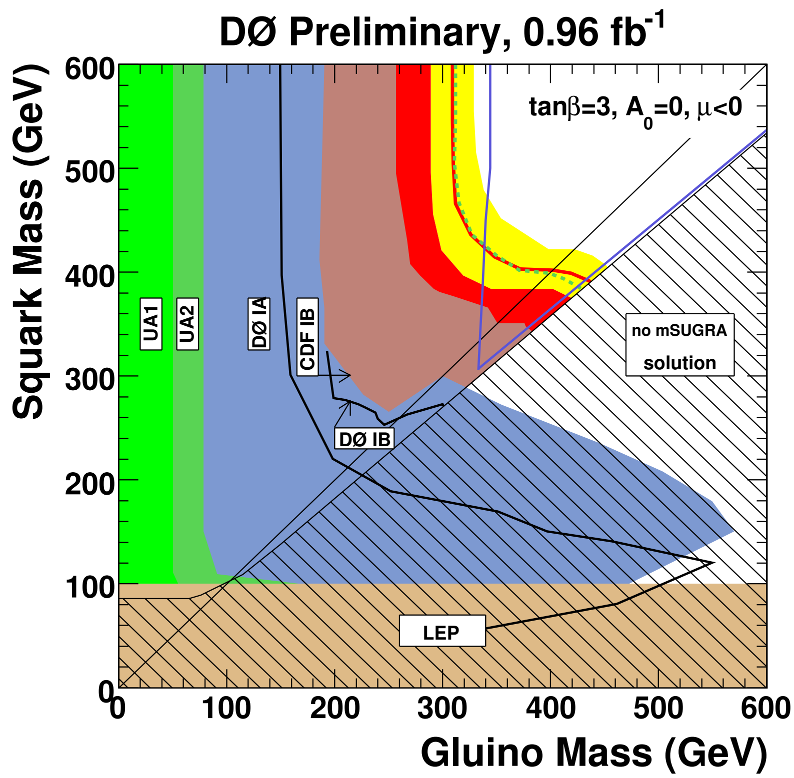

Figure 3: Region in the $(m_{\tilde{g}}, m_{\tilde{q}})$ plane excluded by DØ and by earlier experiments. The red curve corresponds to the nominal scale and PDF choices. The yellow band represents the uncertainty associated with these choices. The blue curves represent the indirect limits inferred from the LEP chargino and slepton searches. See full-color version on color pages at end of book.

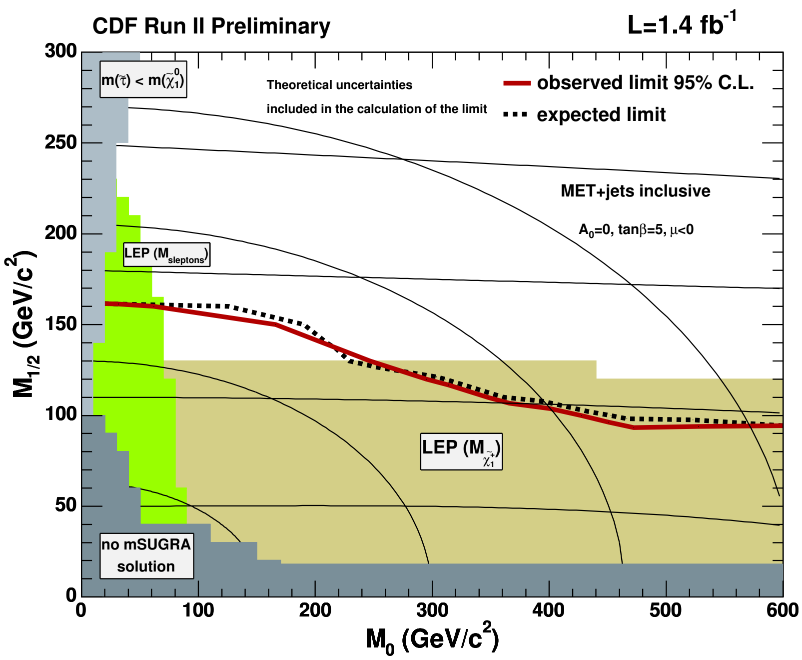

Figure 4: Region in the $(m_0, m_{1/2})$ plane excluded by CDF and by the LEP experiments. The nearly horizontal black lines are the iso-mass curves for gluinos corresponding to masses of 150, 300, 450 and 600 GeV. The other lines are iso-mass curves for squarks, corresponding to masses of 150, 300, 450 and 600 GeV. See full-color version on color pages at end of book.

For larger values of $\tan\beta$, mass hierarchies such as $m_{\tilde{q}_L} > m_{\tilde{e}} \sim m_{\tilde{\mu}} > m_{\tilde{\chi}^{\pm}} > m_{\tilde{\tau}}$ are not uncommon, for which squark pair production leads to final states involving jets, τs, and $\not\!\!E_T$. A dedicated search for these topologies was performed by DØ [25], which provides additional sensitivity for squark searches at larger values of $\tan\beta$.

Stop and sbottom: As explained earlier, a stop mass eigenstate could be much lighter than the other squarks. Dedicated searches were therefore performed for stop pair production followed by $\tilde{t} \to c\tilde{\chi}_1^0$ decays. The final state is a pair of acoplanar charm jets with $\not\!\!E_T$. Compared to the previous case of generic squarks, the cross section is much smaller because only one squark specie is produced. The mass range probed is, therefore, accordingly smaller. Consequently, the jets are softer and there is less $\not{E}_T$. A lifetime-based heavy-flavor tagging is used in the selection to mitigate the corresponding loss of sensitivity. The published CDF [26] and DØ [27] results, based on integrated luminosities of 295 and 360 pb^{-1}, respectively, exclude stop masses up to 134 GeV for $m_{\tilde{\chi}_1^0} = 48$ GeV. A preliminary result from DØ [28], based on an integrated luminosity of ~ 1 fb^{-1}, excludes $m_{\tilde{t}} < 149$ GeV for $m_{\tilde{\chi}_1^0} = 63$ GeV, as shown in Fig. 5, with theoretical uncertainties taken into account as explained above. These stop searches at the Tevatron lose their sensitivity when the $\tilde{t}$–$\tilde{\chi}_1^0$ mass difference becomes smaller than ~ 40 GeV, because of the $\not{E}_T$ requirement applied to reduce the otherwise overwhelming QCD background, so that the LEP constraints remain relevant, although restricted to $m_{\tilde{t}} < 100$ GeV.

Similar searches were performed for sbottom pair production [26,29], with $\tilde{b} \rightarrow b\tilde{\chi}_1^0$. The sensitivity extends to higher masses than in the stop case because heavy-flavor tagging is more efficient for b than for c jets. The lower $\tilde{b}$ mass limit set by DØ reaches 222 GeV for $m_{\tilde{\chi}_1^0} < 60$ GeV. The CDF collaboration investigated the configuration where gluinos are lighter than all squark species except for the sbottom, thus decaying according to $\tilde{g} \rightarrow b\tilde{b}$, followed by $\tilde{b} \rightarrow b\tilde{\chi}_1^0$. The final state consists of four b jets with $\not{E}_T$. Gluino and sbottom mass lower limits reaching 280 and 240 GeV, respectively, were obtained for $m_{\tilde{\chi}_1^0} = 60$ GeV, based on an integrated luminosity of 156 pb^{-1} [30].

A search for stop pair production followed by $\tilde{t} \rightarrow b\ell\tilde{\nu}$ decays was also performed by DØ, based on 400 pb^{-1}, to address the parameter configurations leading to light sneutrinos. Final states with two muons or with a muon and an electron together with b jets and $\not{E}_T$ were investigated. The largest stop mass excluded is 186 GeV for a sneutrino mass of 71 GeV [31].

Finally, the possibility of a stop stable on the scale of the time needed to escape the detector was considered by the CDF collaboration [32]. The resulting R-hadron would behave as a slow moving muon, and can be discriminated from the real muon background by comparing its momentum and its velocity, using

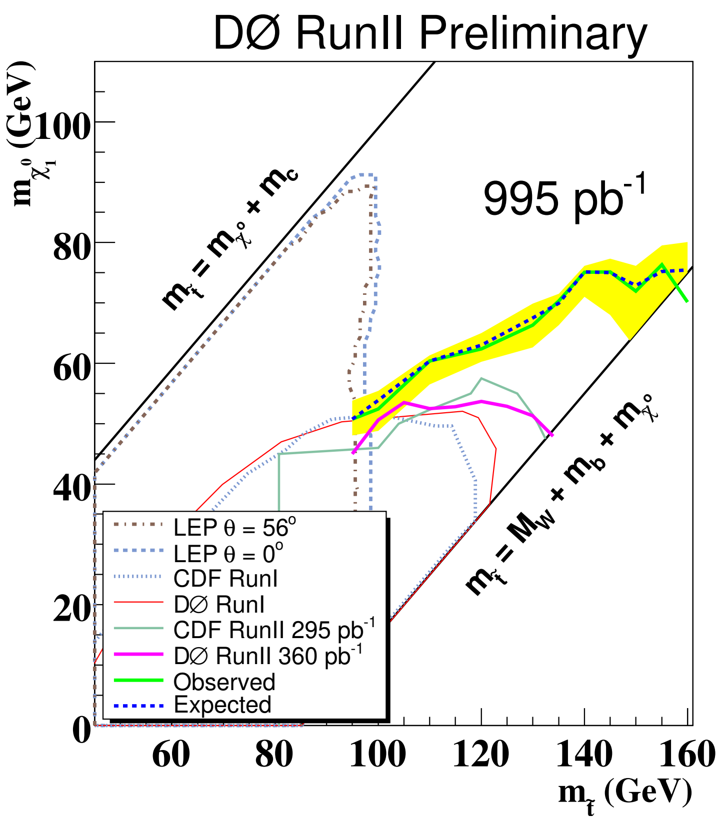

Figure 5: Region in the $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ plane excluded by DØ and by earlier experiments. The solid curve corresponds to the nominal scale and PDF choices. The yellow band represents the uncertainty associated with these choices. See full-color version on color pages at end of book.

a time-of-flight measurement. A preliminary mass lower limit of 250 GeV was obtained, based on an integrated luminosity of 1 fb^{-1}.

Charginos and neutralinos: Associated chargino-neutralino production, $p\bar{p} \to \tilde{\chi}^{\pm}\tilde{\chi}_2^0$, proceeds via s-channel W and t-channel squark exchange, with destructive interference. This process could provide a distinct trilepton+$\not\!\!E_T$ signal at the Tevatron if the branching ratios for leptonic decays ($\tilde{\chi}^{\pm} \to \ell^{\pm}\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$) are sufficiently large. Since these decays are mediated by virtual vector boson or sfermion exchange, this condition will be satisfied if sleptons are sufficiently light. The search is nevertheless challenging because the final state leptons carry little energy, and the production cross section is only a fraction of a picobarn.

In order to reduce the impact of lepton identification inefficiencies, and also to retain some sensitivity for final states involving τs, only two leptons were required to be positively identified as electrons or muons, while for the third lepton only an isolated charged track requirement was imposed. In addition, searches were performed for same sign leptons since in that case SM backgrounds from Z/γ^* production are much smaller. Series of analysis criteria involving requirements on the lepton and third track isolation, on the amount of $\not\!\!E_T$, and on the absence of energetic jets were applied.

No significant excess over SM background expectation was observed by DØ [33] or CDF [34], based on 320 pb^{-1} and 1.1 fb^{-1}, respectively. These results were interpreted within slightly modified versions of mSUGRA. In the case of CDF, m_0 was set equal to 70 GeV, while for DØ m_0 was adjusted for every value of $m_{1/2}$ such that the slepton masses are just above $m_{\tilde{\chi}_2^0}$ (this configuration is denoted "3l-max"). In practice, the CDF and DØ prescriptions favor two- and three-body decays, respectively. Both collaborations set $\tan\beta = 3$ and $\mu > 0$, and adjust A_0 so that there is no mixing in the stau sector. The chargino mass limit obtained by CDF under these conditions is 129 GeV. A recent update from DØ [35], based on 0.9 to 1.7 fb^{-1}, depending on the channel, provides a preliminary chargino mass lower limit of 145 GeV, as shown in Fig. 6. For large values of m_0, the leptonic branching ratios are reduced, so that the current searches do not have sensitivity beyond the LEP limit of 103 GeV.

R-parity violation: A whole new phenomenology opens up if R-parity is not assumed to be conserved. The searches can be divided into two classes.

First, R-parity conserving pair production of SUSY particles has been considered, with R-parity violation appearing only in the LSP decay at the end of the decay chains. The case

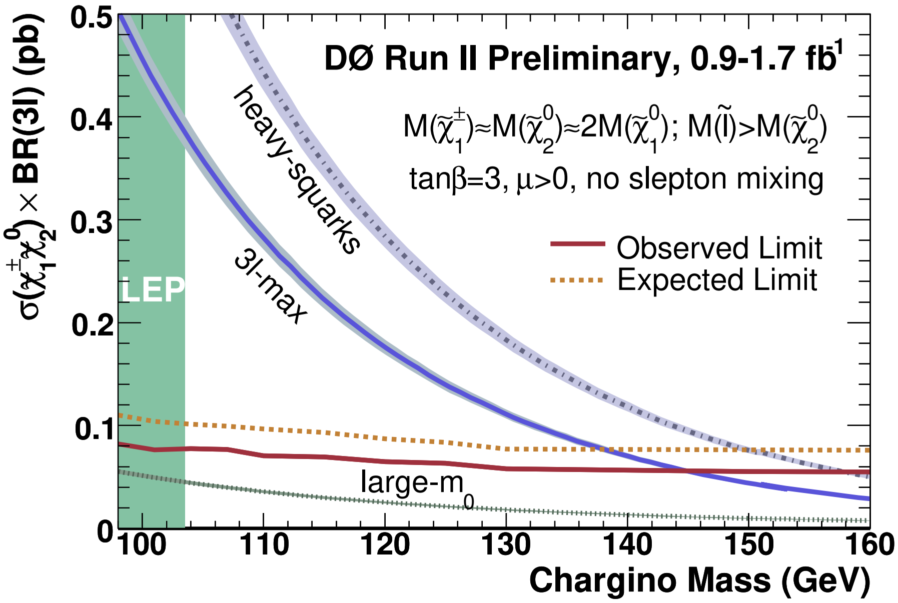

Figure 6: Upper limit from DØ on the product of cross section times branching ratio into three leptons for the associated $\tilde{\chi}^{\pm}\tilde{\chi}_2^0$ production at the Tevatron. The "3l-max" theoretical curve corresponds to the hypotheses detailed in the text. See full-color version on color pages at end of book.

of gaugino pair production, with a lepton-number violating coupling of the λ type in the neutralino LSP decay, has been extensively studied. Four charged leptons are expected in the final state, with flavors depending on the generation indices in the λ_{ijk} coupling, and there is also some $\not\!\!E_T$ from the two neutrinos. Searches have been performed by CDF [36] and DØ [37] in the cases of λ_{121} and λ_{122} couplings, and by DØ in the case of a λ_{133} coupling for which τs appear in the final state. The chargino mass lower limits obtained by DØ in the mSUGRA framework with $m_0 = 1$ TeV, $\tan\beta = 5$, and $\mu > 0$ are 231, 229, and 166 GeV for the λ_{121}, λ_{122}, and λ_{133} couplings, respectively, based on 360 pb^{-1}.

The CDF collaboration also searched for stop pair production, with $\tilde{t} \to b\tau$ decays mediated by a λ'_{333} coupling [38]. No such signal was observed in the topology where one τ decays into an electron or a muon and the other into hadrons, and a stop mass lower limit of 151 GeV was derived, based on 322 pb^{-1}.

The DØ collaboration investigated the case of pair production of a neutralino LSP with a mass of a few GeV, followed by $\tilde{\chi}_1^0 \to \mu^+\mu^-\nu$ decays via a λ_{i22} coupling [39]. The values of the coupling considered were such that the $\tilde{\chi}_1^0$ is long-lived, and the search was therefore directed toward dimuon vertices displaced from the main interaction vertex. This search was motivated by anomalous dimuon events observed by the NuTeV collaboration in a neutrino experiment [40]. With no signal observed by DØ, such an explanation for those events has been ruled out.

Second, resonant slepton production could occur via a λ'_{i11} R-parity violating coupling. The case of a λ'_{211} coupling was considered by DØ [41], with R-parity conserving decays of the resonantly produced slepton ($\tilde{\mu} \to \tilde{\chi}_i^0\mu$ and $\tilde{\nu}_\mu \to \tilde{\chi}^\pm\mu$). The violation of R-parity is again manifest in the decay of the neutralino LSP into a muon or a neutrino + two jets. No excess over background was observed, and an exclusion domain was placed in the $(m_{\tilde{\mu}}, \lambda'_{211})$ plane, the production cross section now depending on the value of λ'_{211}. For $\lambda'_{211} = 0.1$, a smuon mass lower limit of 363 GeV is obtained in mSUGRA with $\tan\beta = 5$, $A_0 = 0$ and $\mu < 0$, based on 380 pb^{-1}.

Resonant sneutrino production was also investigated by the CDF collaboration in the case where the sneutrino decays via a λ type coupling, hence different from the coupling involved in the production. The decay channels considered were ee, $\mu\mu$, $\tau\tau$ and $e\mu$. Sneutrino mass limits were derived, dependent on the product of the λ' and λ couplings considered [42].

Other non-canonical scenarios: As discussed earlier, a neutralino or stau NLSP is expected in GMSB. SUSY particle pair production, with cascade decays to a $\tilde{\chi}_1^0$ NLSP followed by $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ has been investigated by both CDF and DØ through inclusive searches for diphoton final states with large $\not{\!\!E}_T$. Backgrounds from photon misidentification or from fake $\not{\!\!E}_T$ were determined from data, and no significant excess of events was observed. The two collaborations combined their published results [43], based on 200–260 pb^{-1}, to set a chargino mass lower limit of 209 GeV in a benchmark GMSB model known as the "Snowmass slope SPS 8" [44]. (This model has one parameter, the effective SUSY-breaking scale Λ, with $N_5 = 1$ messenger, a messenger mass of 2Λ, $\tan\beta = 15$ and $\mu > 0$.) A recent preliminary result from DØ, based on 1.1 fb^{-1}, increased the chargino mass limit to 231 GeV [45].

The additional possibility of non-prompt $\tilde{\chi}_1^0$ decays was considered by CDF, taking advantage of the timing information provided by their calorimeter [46]. No signal of delayed photons was observed in 570 pb^{-1}, and an excluded domain in the $(m_{\tilde{\chi}_1^0}, \tau_{\tilde{\chi}_1^0})$ plane was derived, where $\tau_{\tilde{\chi}_1^0}$ is the $\tilde{\chi}_1^0$ lifetime, extending out to 101 GeV for $\tau_{\tilde{\chi}_1^0} = 5$ ns.

The case of a long-lived stau NLSP was also investigated. Pair production would resemble a pair of slow-moving muons. The timing information of their muon system was used by DØ, and no excess of such anomalously slow muons was observed in 390 pb^{-1} [47]. However, the sensitivity of the search is not yet sufficient to set a stau mass lower limit. Long-lived charginos as in AMSB would lead to the same signature. The larger production cross section allowed a preliminary lower limit of 174 GeV to be set on the mass of such long-lived gaugino-like charginos.

Within the recently proposed model of split SUSY, gluinos are expected to acquire a substantial lifetime. After hadronization into a R-hadron, such a long-lived gluino produced in a $p\bar{p}$ collision could come to rest in a calorimeter, and decay during a later bunch crossing than that during which it was produced [48]. The main decay mode is expected to be $\tilde{g} \to g\tilde{\chi}_1^0$, with some competition from $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$. Such a late gluino decay would appear as a jet not pointing toward the detector center in an otherwise empty event. Such a possibility was considered by the DØ collaboration. The main backgrounds, coming from showering cosmic muons and from muons belonging to the beam halo, were estimated from data, and no excess of such a topology was observed. Based on an integrated luminosity of 410 pb^{-1}, limits were set on the mass of such a gluino, with some dependence on the lifetime, the decay branching ratio, the $\tilde{\chi}_1^0$ mass, and the probability for a neutral R-hadron to convert into a charged one in the calorimeter [49]. For instance, for a lifetime smaller than three hours, a neutralino mass of 50 GeV, a conversion cross section of 3 mb, and a 100% branching ratio into $g\tilde{\chi}_1^0$, a mass limit of 270 GeV was obtained.

II.8. Conclusion: The masses of SUSY particles other than the gluino and the LSP have been constrained at LEP to be larger than $\sim$ 100 GeV, essentially independent of any specific model. Within the MSSM with unification of gaugino and sfermion masses, an indirect lower limit of 47 GeV has been set by the LEP experiments for the mass of a neutralino LSP. The mass reach at the Tevatron is much larger than at LEP, but the results need to be interpreted in the context of specific models. Based on an integrated luminosity of 1 fb^{-1}, the current squark and gluino mass lower limits are 375 and 289 GeV, respectively, within the mSUGRA framework at low $\tan\beta$. It is expected that 6–7 fb^{-1} will be accumulated at the Tevatron by 2009, and that the LHC will begin operation in the course of 2008, which will open a whole new window for SUSY searches.

References

1. M. Drees and G. Gerbier, *Dark matter*, in this volume of The Review of Particle Physics.
2. Y. Kwon and G. Punzi, *Production and decay of b-flavored hadrons*, in this volume of The Review of Particle Physics.
3. A. Höcker and W.J. Marciano, *The muon anomalous moment*, in this volume of The Review of Particle Physics.
4. LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL experiments, note LEPSUSYWG/04-01.1, `http://lepsusy.web.cern.ch/lepsusy/Welcome.html`.
5. ALEPH Coll., Phys. Lett. **B544**, 73 (2002); L3 Coll., Phys. Lett. **B580**, 37 (2004).
6. The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavours Groups, Phys. Reports **427**, 257 (2006).
7. LEPSUSYWG, *ibid.*, note LEPSUSYWG/01-03.1.
8. LEPSUSYWG, *ibid.*, note LEPSUSYWG/02-04.1.
9. LEPSUSYWG, *ibid.*, note LEPSUSYWG/04-07.1.
10. LEPSUSYWG, *ibid.*, note LEPSUSYWG/02-06.2.

11. LEPSUSYWG, *ibid.*, note LEPSUSYWG/04-02.1.
12. ALEPH Coll., Phys. Lett. **B537**, 5 (2002).
13. C. Boehm, A. Djouadi, and Y. Mambrini, Phys. Rev. **D61**, 095006 (2000).
14. LEPSUSYWG, *ibid.*, note LEPSUSYWG/04-09.1.
15. CDF Coll., Phys. Rev. **D59**, 092002 (1999).
16. ALEPH Coll., Eur. Phys. J. **C25**, 339 (2002);
OPAL Coll., Eur. Phys. J. **C46**, 307 (2006).
17. LEPSUSYWG, *ibid.*, note LEPSUSYWG/02-09.2.
18. ALEPH Coll., Eur. Phys. J. **C31**, 327 (2003);
DELPHI Coll., Eur. Phys. J. **C26**, 505 (2003).
19. LEPSUSYWG, *ibid.*, note LEPSUSYWG/02-10.1;
ALEPH Coll., Eur. Phys. J. **C31**, 1 (2003);
DELPHI Coll., Eur. Phys. J. **C36**, 1 (2004);
L3 Coll., Phys. Lett. **B524**, 65 (2002);
OPAL Coll., Eur. Phys. J. **C33**, 149 (2004).
20. ALEPH Coll., Eur. Phys. J. **C19**, 415 (2001) and Eur. Phys. J. **C25**, 1 (2002);
DELPHI Coll., Eur. Phys. J. **C28**, 15 (2003);
L3 Coll., Phys. Lett. **B414**, 373 (1997):
OPAL Coll., Eur. Phys. J. **C13**, 553 (2000).
21. H1 Coll., Phys. Lett. **B599**, 159 (2004);
H1 Coll., Eur. Phys. J. **C36**, 425 (2004);
ZEUS Coll., Eur. Phys. J. **C50**, 269 (2007).
22. DØ Coll., Phys. Lett. **B638**, 119 (2006).
23. DØ Coll., *Search for squarks and gluinos in events with jets and missing transverse energy with the DØ detector using 1 fb^{-1} of Run IIa data*, DØ-Note 5312-CONF.
24. CDF Coll., *Search for Squark/Gluino Production in MET+ jets Final State (1.4 fb^{-1} analysis)*,
`http://www-cdf.fnal.gov/physics/exotic/r2a/20070809.squark_gluino/public.html`.
25. DØ Coll., *Search for squark production in events with jets, hadronically decaying taus and missing transverse energy with the DØ detector at $\sqrt{s}$ =1.96 TeV in the Run IIa data*, DØ-Note 5468-CONF.
26. CDF Coll., Phys. Rev. **D76**, 072010 (2007).
27. DØ Coll., Phys. Lett. **B645**, 119 (2007).
28. DØ Coll., *Search for the pair production of scalar top quarks in acoplanar charm jet + missing transverse energy final state in $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV*, DØ-Note 5436-CONF.
29. DØ Coll., Phys. Rev. Lett. **97**, 171806 (2006).

30. CDF Coll., Phys. Rev. Lett. **96**, 171802 (2006).
31. DØ Coll., *Search for the lightest scalar top quark in events with two leptons in $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV*, submitted to Phys. Lett. **B**, `arXiv:0707.2864v1`[hep-ex].
32. CDF Coll., *Search for charged, massive stable particles*, CDF-Note 8701.
33. DØ Coll., Phys. Rev. Lett. **95**, 151805 (2005).
34. CDF Coll., Phys. Rev. Lett. **98**, 221803 (2007) and *Search for chargino-neutralino production in $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV*, accepted for publication in Phys. Rev. Lett., `arXiv:0707.2362v1`[hep-ex].
35. DØ Coll., *Search for the Associated Production of Chargino and Neutralino in Final States with Two Electrons and an Additional Lepton*, DØ-Note 5464-CONF.
36. CDF Coll., Phys. Rev. Lett. **98**, 131804 (2007).
37. DØ Coll., Phys. Lett. **B638**, 441 (2006).
38. CDF Coll., *Search for Pair Production of Scalar Top Quarks Decaying to a τ Lepton and a b Quark*, CDF-Note 7835.
39. DØ Coll., Phys. Rev. Lett. **97**, 161802 (2006).
40. NuTeV Coll., Phys. Rev. Lett. **87**, 041801 (2001).
41. DØ Coll., Phys. Rev. Lett. **97**, 111801 (2006).
42. CDF Coll., Phys. Rev. Lett. **95**, 252001 (2005);
CDF Coll., Phys. Rev. Lett. **95**, 131801 (2005);
CDF Coll., Phys. Rev. Lett. **96**, 211802 (2006).
43. V. Buescher *et al.*, for the CDF and DØ Collaborations, *Combination of CDF and DØ Limits on a Gauge Mediated SUSY Model Using Diphoton and Missing Transverse Energy Channel*, arXiv:hep-ex/0504004v1.
44. B.C. Allanach *et al.*, Eur. Phys. J. **C25**, 113 (2002).
45. DØ Coll., *Search for GMSB in diphoton final states by DØ at $\sqrt{s}$ =1.96 TeV*, DØ-Note 5427-CONF.
46. CDF Coll., Phys. Rev. Lett. **99**, 121801 (2007).
47. DØ Coll., *A Search for Charged Massive Stable Particles at DØ*, DØ-Note 4746-CONF.
48. A. Arvanitaki *et al.*, *Stopping Gluinos*, `arXiv:hep-ph/0506242v2`.
49. DØ Coll., Phys. Rev. Lett. **99**, 131801 (2007).