Supersymmetric Particle Searches

SUPERSYMMETRY

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This review is divided into two parts:

Supersymmetry, Part I (Theory)

Supersymmetry, Part II (Experiment)

SUPERSYMMETRY, PART I (THEORY)

(by H.E. Haber)

I.1. Introduction: Supersymmetry (SUSY) is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and vice versa. It also provides a framework for the unification of particle physics and gravity [1–4], which is governed by the Planck scale, $M_{\rm P} \approx 10^{19}$ GeV (defined to be the energy scale where the gravitational interactions of elementary particles become comparable to the gauge interactions). In particular, it is possible that supersymmetry will ultimately explain the origin of the large hierarchy of energy scales from the W and Z masses to the Planck scale. The stability of this hierarchy in the presence of radiative corrections is not possible in the Standard Model, but can be maintained in supersymmetric theories.

If supersymmetry were an exact symmetry of nature, then particles and their superpartners (which differ in spin by half a unit) would be degenerate in mass. Since this is not observed in data, supersymmetry cannot be an exact symmetry and must be broken. Nevertheless, the stability of the hierarchy of scales mentioned above can still be maintained if the supersymmetry breaking is *soft* [5] and the corresponding supersymmetry-breaking mass terms are no larger than a few TeV. (In softly-broken supersymmetry, the theory behaves like an unbroken supersymmetric theory at energy scales much larger than the size of the supersymmetry-breaking masses.) The most interesting theories of this type are theories of "low-energy" (or "weak-scale") supersymmetry, where the effective scale of supersymmetry breaking is tied to the scale of electroweak symmetry breaking [6–8]. The latter is characterized by the Standard Model Higgs vacuum expectation value, $v = 246$ GeV.

At present, there are no unambiguous experimental results that require the existence of low-energy supersymmetry. However, one tantalizing clue may be the observed unification of the three gauge couplings at an energy scale close to the Planck scale. The unification of gauge couplings does not occur in the Standard Model, but is achievable in the minimal supersymmetric extension of the Standard Model, and provides an additional motivation for seriously considering the low-energy supersymmetric framework [9]. If experimentation at future colliders uncovers evidence for supersymmetry, this would have a profound effect on the study of TeV-scale physics, and the development of a more fundamental theory of mass and symmetry-breaking phenomena in particle physics.

I.2. Structure of the MSSM: The minimal supersymmetric extension of the Standard Model (MSSM) consists of taking the Standard Model and adding the corresponding supersymmetric partners [3,10]. In addition, the MSSM contains two hypercharge $Y = \pm 1$ Higgs doublets, which is the minimal structure for the Higgs sector of an anomaly-free supersymmetric extension of the Standard Model. The supersymmetric structure of the theory also requires (at least) two Higgs doublets to generate mass for both "up"-type and "down"-type quarks (and charged leptons) [11,12]. All renormalizable supersymmetric interactions consistent with (global) B–L conservation (B =baryon number and L =lepton number) are included. Finally, the most general soft-supersymmetry-breaking terms are added [5]. To generate nonzero neutrino masses, extra structure is needed as discussed briefly in section I.8.

If supersymmetry is associated with the origin of the scale of electroweak interactions, then the mass parameters introduced by the soft-supersymmetry-breaking must be generally of order 1 TeV or below [13] (although models have been proposed in which some supersymmetric particle masses can be larger, in the range of 1–10 TeV [14]). Some lower bounds on these parameters exist due to the absence of supersymmetric-particle production at current accelerators [15]. Additional constraints arise from limits on the contributions of virtual supersymmetric particle exchange to a variety of Standard Model processes [16,17].

For example, the Standard Model global fit to precision electroweak data is quite good [18]. If all supersymmetric particle masses are significantly heavier than m_Z (in practice, masses greater than 300 GeV are sufficient [19]), then the effects of the supersymmetric particles decouple in loop-corrections to electroweak observables [20]. In this case, the Standard Model global fit to precision data and the corresponding MSSM fit yield similar results. On the other hand, regions of parameter space with light supersymmetric particle masses (just above the present day experimental limits) can in some cases generate significant one-loop corrections, resulting in a slight improvement or worsening of the overall global fit to the electroweak data depending on the choice of the MSSM parameters [21]. Thus, the precision electroweak data provide some constraints on the magnitude of the soft-supersymmetry-breaking terms.

There are a number of other low-energy measurements that are especially sensitive to the effects of new physics through virtual loops. For example, the virtual exchange of supersymmetric particles can contribute to the muon anomalous magnetic moment, $a_\mu \equiv \frac{1}{2}(g-2)_\mu$, and to the inclusive decay rate for $b \to s\gamma$. The most recent theoretical analysis of $(g-2)_\mu$ finds only a small deviation (less than two standard deviations) of the theoretical prediction from the experimentally observed value [22]. The theoretical prediction for $\Gamma(b \to s\gamma)$ agrees quite well (within the error bars) to the experimental observation [23]. In both cases, supersymmetric corrections could have generated an observable shift from the Standard Model prediction in some regions of the MSSM parameter space [23–25]. The absence of a significant deviation places interesting constraints on the low-energy supersymmetry parameters.

As a consequence of B–L invariance, the MSSM possesses a multiplicative R-parity invariance, where $R = (-1)^{3(B-L)+2S}$ for a particle of spin S [26]. Note that this implies that all the ordinary Standard Model particles have even R parity, whereas the corresponding supersymmetric partners have odd R parity. The conservation of R parity in scattering and decay processes has a crucial impact on supersymmetric phenomenology. For example, starting from an initial state involving ordinary (R-even) particles, it follows that supersymmetric particles must be produced in pairs. In general, these particles are highly unstable and decay into lighter states. However, R-parity invariance also implies that the lightest supersymmetric particle (LSP) is absolutely stable, and must eventually be produced at the end of a decay chain initiated by the decay of a heavy unstable supersymmetric particle.

In order to be consistent with cosmological constraints, a stable LSP is almost certainly electrically and color neutral [27]. (There are some model circumstances in which a colored gluino LSP is allowed [28], but we do not consider this possibility further here.) Consequently, the LSP in an R-parity-conserving theory is weakly interacting with ordinary matter, *i.e.*, it behaves like a stable heavy neutrino and will escape collider detectors without being directly observed. Thus, the canonical signature for conventional R-parity-conserving supersymmetric theories is missing (transverse) energy, due to the escape of the LSP. Moreover, the LSP is a prime candidate for "cold dark matter" [29], a potentially important component of the non-baryonic dark matter that is required in many models of cosmology and galaxy formation [30]. Further aspects of dark matter can be found in Ref. [31].

In the MSSM, supersymmetry breaking is accomplished by including the most general renormalizable soft-supersymmetry-breaking terms consistent with the SU(3)×SU(2)×U(1) gauge symmetry and R-parity invariance. These terms parameterize our ignorance of the fundamental mechanism of supersymmetry breaking. If supersymmetry breaking occurs spontaneously, then a massless Goldstone fermion called the *goldstino* ($\widetilde{G}$) must exist. The goldstino would then be the LSP and could play an important role in supersymmetric phenomenology [32]. However, the goldstino is a physical degree of freedom only in models of spontaneously broken global supersymmetry. If the supersymmetry is a local symmetry, then the theory must incorporate gravity; the resulting theory is called supergravity. In models of spontaneously broken supergravity, the goldstino is "absorbed" by the *gravitino* ($\widetilde{g}_{3/2}$), the spin-3/2 partner of the graviton [33]. By this super-Higgs mechanism, the goldstino is removed from the physical spectrum and the gravitino acquires a mass ($m_{3/2}$).

It is very difficult (perhaps impossible) to construct a realistic model of spontaneously-broken low-energy supersymmetry where the supersymmetry breaking arises solely as a consequence of the interactions of the particles of the MSSM. A more viable scheme posits a theory consisting of at least two distinct sectors: a "hidden" sector consisting of particles that are completely neutral with respect to the Standard Model gauge group, and a "visible" sector consisting of the particles of the MSSM. There are no renormalizable tree-level interactions between particles of the visible and hidden sectors. Supersymmetry breaking is assumed to occur in the hidden sector, and to then be transmitted to the MSSM by some mechanism. Two theoretical scenarios have been examined in detail: gravity-mediated and gauge-mediated supersymmetry breaking.

Supergravity models provide a natural mechanism for transmitting the supersymmetry breaking of the hidden sector to the particle spectrum of the MSSM. In models of *gravity-mediated* supersymmetry breaking, gravity is the messenger of supersymmetry breaking [34,35]. More precisely, supersymmetry breaking is mediated by effects of gravitational strength (suppressed by an inverse power of the Planck mass). In this scenario, the gravitino mass is of order the electroweak-symmetry-breaking scale, while its couplings are roughly gravitational in strength [1,36]. Such a gravitino would play no role in supersymmetric phenomenology at colliders.

In *gauge-mediated* supersymmetry breaking, supersymmetry breaking is transmitted to the MSSM via gauge forces. A typical structure of such models involves a hidden sector where supersymmetry is broken, a "messenger sector" consisting of particles (messengers) with SU(3)×SU(2)×U(1) quantum numbers, and the visible sector consisting of the fields of the MSSM [37,38]. The direct coupling of the messengers to the hidden sector generates a supersymmetry breaking spectrum in the messenger sector. Finally, supersymmetry breaking is transmitted to the MSSM via the virtual exchange of the messengers. If this approach is extended to incorporate gravitational phenomena, then supergravity effects will also contribute to supersymmetry breaking. However, in models of gauge-mediated supersymmetry breaking, one usually chooses the model parameters in such a way that the virtual exchange of the messengers dominates the effects of the direct gravitational interactions between the hidden and visible sectors. In this scenario, the gravitino mass is typically in the eV to keV range, and is therefore the LSP. The helicity $\pm\frac{1}{2}$ components of $\widetilde{g}_{3/2}$ behave approximately like the goldstino; its coupling to the particles of the MSSM is significantly stronger than a coupling of gravitational strength.

During the last few years, new approaches to supersymmetry breaking have been proposed, based on theories in which the number of space dimensions is greater than three. This is not a new idea-consistent superstring theories are formulated in ten spacetime dimensions, and the associated M-theory is based in eleven spacetime dimensions [39]. Nevertheless, in all approaches considered above, the string scale and the inverse size of the extra dimensions are assumed to be at or near the Planck scale, below which an effective four spacetime dimensional broken supersymmetric field theory emerges. More recently, a number of supersymmetry-breaking mechanisms have been proposed that are inherently extra-dimensional. In some cases, the size of the extra dimensions can be significantly larger than $M_{\rm P}^{-1}$; in some cases of order $({\rm TeV})^{-1}$ or even larger [40,41]. For example, in one approach, the fields of the MSSM live on some brane (a lower-dimensional manifold existing in a higher dimensional spacetime), while the sector of the theory that breaks supersymmetry lives on a second separated brane. Two examples of this approach are anomaly-mediated supersymmetry breaking of Ref. [42] and gaugino-mediated supersymmetry breaking of Ref. [43]; in both cases supersymmetry-breaking is transmitted through fields that live in the bulk (the higher dimensional space between the two branes). This setup has some features in common with both gravity-mediated and gauge-mediated supersymmetry breaking (*e.g.*, a hidden and visible sector and messengers). In another approach, one starts with a higher dimensional theory, which is compactified to four spacetime dimensions. In this approach, supersymmetry is broken by boundary conditions on the compactified space that distinguish between fermions and bosons [44](the so-called Scherk-Schwarz mechanism [45]). The phenomenology of such models can be strikingly different from the usual MSSM [46]. These approaches clearly deserve further investigation, although they will not be discussed further here.

I.3. Parameters of the MSSM: The parameters of the MSSM are conveniently described by considering separately the supersymmetry-conserving sector and the supersymmetry-breaking sector. A careful discussion of the conventions used in defining the MSSM parameters can be found in Ref. [47]. For simplicity, consider the case of one generation of quarks, leptons, and their scalar superpartners. The parameters of the supersymmetry-conserving sector consist of: (i) gauge couplings: g_s, g, and g', corresponding to the Standard Model gauge group SU(3)×SU(2)×U(1) respectively; (ii) a supersymmetry-conserving Higgs mass parameter μ; and (iii) Higgs-fermion Yukawa coupling constants: λ_u, λ_d, and λ_e (corresponding to the coupling of one generation of quarks, leptons, and their superpartners to the Higgs bosons and higgsinos).

The supersymmetry-breaking sector contains the following set of parameters: (i) gaugino Majorana masses M_3, M_2, and M_1 associated with the SU(3), SU(2), and U(1) subgroups of the Standard Model; (ii) five scalar squared-mass parameters for the squarks and sleptons, $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, $M^2_{\widetilde{L}}$, and $M^2_{\widetilde{E}}$ [corresponding to the five electroweak gauge multiplets, *i.e.*, superpartners of $(u,d)_L$, u^c_L, d^c_L, $(\nu,\, e^-)_L$, and e^c_L, where the superscript c indicates a charge-conjugated fermion]; (iii) Higgs-squark-squark and Higgs-slepton-slepton trilinear interaction terms, with coefficients A_u, A_d, and A_e (these are the so-called "A parameters"); and (iv) three scalar Higgs squared-mass parameters-two of which (m_1^2 and m_2^2) contribute to the diagonal

Higgs squared-masses, given by $m_1^2 + |\mu|^2$ and $m_2^2 + |\mu|^2$, and a third which contributes to the off-diagonal Higgs squared-mass term, $m_{12}^2 \equiv B\mu$ (which defines the "B-parameter"). These three squared-mass parameters can be re-expressed in terms of the two Higgs vacuum expectation values, v_d and v_u (also called v_1 and v_2, respectively, in the literature), and one physical Higgs mass. Here, v_d (v_u) is the vacuum expectation value of the Higgs field which couples exclusively to down-type (up-type) quarks and leptons. Note that $v_d^2 + v_u^2 = 4m_W^2/g^2 = (246\ \text{GeV})^2$ is fixed by the W mass and the gauge coupling, whereas the ratio

$$\tan\beta = v_u/v_d \tag{1}$$

is a free parameter of the model.

The total number of degrees of freedom of the MSSM is quite large, primarily due to the parameters of the soft-supersymmetry-breaking sector. In particular, in the case of three generations of quarks, leptons, and their superpartners, $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, $M^2_{\widetilde{L}}$, and $M^2_{\widetilde{E}}$ are hermitian 3×3 matrices, and the A parameters are complex 3×3 matrices. In addition, M_1, M_2, M_3, B, and μ are in general complex. Finally, as in the Standard Model, the Higgs-fermion Yukawa couplings, λ_f ($f = u$, d, and e), are complex 3×3 matrices that are related to the quark and lepton mass matrices via: $M_f = \lambda_f v_f/\sqrt{2}$, where $v_e \equiv v_d$ (with v_u and v_d as defined above). However, not all these parameters are physical. Some of the MSSM parameters can be eliminated by expressing interaction eigenstates in terms of the mass eigenstates, with an appropriate redefinition of the MSSM fields to remove unphysical degrees of freedom. The analysis of Ref. [48] shows that the MSSM possesses 124 independent parameters. Of these, 18 parameters correspond to Standard Model parameters (including the QCD vacuum angle $\theta_{\rm QCD}$), one corresponds to a Higgs sector parameter (the analogue of the Standard Model Higgs mass), and 105 are genuinely new parameters of the model. The latter include: five real parameters and three CP-violating phases in the gaugino/higgsino sector, 21 squark and slepton masses, 36 real mixing angles to define the squark and slepton mass eigenstates, and 40 CP-violating phases that can appear in squark and slepton interactions. The most general R-parity-conserving minimal supersymmetric extension of the Standard Model (without additional theoretical assumptions) will be denoted henceforth as MSSM-124 [49].

I.4. The supersymmetric-particle sector: Consider the sector of supersymmetric particles (*sparticles*) in the MSSM. The supersymmetric partners of the gauge and Higgs bosons are fermions, whose names are obtained by appending "ino" at the end of the corresponding Standard Model particle name. The *gluino* is the color octet Majorana fermion partner of the gluon with mass $M_{\widetilde{g}} = |M_3|$. The supersymmetric partners of the electroweak gauge and Higgs bosons (the *gauginos* and *higgsinos*) can mix. As a result, the physical mass eigenstates are model-dependent linear combinations of these states, called *charginos* and *neutralinos*, which are obtained by diagonalizing the corresponding mass matrices. The chargino-mass matrix depends on M_2, μ, $\tan\beta$, and m_W [50].

The corresponding chargino-mass eigenstates are denoted by $\widetilde{\chi}_1^+$ and $\widetilde{\chi}_2^+$, with masses

$$M^2_{\widetilde{\chi}_1^+,\widetilde{\chi}_2^+} = \tfrac{1}{2}\Bigg\{|\mu|^2 + |M_2|^2 + 2m_W^2 \mp \Bigg[\Big(|\mu|^2 + |M_2|^2 + 2m_W^2\Big)^2 - 4|\mu|^2|M_2|^2 - 4m_W^4\sin^2 2\beta + 8m_W^2\sin 2\beta\,{\rm Re}(\mu M_2)\Bigg]^{1/2}\Bigg\}, \quad (2)$$

where the states are ordered such that $M_{\widetilde{\chi}_1^+} \leq M_{\widetilde{\chi}_2^+}$. If CP-violating effects are neglected (in which case, M_2 and μ are real parameters), then one can choose a convention where $\tan\beta$ and M_2 are positive. (Note that the relative sign of M_2 and μ is meaningful. The sign of μ is convention-dependent; the reader is warned that both sign conventions appear in the literature.) The sign convention for μ implicit in Eq. (2) is used by the LEP collaborations [15] in their plots of exclusion contours in the M_2 vs. μ plane derived from the non-observation of $e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$.

The neutralino mass matrix depends on M_1, M_2, μ, $\tan\beta$, m_Z, and the weak mixing angle θ_W [50]. The corresponding neutralino eigenstates are usually denoted by $\widetilde{\chi}_i^0$ ($i = 1, \ldots 4$), according to the convention that $M_{\widetilde{\chi}_1^0} \leq M_{\widetilde{\chi}_2^0} \leq M_{\widetilde{\chi}_3^0} \leq M_{\widetilde{\chi}_4^0}$. If a chargino or neutralino eigenstate approximates a particular gaugino or higgsino state, it is convenient to employ the corresponding nomenclature. Specifically, if M_1 and M_2 are small compared to m_Z and $|\mu|$, then the lightest neutralino $\widetilde{\chi}_1^0$ would be nearly a pure *photino*, $\widetilde{\gamma}$, the supersymmetric partner of the photon. If M_1 and m_Z are small compared to M_2 and $|\mu|$, then the lightest neutralino would be nearly a pure *bino*, $\widetilde{B}$, the supersymmetric partner of the weak hypercharge gauge boson. If M_2 and m_Z are small compared to M_1 and $|\mu|$, then the lightest chargino pair and neutralino would constitute a triplet of roughly mass-degenerate pure *winos*, $\widetilde{W}^{\pm}$, and $\widetilde{W}_3^0$, the supersymmetric partners of the weak SU(2) gauge bosons. Finally, if $|\mu|$ and m_Z are small compared to M_1 and M_2, then the lightest neutralino would be nearly a pure *higgsino*. Each of the above cases leads to a strikingly different phenomenology.

The supersymmetric partners of the quarks and leptons are spin-zero bosons: the *squarks*, charged *sleptons*, and *sneutrinos*. For simplicity, only the one-generation case is illustrated below (using first-generation notation). For a given fermion f, there are two supersymmetric partners, $\widetilde{f}_L$ and $\widetilde{f}_R$, which are scalar partners of the corresponding left- and right-handed fermion. (There is no $\widetilde{\nu}_R$ in the MSSM.) However, in general, $\widetilde{f}_L$ and $\widetilde{f}_R$ are not mass-eigenstates, since there is $\widetilde{f}_L$-$\widetilde{f}_R$ mixing which is proportional in strength to the corresponding element of the scalar squared-mass matrix [51]

$$M^2_{LR} = \begin{cases} m_d(A_d - \mu \tan\beta), & \text{for “down”-type } f \\ m_u(A_u - \mu \cot\beta), & \text{for “up”-type } f, \end{cases} \tag{3}$$

where m_d (m_u) is the mass of the appropriate “down” (“up”) type quark or lepton. The signs of the A parameters are also convention-dependent; see Ref. [47]. Due to the appearance of the *fermion* mass in Eq. (3), one expects M_{LR} to be small compared to the diagonal squark and slepton masses, with the possible exception of the top-squark, since m_t is large, and the bottom-squark and tau-slepton if $\tan\beta \gg 1$.

The (diagonal) L- and R-type squark and slepton squared-masses are given by

$$\begin{aligned} M^2_{\widetilde{f}_L} &= M^2_{\widetilde{F}} + m^2_f + (T_{3f} - e_f \sin^2\theta_W) m^2_Z \cos 2\beta \,, \\ M^2_{\widetilde{f}_R} &= M^2_{\widetilde{R}} + m^2_f + e_f \sin^2\theta_W m^2_Z \cos 2\beta \,, \end{aligned} \tag{4}$$

where $M^2_{\widetilde{F}} \equiv M^2_{\widetilde{Q}}$ [$M^2_{\widetilde{L}}$] for $\widetilde{u}_L$ and $\widetilde{d}_L$ [$\widetilde{\nu}_L$ and $\widetilde{e}_L$], and $M^2_{\widetilde{R}} \equiv M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, and $M^2_{\widetilde{E}}$ for $\widetilde{u}_R$, $\widetilde{d}_R$, and $\widetilde{e}_R$, respectively. In addition, $e_f = \frac{2}{3}$, $-\frac{1}{3}$, 0, -1 for $f = u$, d, ν, and e, respectively, $T_{3f} = \frac{1}{2}$ [$-\frac{1}{2}$] for up-type [down-type] squarks and sleptons, and m_f is the corresponding quark or lepton mass. Squark and slepton mass eigenstates, generically called $\widetilde{f}_1$ and $\widetilde{f}_2$ (these are linear combinations of $\widetilde{f}_L$ and $\widetilde{f}_R$), are obtained by diagonalizing the corresponding 2×2 squared-mass matrices.

In the case of three generations, the general analysis is more complicated. The scalar squared-masses [$M^2_{\widetilde{F}}$ and $M^2_{\widetilde{R}}$ in Eq. (4)], the fermion masses m_f, and the A parameters are now 3×3 matrices as noted in Section I.3. Thus, to obtain the squark and slepton mass eigenstates, one must diagonalize 6×6 mass matrices. As a result, intergenerational mixing is possible, although there are some constraints from the nonobservation of FCNC's [16,17]. In practice, because off-diagonal scalar mixing is appreciable only for the third generation, this additional complication can usually be neglected.

It should be noted that all mass formulae quoted in this section are tree-level results. One-loop corrections will modify all these results, and eventually must be included in any precision study of supersymmetric phenomenology [52].

I.5. The Higgs sector of the MSSM: Next, consider the MSSM Higgs sector [11,12,53]. Despite the large number of potential CP-violating phases among the MSSM-124 parameters, the tree-level MSSM Higgs sector is automatically CP-conserving. That is, unphysical phases can be absorbed into the definition of the Higgs fields such that $\tan\beta$ is a real parameter (conventionally chosen to be positive). Moreover, the physical neutral Higgs scalars are CP eigenstates. The model contains five physical Higgs particles: a charged Higgs boson pair ($H^{\pm}$), two CP-even neutral Higgs bosons (denoted by h^0 and H^0 where $m_h \leq m_H$), and one CP-odd neutral Higgs boson (A^0).

The properties of the Higgs sector are determined by the Higgs potential, which is made up of quadratic terms [whose squared-mass coefficients were mentioned above Eq. (1)] and quartic interaction terms whose coefficients are dimensionless couplings. The quartic interaction terms are manifestly supersymmetric at tree-level (and are modified by supersymmetry-breaking effects only at the loop level). In general, the quartic couplings arise from two sources: (i) the supersymmetric generalization of the scalar potential (the so-called "F-terms"), and (ii) interaction terms related by supersymmetry to the coupling of the scalar fields and the gauge fields, whose coefficients are proportional to the corresponding gauge couplings (the so-called "D-terms"). In the MSSM, F-term contributions to the quartic couplings are absent (although such terms may be present in extensions of the MSSM, *e.g.*, models with Higgs singlets). As a result, the strengths of the MSSM quartic Higgs interactions are fixed in terms of the gauge couplings. Due to the resulting constraint on the form of the two-Higgs-doublet scalar potential, all the tree-level MSSM Higgs-sector parameters depend only on two quantities: $\tan\beta$ [defined in Eq. (1)] and one Higgs mass (usually taken to be m_A). From these two quantities, one can predict the values of the remaining Higgs boson masses, an angle α (which measures the component of the original $Y = \pm 1$ Higgs doublet states in the physical CP-even neutral scalars), and the Higgs boson self-couplings.

When one-loop radiative corrections are incorporated, additional parameters of the supersymmetric model enter via virtual loops. The impact of these corrections can be significant [54]. For example, at tree-level, MSSM-124 predicts $m_h \leq m_Z|\cos 2\beta| \leq m_Z$ [11,12]. If this prediction were unmodified, it would be in conflict with the MSSM Higgs mass bounds obtained at LEP [55]. However, when radiative corrections are included, the light Higgs-mass upper bound may be significantly increased. The qualitative behavior of the radiative corrections can be most easily seen in the large top-squark mass limit, where in addition, both the splitting of the two diagonal entries [Eq. (4)] and the two off-diagonal entries [Eq. (3)] of the top-squark squared-mass matrix are small in comparison to the average of the two top-squark squared-masses, $M_{\rm S}^2 \equiv \frac{1}{2}(M^2_{\widetilde{t}_1} + M^2_{\widetilde{t}_2})$. In this case (assuming $m_A > m_Z$), the upper bound on the lightest CP-even Higgs mass at one-loop is approximately given by

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left\{\ln\left(M_{\rm S}^2/m_t^2\right) + \frac{X_t^2}{M_{\rm S}^2}\left(1 - \frac{X_t^2}{12 M_{\rm S}^2}\right)\right\}, \quad (5)$$

where $X_t \equiv A_t - \mu\cot\beta$ is the top-squark mixing factor [see Eq. (3)]. A more complete treatment of the radiative corrections [56] shows that Eq. (5) somewhat overestimates the true upper bound of m_h. These more refined computations, which incorporate renormalization group improvement and the leading two-loop contributions, yield $m_h \lesssim 130$ GeV (with an accuracy of a few GeV) for $m_t = 175$ GeV and $M_S \lesssim 2$ TeV [56].

In addition, one-loop radiative corrections can introduce CP-violating effects in the Higgs sector, which depend on some of the CP-violating phases among the MSSM-124 parameters [57]. Although these effects are more model-dependent, they can have a non-trivial impact on the Higgs searches at future colliders.

I.6. Reducing the MSSM parameter freedom: In Sections I.4 and I.5 we surveyed the parameters that comprise the MSSM-124. However in its most general form, the MSSM-124 is not a phenomenologically-viable theory over most of its parameter space. This conclusion follows from the observation that a generic point in the MSSM-124 parameter space exhibits: (i) no conservation of the separate lepton numbers L_e, L_μ, and L_τ; (ii) unsuppressed FCNC's; and (iii) new sources of CP violation that are inconsistent with the experimental bounds.

For example, the MSSM contains many new sources of CP violation [58]. In particular, some combination of the complex phases of the gaugino-mass parameters, the A parameters, and μ must be less than of order 10^{-2}–10^{-3} (for a supersymmetry-breaking scale of 100 GeV) to avoid generating electric dipole moments for the neutron, electron, and atoms in conflict with observed data [59,60]. As a result of the phenomenological deficiencies listed above, almost the entire MSSM-124 parameter space is ruled out! This theory is viable only at very special "exceptional" points of the full parameter space.

The MSSM-124 is also theoretically incomplete since it provides no explanation for the origin of the supersymmetry-breaking parameters (and in particular, why these parameters should conform to the exceptional points of the parameter space mentioned above). Moreover, there is no understanding of the choice of parameters that leads to the breaking of the electroweak symmetry. What is needed ultimately is a fundamental theory of supersymmetry breaking, which would provide a rationale for some set of soft-supersymmetry breaking terms that would be consistent with the phenomenological constraints referred to above. Presumably, the number of independent parameters characterizing such a theory would be considerably less than 124.

In the absence of a fundamental theory of supersymmetry breaking, there are two general approaches for reducing the parameter freedom of MSSM-124. In the low-energy approach, an attempt is made to elucidate the nature of the exceptional points in the MSSM-124 parameter space that are phenomenologically viable. Consider the following two possible choices. First, one can assume that $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$, $M^2_{\widetilde{L}}$, $M^2_{\widetilde{E}}$, and the matrix A parameters are generation-independent (horizontal universality [7,48,61]). Alternatively, one can simply require that all the aforementioned matrices are flavor diagonal in a basis where the quark and lepton mass matrices are diagonal (flavor alignment [62]). In either case, L_e, L_μ, and L_τ are separately conserved, while tree-level FCNC's are automatically absent. In both cases, the number of free parameters characterizing the MSSM is substantially less than 124. Both scenarios are phenomenologically viable, although there is no strong theoretical basis for either scenario.

In the high-energy approach, one treats the parameters of the MSSM as running parameters and imposes a particular structure on the soft-supersymmetry-breaking terms at a common high-energy scale (such as the Planck scale, $M_{\rm P}$). Using the renormalization group equations, one can then derive the low-energy MSSM parameters. The initial conditions (at the appropriate high-energy scale) for the renormalization group equations depend on the mechanism by which supersymmetry breaking is communicated to the effective low energy theory. Examples of this scenario are provided by models of gravity-mediated and gauge-mediated supersymmetry breaking (see Section I.2). One bonus of such an approach is that one of the diagonal Higgs squared-mass parameters is typically driven negative by renormalization group evolution. Thus, electroweak symmetry breaking is generated radiatively, and the resulting electroweak symmetry-breaking scale is intimately tied to the scale of low-energy supersymmetry breaking.

One prediction of the high-energy approach that arises in most grand unified supergravity models and gauge-mediated supersymmetry-breaking models is the unification of the (tree-level) gaugino mass parameters at some high-energy scale $M_{\rm X}$, *i.e.*,

$$M_1(M_X) = M_2(M_X) = M_3(M_X) = m_{1/2}\,. \tag{6}$$

Consequently, the effective low-energy gaugino mass parameters (at the electroweak scale) are related:

$$M_3 = (g_s^2/g^2)M_2 \ , \qquad M_1 = (5g'^2/3g^2)M_2 \simeq 0.5M_2 \ . \quad (7)$$

In this case, the chargino and neutralino masses and mixing angles depend only on three unknown parameters: the gluino mass, μ, and $\tan\beta$. If in addition $|\mu| \gg M_1$, m_Z, then the lightest neutralino is nearly a pure bino, an assumption often made in supersymmetric particle searches at colliders.

In a certain class of supergravity models, tree-level masses for the gauginos are absent. The gaugino mass parameters arise at one-loop and do not satisfy Eq. (7). In this case, one finds a model-independent contribution to the gaugino mass whose origin can be traced to the super-conformal (super-Weyl) anomaly, which is common to all supergravity models [42]. This approach is called *anomaly-mediated* supersymmetry breaking. Eq. (7) is then replaced (in the one-loop approximation) by:

$$M_i \simeq \frac{b_i g_i^2}{16\pi^2} m_{3/2} \,, \quad (8)$$

where $m_{3/2}$ is the gravitino mass (assumed to be of order 1 TeV), and b_i are the coefficients of the MSSM gauge beta-functions corresponding to the corresponding U(1), SU(2) and SU(3) gauge groups: $(b_1, b_2, b_3) = (\frac{33}{5}, 1, -3)$. Eq. (8) yields $M_1 \simeq 2.8M_2$ and $M_3 \simeq -8.3M_2$, which implies that over most of the MSSM parameter space the lightest chargino pair and neutralino make up a nearly mass-degenerate triplet of winos. (For example, if $|\mu| \gg m_Z$, then Eq. (8) implies that $M_{\widetilde{\chi}_1^\pm} \simeq M_{\widetilde{\chi}_1^0} \simeq M_2$ [63].) The corresponding supersymmetric phenomenology differs significantly from the standard phenomenology based on Eq. (7), and is explored in detail in Ref. [64]. Anomaly-mediated supersymmetry breaking also generates (approximate) flavor-diagonal squark and slepton mass matrices. However, this yields negative squared-mass contributions for the sleptons in the MSSM. This fatal flaw may be possible to cure in approaches beyond the minimal supersymmetric model [65]. Alternatively, one may conclude that anomaly-mediation is not the sole source of supersymmetry-breaking in the slepton sector.

I.7. The constrained MSSMs: mSUGRA, GMSB, and SGUTs: One way to guarantee the absence of significant FCNC's mediated by virtual supersymmetric-particle exchange is to posit that the diagonal soft-supersymmetry-breaking scalar squared-masses are universal at some energy scale. In models of gauge-mediated supersymmetry breaking, scalar squared-masses are expected to be flavor-independent since gauge forces are flavor-blind. In the *minimal* supergravity (mSUGRA) framework [1–3], the soft-supersymmetry-breaking parameters at the Planck scale take a particularly simple form in which the scalar squared-masses and the A parameters are flavor-diagonal and universal [34]:

$$
\begin{aligned}
& M^2_{\widetilde{Q}}(M_{\rm P}) = M^2_{\widetilde{U}}(M_{\rm P}) = M^2_{\widetilde{D}}(M_{\rm P}) = m_0^2\mathbf{1}\,, \\
& M^2_{\widetilde{L}}(M_{\rm P}) = M^2_{\widetilde{E}}(M_{\rm P}) = m_0^2\mathbf{1}\,, \\
& m_1^2(M_{\rm P}) = m_2^2(M_{\rm P}) = m_0^2\,, \\
& A_U(M_{\rm P}) = A_D(M_{\rm P}) = A_L(M_{\rm P}) = A_0\mathbf{1}\,,
\end{aligned} \tag{9}
$$

where $\mathbf{1}$ is a 3×3 identity matrix in generation space. Renormalization group evolution is then used to derive the values of the supersymmetric parameters at the low-energy (electroweak) scale. For example, to compute squark and slepton masses, one must use the *low-energy* values for $M^2_{\widetilde{F}}$ and $M^2_{\widetilde{R}}$ in Eq. (4).

Through the renormalization group running with boundary conditions specified in Eq. (7) and Eq. (9), one can show that the low-energy values of $M^2_{\widetilde{F}}$ and $M^2_{\widetilde{R}}$ depend primarily on m_0^2 and $m^2_{1/2}$. A number of useful approximate analytic expressions for superpartner masses in terms of the mSUGRA parameters can be found in Ref. [66].

Clearly, in the mSUGRA approach, the MSSM-124 parameter freedom has been significantly reduced. For example, typical mSUGRA models give low-energy values for the scalar mass parameters that satisfy $M_{\widetilde{L}} \approx M_{\widetilde{E}} < M_{\widetilde{Q}} \approx M_{\widetilde{U}} \approx M_{\widetilde{D}}$, with the squark mass parameters somewhere between a factor of 1–3 larger than the slepton mass parameters (*e.g.*, see Ref. [66]). More precisely, the low-energy values of the squark mass parameters of the first two generations are roughly degenerate, while $M_{\widetilde{Q}_3}$ and $M_{\widetilde{U}_3}$ are typically reduced by a factor of 1–3 from the values of the first and second generation squark mass parameters, because of renormalization effects due to the heavy top quark mass.

As a result, one typically finds that four flavors of squarks (with two squark eigenstates per flavor) and $\widetilde{b}_R$ are nearly mass-degenerate. The $\widetilde{b}_L$ mass and the diagonal $\widetilde{t}_L$ and $\widetilde{t}_R$ masses are reduced compared to the common squark mass of the first two generations. (If $\tan\beta \gg 1$, then the pattern of third generation squark masses is somewhat altered; *e.g.*, see Ref. [67].) In addition, there are six flavors of nearly mass-degenerate sleptons (with two slepton eigenstates per flavor for the charged sleptons and one per flavor for the sneutrinos); the sleptons are expected to be somewhat lighter than the mass-degenerate squarks. Finally, third generation squark masses and tau-slepton masses are sensitive to the strength of the respective $\widetilde{f}_L$–$\widetilde{f}_R$ mixing, as discussed below Eq. (3).

Due to the implicit $m_{1/2}$ dependence in the low-energy values of $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$, and $M^2_{\widetilde{D}}$, there is a tendency for the gluino in mSUGRA models to be lighter than the first- and second-generation squarks. Moreover, the LSP is typically the lightest neutralino, $\widetilde{\chi}^0_1$, which is dominated by its bino component. However, there are some regions of mSUGRA parameter space where the above conclusions do not hold. For example, one can reject those mSUGRA parameter regimes in which the LSP is a chargino. In general, if one imposes the constraints of supersymmetric particle searches and those of cosmology (say, by requiring the LSP to be a suitable dark matter candidate), one obtains significant restrictions to the mSUGRA parameter space. A recent compilation of benchmark mSUGRA points consistent with present data from particle physics and cosmology can be found in Ref. [68].

One can count the number of independent parameters in the mSUGRA framework. In addition to 18 Standard Model parameters (excluding the Higgs mass), one must specify m_0, $m_{1/2}$, A_0, and Planck-scale values for μ and B-parameters (denoted by μ_0 and B_0). In principle, A_0, B_0, and μ_0 can be complex, although in the mSUGRA approach, these parameters are taken (arbitrarily) to be real. As previously noted, renormalization group evolution is used to compute the low-energy values of the mSUGRA parameters, which then fixes all the parameters of the low-energy MSSM. In particular, the two Higgs vacuum expectation values (or equivalently, m_Z and $\tan\beta$) can be expressed as a function of the Planck-scale supergravity parameters. The simplest procedure is to remove μ_0 and B_0 in favor of m_Z and $\tan\beta$ (the sign of μ_0 is not fixed in this process). In this case, the MSSM spectrum and its interaction strengths are determined by five parameters: m_0, A_0, $m_{1/2}$, $\tan\beta$, and the sign of μ_0, in addition to the 18 parameters of the Standard Model. However, the mSUGRA approach is probably too simplistic. Theoretical considerations suggest that the universality of Planck-scale soft-supersymmetry-breaking parameters is not generic [69]. In particular, it is easy to write down effective operators at the Planck scale that do not respect flavor universality, and it is difficult to find a theoretical principle that would forbid them.

In contrast, in gauge-mediated supersymmetry breaking, universality of the fundamental soft-supersymmetry-breaking squark and slepton squared-mass parameters is guaranteed because the supersymmetry-breaking is communicated to the sector of MSSM fields via gauge interactions. In the minimal gauge-mediated supersymmetry-breaking (GMSB) approach, there is one effective mass scale, Λ, that determines all low-energy scalar and gaugino mass parameters through loop-effects (while the resulting A parameters are suppressed). In order that the resulting superpartner masses be of order 1 TeV or less, one must have $\Lambda \sim 100$ TeV. The origin of the μ and B-parameters is quite model-dependent, and lies somewhat outside the ansatz of gauge-mediated supersymmetry breaking. The simplest models of this type are even more restrictive than mSUGRA, with two fewer degrees of freedom. However, minimal GMSB is not a fully realized model. The sector of supersymmetry-breaking dynamics can be very complex, and no complete model of gauge-mediated supersymmetry yet exists that is both simple and compelling.

It was noted in Section I.2 that the gravitino is the LSP in GMSB models. Thus, in such models, the next-to-lightest supersymmetric particle (NLSP) plays a crucial role in the phenomenology of supersymmetric particle production and decay.

Note that unlike the LSP, the NLSP can be charged. In GMSB models, the most likely candidates for the NLSP are $\widetilde{\chi}_1^0$ and $\widetilde{\tau}_R^{\pm}$. The NLSP will decay into its superpartner plus a gravitino (*e.g.*, $\widetilde{\chi}_1^0 \to \gamma\widetilde{g}_{3/2}$, $\widetilde{\chi}_1^0 \to Z\widetilde{g}_{3/2}$ or $\widetilde{\tau}_R^{\pm} \to \tau^{\pm}\widetilde{g}_{3/2}$), with lifetimes and branching ratios that depend on the model parameters.

Different choices for the identity of the NLSP and its decay rate lead to a variety of distinctive supersymmetric phenomenologies [38,70]. For example, a long-lived $\widetilde{\chi}_1^0$-NLSP that decays outside collider detectors leads to supersymmetric decay chains with missing energy in association with leptons and/or hadronic jets (this case is indistinguishable from the canonical phenomenology of the $\widetilde{\chi}_1^0$-LSP). On the other hand, if $\widetilde{\chi}_1^0 \to \gamma\widetilde{g}_{3/2}$ is the dominant decay mode, and the decay occurs inside the detector, then nearly *all* supersymmetric particle decay chains would contain a photon. In contrast, the case of a $\widetilde{\tau}_R^{\pm}$-NLSP would lead either to a new long-lived charged particle (*i.e.*, the $\widetilde{\tau}_R^{\pm}$) or to supersymmetric particle decay chains with τ leptons.

Finally, grand unification [71] can impose additional constraints on the MSSM parameters. Perhaps one of the most compelling hints for low-energy supersymmetry is the unification of SU(3)×SU(2)×U(1) gauge couplings predicted by models of supersymmetric grand unified theories (SGUTs) [7,9,72](with the supersymmetry-breaking scale of order 1 TeV or below). Gauge coupling unification, which takes place at an energy scale of order 10^{16} GeV, is quite robust [73]. For example, successful unification depends weakly on the details of the theory at the unification scale. In particular, given the low-energy values of the electroweak couplings $g(m_Z)$ and $g'(m_Z)$, one can predict $\alpha_s(m_Z)$ by using the MSSM renormalization group equations to extrapolate to higher energies, and by imposing the unification condition on the three gauge couplings at some high-energy scale, M_{X}. This procedure, which fixes M_{X}, can be successful (*i.e.*, three running couplings will meet at a single point) only for a unique value of $\alpha_s(m_Z)$. The extrapolation depends somewhat on the low-energy supersymmetric spectrum (so-called low-energy "threshold effects"), and on the SGUT spectrum (high-energy threshold effects), which can somewhat alter the evolution of couplings. Ref. [74] summarizes the comparison of present data with the expectations of SGUTs, and shows that the measured value of $\alpha_s(m_Z)$ is in good agreement with the predictions of supersymmetric grand unification for a reasonable choice of supersymmetric threshold corrections.

Additional SGUT predictions arise through the unification of the Higgs-fermion Yukawa couplings (λ_f). There is some evidence that $\lambda_b = \lambda_\tau$ leads to good low-energy phenomenology [75], and an intriguing possibility that $\lambda_b = \lambda_\tau = \lambda_t$ may be phenomenologically viable [67,76] in the parameter regime where $\tan\beta \simeq m_t/m_b$. Finally, grand unification imposes constraints on the soft-supersymmetry-breaking parameters. For example, gaugino-mass unification leads to the relations given by Eq. (7). Diagonal squark and slepton soft-supersymmetry-breaking scalar masses may also be unified, which is analogous to the unification of Higgs-fermion Yukawa couplings.

In the absence of a fundamental theory of supersymmetry breaking, further progress will require a detailed knowledge of the supersymmetric-particle spectrum in order to determine the nature of the high-energy parameters. Of course, any of the theoretical assumptions described in this section could be wrong and must eventually be tested experimentally.

I.8. Beyond the MSSM: Non-minimal models of low-energy supersymmetry can also be constructed. One approach is to add new structure beyond the Standard Model at the TeV scale or below. The supersymmetric extension of such a theory would be a non-minimal extension of the MSSM. Possible new structures include: (i) the supersymmetric generalization of the see-saw model of neutrino masses [77,78]; (ii) an enlarged electroweak gauge group beyond SU(2)×U(1) [79]; (iii) the addition of new, possibly exotic, matter multiplets [*e.g.*, a vector-like color triplet with electric charge $\frac{1}{3}e$; such states sometimes occur as low-energy remnants in E_6 grand unification models]; and/or (iv) the addition of low-energy SU(3)×SU(2)×U(1) singlets [80]. A possible theoretical motivation for such new structure arises from the study of phenomenologically viable string theory ground states [81].

A second approach is to retain the minimal particle content of the MSSM but remove the assumption of R-parity invariance. The most general R-parity-violating (RPV) theory involving the MSSM spectrum introduces many new parameters to both the supersymmetry-conserving and the supersymmetry-breaking sectors. Each new interaction term violates either B or L conservation. For example, consider new scalar-fermion Yukawa couplings derived from the following interactions:

$$(\lambda_L)_{pmn}\widehat{L}_p\widehat{L}_m\widehat{E}^c_n+(\lambda'_L)_{pmn}\widehat{L}_p\widehat{Q}_m\widehat{D}^c_n+(\lambda_B)_{pmn}\widehat{U}^c_p\widehat{D}^c_m\widehat{D}^c_n\,, \quad (10)$$

where p, m, and n are generation indices, and gauge group indices are suppressed. In the notation above, $\widehat{Q}$, $\widehat{U}^c$, $\widehat{D}^c$, $\widehat{L}$, and $\widehat{E}^c$ respectively represent $(u,d)_L$, u^c_L, d^c_L, $(\nu,\, e^-)_L$, and e^c_L and the corresponding superpartners. The Yukawa interactions are obtained from Eq. (10) by taking all possible combinations involving two fermions and one scalar superpartner. Note that the term in Eq. (10) proportional to λ_B violates B, while the other two terms violate L. Even if all the terms of Eq. (10) are absent, there is one more possible supersymmetric source of R-parity violation. In the notation of Eq. (10), one can add a term of the form $(\mu_L)_p \widehat{H}_u \widehat{L}_p$, where $\widehat{H}_u$ represents the $Y = 1$ Higgs doublet and its higgsino superpartner. This term is the RPV generalization of the supersymmetry-conserving Higgs mass parameter μ of the MSSM, in which the $Y = -1$ Higgs/higgsino super-multiplet $\widehat{H}_d$ is replaced by the lepton/slepton super-multiplet $\widehat{L}_p$. The RPV-parameters $(\mu_L)_p$ also violate L.

Phenomenological constraints on various low-energy B- and L-violating processes can be used to derive limits on each of the coefficients $(\lambda_L)_{pmn}$, $(\lambda'_L)_{pmn}$, and $(\lambda_B)_{pmn}$ taken one at a time [82]. If more than one coefficient is simultaneously non-zero, then the limits are, in general, more complicated. All possible RPV terms cannot be simultaneously present and unsuppressed; otherwise the proton decay rate would be many orders of magnitude larger than the present experimental bound. One way to avoid proton decay is to impose B or L invariance (either one alone would suffice). Otherwise, one must accept the requirement that certain RPV coefficients must be extremely suppressed.

One particularly interesting class of RPV models is one in which B is conserved, but L is violated. It is possible to enforce baryon number conservation, while allowing for lepton number violating interactions by imposing a discrete baryon $\mathbf{Z_3}$ symmetry on the low-energy theory [83], in place of the standard $\mathbf{Z_2}$ R parity. In these models, supersymmetric phenomenology exhibits features that are quite distinct from that of the MSSM. The LSP is no longer stable, which implies that not all supersymmetric decay chains must yield missing-energy events at colliders. Both $\Delta L = 1$ and $\Delta L = 2$ phenomena are allowed (if L is violated), leading to neutrino masses and mixing [84], neutrinoless double-beta decay [85], sneutrino-antisneutrino mixing [78,86,87], and s-channel resonant production of the sneutrino in e^+e^- collisions [88]. Since the distinction between the Higgs and matter super-multiplets is lost, R-parity violation permits the mixing of sleptons and Higgs bosons, the mixing of neutrinos and neutralinos, and the mixing of charged leptons and charginos, leading to more complicated mass matrices and mass eigenstates than in the MSSM. Note that if $\lambda'_L \neq 0$, then squarks can behave as leptoquarks since the following processes are allowed: $e^+\overline{u}_m \to \overline{\widetilde{d}}_n \to e^+\overline{u}_m, \overline{\nu}\overline{d}_m$, and $e^+d_m \to \widetilde{u}_n \to e^+d_m$. (As above, m and n are generation labels, so that $d_2 = s$, $d_3 = b$, *etc.*)

Of course, R-parity-violation can also enter via the soft-supersymmetry-breaking terms, leading to an explosion of unknown parameters (well beyond the 124 of the MSSM in the most general case). As in the MSSM, one can consider constrained versions of RPV supersymmetry, in which simplified assumptions are made about the structure of the supersymmetry breaking terms at some high energy scale. Moreover, one can make additional assumptions regarding the RPV parameters. For example, in the bilinear RPV model [89], the trilinear RPV terms of Eq. (10) (and the corresponding supersymmetry-breaking "A-parameters") are absent, and the only source of R-parity violation arises from $(\mu_L)_p$ and L-violating soft-supersymmetry-breaking "B-parameters" and squared-mass terms.

With the overwhelming evidence for neutrino masses and mixing [90], it is clear that any viable supersymmetric model of fundamental particles must incorporate some form of L violation in the low-energy theory [91]. The supersymmetric generalization of the see-saw mechanism and RPV supersymmetry provide two possible frameworks for non-zero neutrino masses. For example, Ref. [92] demonstrates how one can fit both the solar and atmospheric neutrino data in the bilinear RPV supersymmetric model. In addition, experimental and theoretical constraints from collider physics also places some non-trivial restrictions on general R-parity-violating alternatives to the MSSM (see Refs. [82] and [93] for further details).

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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 also have 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.

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, the quantum number which distinguishes 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 gluons 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 deposits 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–violating 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 LSP's themselves provide a visible signal by virtue or their decay to ordinary fermions. Note that the cosmological constraint which requires stable LSP's to be charge and color neutral no longer applies when there R-parity is violated.

In models assuming gauge-mediated supersymmetry breaking (GMSB) [4], the gravitino, $\widetilde{g}_{3/2}$, is a weakly-interacting fermion with a mass so small that it can be neglected when considering the event kinematics. It is the LSP, and the lightest neutralino, $\widetilde{\chi}_1^0$, decays to it radiatively, possibly with a 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 the neutralino decays outside 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. The most important case of this type is the channel $\widetilde{\tau}_R \to \tau\widetilde{G}$. The lifetime of the $\widetilde{\tau}_R$ can vary over a wide range depending on model parameters, leading to new exotic signatures, including quasi-stable, heavily ionizing charged particles.

Finally, there is another phenomenologically important scenario in which the gluino $\widetilde{g}$ is assumed to be relatively light ($M_{\widetilde{g}} < 5$ GeV/c^2). Experimental evidence does not support the hypothesis, however, as discussed further in the review by H. Murayama.

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 Part I of this review, parameter freedom is drastically reduced by requiring related parameters to be equal at the unification scale, M_X. 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 gluino and squark searches at proton machines constrain mainly M_3 and a scalar mass parameter m_0 for the squark masses, while the chargino, neutralino, and slepton searches at e^+e^- colliders constrain M_2 and a scalar mass parameter m_0 for the slepton masses. In addition, results from the Higgs searches can be used to constrain $m_{1/2}$ and m_0 as a function of $\tan\beta$. (The full analysis involves large radiative corrections coming from squark mixing, which is where the dependence on $m_{1/2}$ and m_0 enter.) In the mSUGRA framework, all the scalar mass parameters m_0 are the same and the three gaugino mass parameters are proportional to $m_{1/2}$, so limits from squarks, sleptons, charginos, gluinos, and Higgs all can be used together to constrain the parameter space. A slightly less constrained model allows the Higgs sector to be independent of the sfermion sector, while still requiring that the scalar mass parameter m_0 is the same for sleptons and squarks and that the gaugino mass parameter $m_{1/2}$ is the same for charginos, neutralinos and gluinos. This model is called the 'constrained MSSM' (cMSSM) [5,6].

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 utilization of some sort of organizing device, such as a constrained version of the MSSM, practically unavoidable.

II.4. Supersymmetry searches at e^+e^- colliders:

The large electron-positron collider (LEP) at CERN ran at energies ranging from the Z peak up 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 [7]. 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. Since the last edition of this review, several of the searches at the highest energies have been finalized.

Running at the Z pole, the LEP experiments and SLD at SLAC excluded many 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 relatively insensitive to the details of SUSY particle decays [8]. 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 $\widetilde{\chi}^0_1\widetilde{\chi}^0_2$ 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 ($M_{\rm miss} = \{(\sqrt{s}-E_{\rm vis})^2-\vec{p}^{\,2}_{\rm vis}\}^{1/2}$) which is small if $p_T^{\rm miss}$ is caused by a single neutrino or an 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 ~ 80 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.

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 ~ 200 GeV/c^2, the chargino and neutralino branching ratios are close to those of the W and Z bosons. Enhancements of leptonic branching ratios are important when sleptons are light. 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 many popular models (such as 'supergravity'), 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. However, as explained in the theoretical section of this review, this unification scheme is not required by Supersymmetry, and it is important to consider both $M_1 \approx M_2$ and $M_1 \ll M_2$. 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 μ, $\Delta M \approx M_W$, and cuts designed to reject W background lead to lower efficiencies.

Chargino masses have been excluded up to 103 GeV/c^2. However, this limit can be degraded when the sneutrino is lighter than $\sim$ 200 GeV/c^2. Thanks to the large integrated luminosity and the combination of four experiments [7], the impact for $M_{\widetilde{\nu}_e} \gtrsim 100$ GeV/c^2 is less than a GeV/c^2. The limit is also weakened when the mass difference is small ($\Delta M = M_{\widetilde{\chi}^\pm} - M_{\widetilde{\chi}_1^0} \lesssim 3$ GeV/c^2), as in the higgsino region; however, in this case the associated production of neutralino pairs $\widetilde{\chi}_1^0 \widetilde{\chi}_2^0$ is large and the problem of small mass differences ($M_{\widetilde{\chi}_2^0} - M_{\widetilde{\chi}_1^0}$) less severe. Experimental sensitivity now extends down to mass differences of 3 GeV/c^2, corresponding to M_2 above 2 TeV/c^2.

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

The possibility of extremely small mass differences has been raised in several theoretical papers which propose models

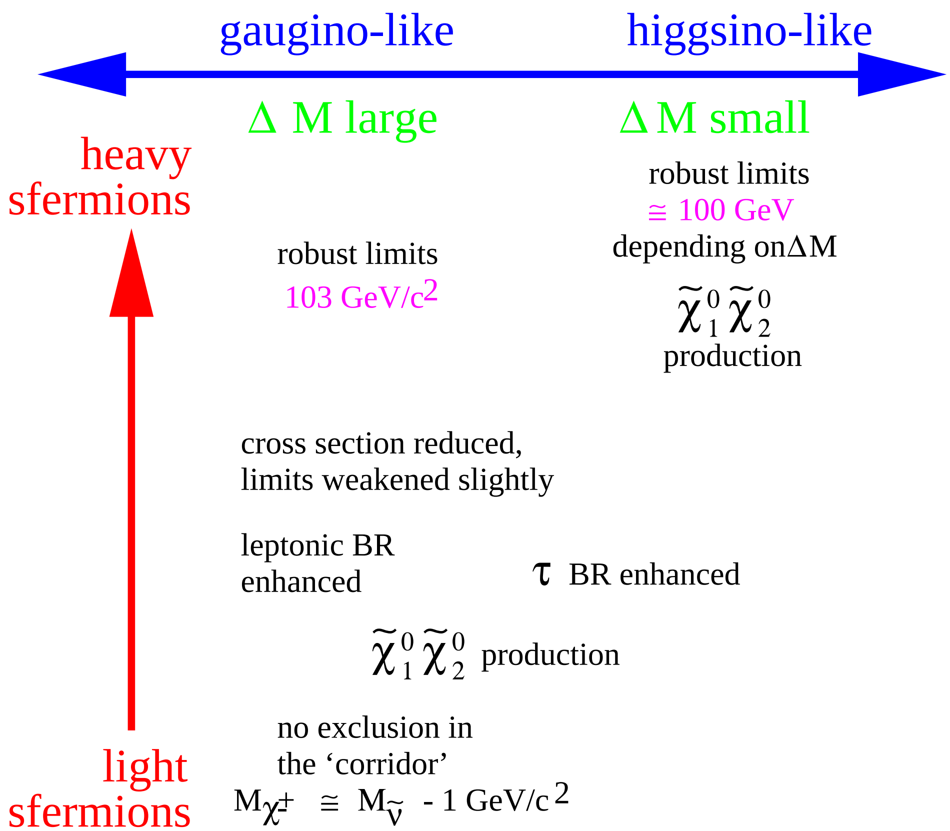

Figure 1: Heuristic diagram of the interplay of chargino field content and sfermion masses. See full-color version on color pages at end of book.

rather different from supergravity [9]. The DELPHI Collaboration was the first to engineer searches to cover this scenario [10], and other collaborations have followed suit [11]. For $\Delta M \sim 1$ 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 $\Delta M \sim 0.2$ 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 vary from 68 to 88 GeV/c^2 depending on the assumed sneutrino mass; the limit is 92 GeV/c^2 from the combination of the four LEP experiments when $M_{\tilde{\nu}_e} > 500$ GeV/c^2 [7].

The limits from chargino and neutralino production are most often used to constrain M_2 and μ for fixed $\tan\beta$. For large $|\mu|$ (the gaugino case), chargino bounds limit M_2, and vice versa (the Higgsino case). When $\tan\beta$ is not large, the region of parameter space with $\mu < 0$ and $|\mu| \sim M_2$ corresponds to 'mixed' field content, and the limits on M_2 and $|\mu|$ are relatively modest, especially when electron sneutrinos are light. This is the weak point when inferring an indirect limit on the LSP mass [12].

When the sleptons are light, branching ratios to leptons are enhanced, especially to τ's via $\widetilde{\tau}$'s when there is non-negligible mixing of $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$. These effects are greatest when the chargino has a large gaugino component. The weakest bounds are found for small negative μ and small $\tan\beta$, as the cross section is reduced with respect to larger $|\mu|$, the impact of $\widetilde{\tau}$ mixing can be large, and the efficiency is not optimal because ΔM is large. If sneutrinos are lighter than the chargino, then two-body decays $\widetilde{\chi}^+ \to \ell^+\widetilde{\nu}$ dominate, and in the 'corridor' $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3$ GeV/c^2 the acceptance is so low that no direct exclusion is possible [13]. 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 γ^* and Z^* exchange. For selectrons there is an important contribution from t-channel neutralino exchange which generally increases the cross section. 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 [14]. 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 $\widetilde{\tau}$ sleptons, mixing can be important.

The simplest slepton topology results from $\tilde{\ell} \to \ell\widetilde{\chi}^0_1$, though for some particular parameter choices, branching ratios for decays to $\widetilde{\chi}^0_2$ reach a few percent. Combined mass limits have been obtained by the LEP SUSY working group [7]. For $\tilde{\mu}_R$, the limit is 95 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 τ's is relatively difficult, the limit is expected to be lower, and the actual limit is 86 GeV/c^2. These limits hold provided the slepton is at least 10 GeV/c^2 heavier than the neutralino.

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 and L3 have used this to close the gap $M_{\tilde{e}_R} - M_{\widetilde{\chi}} \to 0$, and place an absolute limit $M_{\widetilde{e}_R} > 73$ GeV/c^2 [15,16].

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 interaction eigenstates can mix to give a large splitting between the mass eigenstates. While theoretically less natural, light sbottoms also have been considered. LEP limits on stop and sbottom masses vary with the mixing angle because the cross section does: for $\theta_{\widetilde{t}} = 56^\circ$ and $\theta_{\widetilde{b}} = 67^\circ$ 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 [7].

The stop decay $\widetilde{t}_1 \to c\widetilde{\chi}^0_1$ proceeds through loops, giving a lifetime long enough to allow the top squark to form supersymmetric hadrons which provide a pair of jets and missing energy. 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. The same signature obtains when sleptons are light. A somewhat more difficult case comes when $\widetilde{\tau}$'s are light [17,18,16]. Four-fermion final states ($b\,f\,\bar{f}'\,\widetilde{\chi}^0_1$) dominate when charginos are light, a topology covered by ALEPH [18]. Access to very small ΔM is possible due to the visibility of the decay products of the c and b hadrons [19], in which case conservative limit is $M_{\widetilde{t}_1} > 59$ 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 $\widetilde{b}_1 \to b\widetilde{\chi}^0_1$. Use of b-jet tagging helps retain sensitivity: the bound is $M_{\widetilde{b}} > 96$ 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 generally excluded by LEP searches. Ther is, however, a constraint from a CLEO analysis [20] applicable when the sbottoms always decay semileptonically.

The results from the search for acoplanar jets and missing energy has been interpreted as a limit on the production of generic squarks [21,16,7]. 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 [12,22]. 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 high, the bound on $M_{\widetilde{\chi}_1^0}$ is derived from the results of chargino and neutralino searches, and the limit is $M_{\widetilde{\chi}_1^0} > 39\ \mathrm{GeV}/c^2$ [23,11].

When sleptons are lighter than $\sim 200\ \mathrm{GeV}/c^2$, 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 $\tan\beta$: $M_{\widetilde{\chi}_1^0} > 37\ \mathrm{GeV}/c^2$ [23]. 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 $M_{\widetilde{\chi}_1^0} > 45\ \mathrm{GeV}/c^2$ [7].

There is a special case for light neutralinos not excluded by collider experiments: when the $\widetilde{\chi}_1^0$ is a pure bino, the constraints from the invisible Z width and from the cross section for γ+invisible are ineffective [24]. If one does not assume any relation between M_1 and M_2 then the constraints from chargino searches can be evaded also. Thus a bino of mass $\mathcal{O}(0.1\ \mathrm{MeV}/c^2)$ is not excluded by collider experiments.

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, in particular, $\widetilde{\tau}_R$. The gravitino is the LSP, with mass well below a keV.

In the case in which $\widetilde{\chi}_1^0$ is the NLSP, high energy photons are present from the decay $\widetilde{\chi}_1^0 \to \gamma\, \widetilde{g}_{3/2}$. 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 99 GeV/c^2, from ALEPH, assuming the neutralino lifetime is negligible [25]. A more general limit of 54 GeV/c^2 is set by combining searches for photons which do not point back to the interaction point with indirect limits derived from slepton and chargino searches [26]. Also, single-photon production has been used to constrain the processes $e^+e^- \to \widetilde{g}_{3/2}\widetilde{\chi}_1^0$ and $e^+e^- \to \widetilde{g}_{3/2}\widetilde{g}_{3/2}$.

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 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 $\widetilde{\ell}_R \to \ell \widetilde{g}_{3/2}$ 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 82 GeV/c^2 for staus can be placed independent of the slepton lifetime [27,26].

When, due to mixing, the lightest stau is significantly lighter than the other sleptons, special topologies may result. For example, 4τ final states result from neutralino pair production. No evidence for a signal was found [27,28].

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 (λ_{ijk}, λ'_{ijk}, λ''_{ijk}) have been considered. Signatures of indirect and also direct 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 [29]. 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 hadron machines: While the LEP experiments can investigate a wide range of scenarios and cover corners of theoretical parameter space, they cannot match the mass reach of the Tevatron experiments (CDF and DØ). Although the full $p\bar{p}$ 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 an expected 2 fb^{-1} to be logged by 2006.

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 possible presence of several SUSY signals in one data set. A search in a given topology, such as ≥ 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.

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 mismeasurements 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 commonly are based on theoretical cross sections, although in some analyses direct measurements are used to reduce uncertainties.

Squarks and Gluinos: The classic searches [30] 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. The most recent analysis by the CDF Collaboration places significantly stronger bounds that previous analyses [31]. 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 $t\bar{t}$ 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 $\widetilde{q} \to q\widetilde{\chi}_1^0$), 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 (see Fig. 2).

Since these results are expressed in terms of the physical masses relevant to the production process and experimental signature, the excluded region depends primarily on the assumption of nearly equal squark masses with only a small dependence on other parameters such as μ and $\tan\beta$. Direct constraints on the theoretical parameters m_0 and $m_{1/2} \approx 0.34\, M_3$ have been obtained by DØ assuming the mass relations of the mSUGRA model (see the first paper in [30]. These bounds do not carry significantly more information than contained in the region above the diagonal of Fig. 2. It is interesting to note that, if the LEP limits on chargino production are interpreted in this context as an indirect limit on gluinos, then roughly one obtains $M_{\widetilde{g}} > 310\ \text{GeV}/c^2$ [6].

Gauginos: In the context of the mSUGRA model, which fixes $|\mu|$ by the requirement of radiative 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 ($\widetilde{\chi}^{\pm} \to \ell^{\pm}\nu^{(*)}\widetilde{\chi}_1^0$ 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 $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ [32]. The requirement of three energetic leptons (e or μ), augmented by simple angular cuts against Drell-Yan production and cosmic rays, isolation requirements against semileptonic decays of heavy mesons, and significant $\not{E}_T$ reduce backgrounds to a very small level. The bounds have been derived in the context of mSUGRA models, which generally predict modest leptonic branching ratios for charginos and neutralinos. Consequently, in this framework, the results are not competitive with the LEP bounds. When $\tan\beta$ is large, final states with τ's are enhanced, and existing searches are inefficient. Nonetheless the search is completely independent of the jets+$\not{E}_T$ search and could be more effective in particular models with light sleptons, for example.

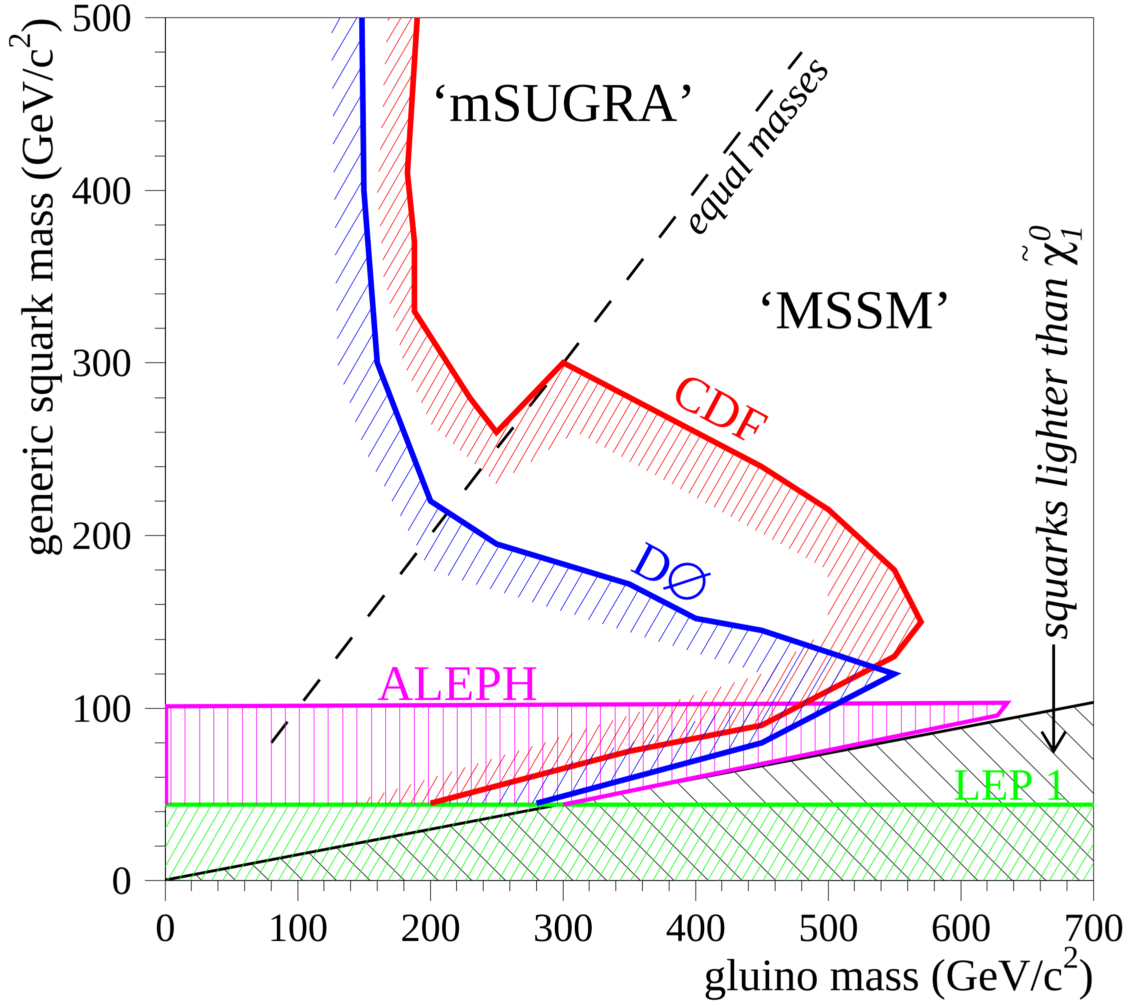

Figure 2: Regions in the $M_{\tilde{g}}$-$M_{\tilde{q}}$ plane excluded by searches for jets and missing energy at CDF, DØ, and LEP. See full-color version on color pages at end of book.

The dilepton signal is geared more for the production of gauginos in gluino and squark cascades [33]. 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 and by a cut on $\not\!\!E_T$. 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+ $\not\!\!E_T$ when couched in an mSUGRA context.

DØ tried to find squarks tagged by $\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1\gamma$, where the $\widetilde{\chi}^0_2$ appear in cascade decays [34]. The branching ratio can be large for a selected set of model parameters leading to a Higgsino-like $\widetilde{\chi}^0_1$ and a gaugino-like $\widetilde{\chi}^0_2$. 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 as the gluino.

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 $\widetilde{t}_1 \rightarrow c\widetilde{\chi}^0$ dominates. If $M_{\widetilde{\chi}^\pm} < M_{\widetilde{t}_1}$, then $\widetilde{t}_1 \rightarrow b\widetilde{\chi}^\pm$ is the main decay mode, and the experimenters assume $BR(\widetilde{\chi}^\pm \rightarrow \ell\nu\widetilde{\chi}^0) = BR(W \rightarrow \ell\nu)$. When charginos are heavy but $M_{\widetilde{\nu}} < M_{\widetilde{t}_1}$, leptonic final states again are favored via $\widetilde{t}_1 \rightarrow b\ell\widetilde{\nu}$. 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 [36].

CDF have obtained a result for the $c\not\!\!E_T$ final state [37]. They employed their vertex detector to select charm jets. After a lepton veto and $\not\!\!E_T$ requirement, this result surpasses the prior result from DØ [38]. 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 first DØ result, however, this search did not exclude any signal in the channel $\widetilde{t}_1 \rightarrow b\widetilde{\chi}^{\pm}$, and covered a small region for $\widetilde{t}_1 \rightarrow b\ell\widetilde{\nu}$. A new result from DØ is much more performant [39] and significantly extends the parameter space excluded by LEP searches. Finally, CDF considered the possibility $t \rightarrow \widetilde{t}_1\widetilde{\chi}$ followed by $\widetilde{t}_1 \rightarrow b\widetilde{\chi}^+$ [40]. Such events would remain in the top event sample and can be discriminated using a multivariate technique. No events were found compatible with the kinematics of SUSY decays, and limits on $BR(t \rightarrow \widetilde{t}_1\widetilde{\chi})$ were derived in a fairly limited range of stop and chargino masses.

The search for light $\widetilde{b}_1 \rightarrow b\widetilde{\chi}$ follows the $\widetilde{t}_1$ search in the charm channel [37]. 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 [41].

A summary of the searches for stops is shown in Fig. 3. Given the modest luminosity and small detection efficiencies, the mass reach of the Tevatron searches is impressive. New data would likely 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,

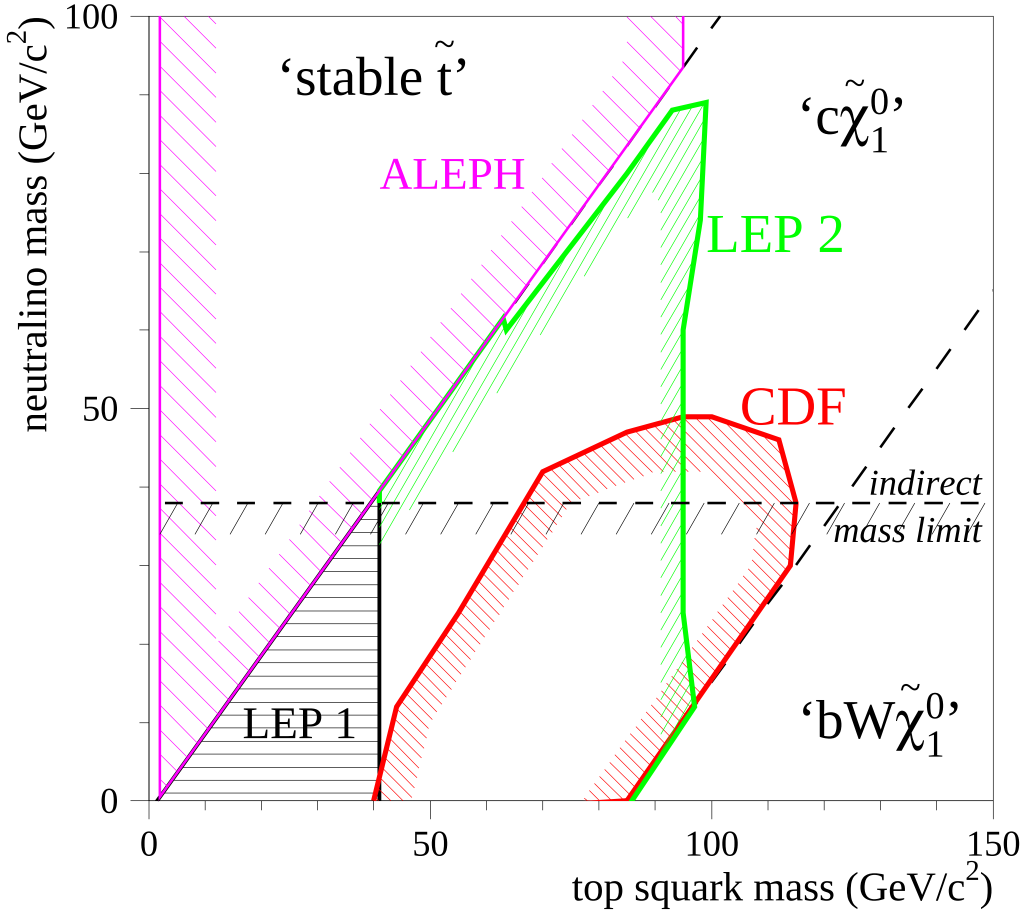

Figure 3: Regions excluded in the $(M_{\widetilde{t}_1}, M_{\widetilde{\chi}})$ plane. The results for the $c\widetilde{\chi}^0_1$ decay mode are displayed from LEP and CDF. A DELPHI result for stable stops is indicated for $M_{\widetilde{t}_1} < M_{\widetilde{\chi}}$. Finally, the indirect limit on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

due to the necessity of requiring a minimum missing energy in the experimental trigger.

R-Parity Violation: The CDF and DØ collaborations have searched for supersymmetry in certain RPV scenarios [42] 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 amounts 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. They also completed a search for R-parity violating stop decays, $\widetilde{t}_1 \to b\tau$ in which one tau decays leptonically and the other hadronically, giving the limit $M_{\widetilde{t}_1} > 122$ GeV/c^2 [43].

Gauge-Mediated Models: Interest in GMSB models was spurred by an anomalous '$ee\gamma\gamma\not{E}_T$' event found by the CDF Collaboration [44]. 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 the decay $\widetilde{\chi}_1^0 \to \gamma\widetilde{g}_{3/2}$ 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 [45]. 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 [44,46]. 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 [47]. The limit

$\sqrt{F} > 215$ GeV/c^2 is placed on the fundamental parameter of this model.

DØ also reported limits on $\widetilde{q}$ and $\widetilde{g}$ production in this same scenario [35]. If $\widetilde{q}$ and $\widetilde{g}$ have similar masses, then that mass is great than 310 GeV/c^2.

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 [48].

The Search for $\boldsymbol{B_s \to \mu^+\mu^-}$***:*** Indirect evidence for SUSY could come from measurements of rare processes, especially those which are highly suppressed in the Standard Model. For example, the branching fraction for the flavor-changing neutral decay $B_s \to \mu^+\mu^-$ is only 3×10^{-9} [49]. In the MSSM, however, it can be greatly enhanced due to Higgsino and possibly gluino contributions, and in fact, $\mathcal{B}(B_s \to \mu^+\mu^-) \propto \tan^6\beta$ [50]. The exact value for the branching fraction is highly model dependent, but in mSUGRA values as high as 0.5×10^{-7} can be obtained for $\tan\beta = 55$.

CDF found no evidence for $B_s \to \mu^+\mu^-$ in their Run I data, and placed the upper limit $\mathcal{B}(B_s \to \mu^+\mu^-) < 20 \times 10^{-7}$ at 90% C.L. [51]. The sensitivity will be substantially improved for Run II due to a much higher trigger acceptance and better vertex reconstruction. Recent preliminary results from Run II have strengthened the bound to 9.5×10^{-7} (CDF, 113 pb^{-1}) and 16×10^{-7} (DØ, $\sim$ 100 pb^{-1}), both at 90% C.L. [52]. The sensitivity for an integrated luminosity of 4 fb^{-1} could reach, optimistically, 0.5×10^{-7} [53].

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 ΔM	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+$\not{E}_T$

If the decay $B_s \rightarrow \mu^+\mu^-$ is observed, then a general lower bound on $\tan\beta$ can be derived [54]. It is also worth noting that, if a signal is observed at the Tevatron, then models based on anomaly-mediated or gauge-mediated supersymmetry breaking would not be favored [50,54].

II.7. Searches at HERA: The initial state for collisions at HERA includes an electron (or positron) and a proton, which provides a special opportunity to probe RPV scenarios with a dominant λ'_{1jk} coupling [55]. The H1 and ZEUS experiments have searched for the resonant production of squarks. The most up-to-date results include the search by H1 based on 37 pb^{-1} of e^+p data [56]. Both R_p-violating and conserving decays of the squark were covered by a combination of seven different topologies. Bounds are placed on the R_p-violating coupling as a function of the squark mass. Completely general limits on the squark mass are impossible. However, in the constrained MSSM, and assuming $M_{\widetilde{\chi}_1^0} > 30$ GeV/c^2, the limit $M_{\tilde{u}_L} > 160$ GeV/c^2 can be placed (235 GeV/c^2 for the third generation). See Ref. [56] for more details, and the Particle Listings for a list of previous results from both H1 and ZEUS.

II.8. 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.

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OPAL: Eur. Phys. J. **C12**, 1 (2000) and Eur. Phys. J. **C11**, 619 (1999);
DELPHI: Phys. Lett. **B502**, 24 (2001);
L3: Eur. Phys. J. **C19**, 397 (2001) and Phys. Lett. **B524**, 65 (2002).
30. **DØ**: Phys. Rev. Lett. **83**, 4937 (1999) and Phys. Rev. Lett. **75**, 618 (1995);
CDF: Phys. Rev. **D56**, 1357 (1997) and Phys. Rev. Lett. **76**, 2006 (1996).
31. **CDF**: Phys. Rev. Lett. **88**, 041801 (2002).
32. **DØ**: Phys. Rev. Lett. **80**, 1591 (1998);
CDF: Phys. Rev. Lett. **80**, 5275 (1998).
33. **DØ**: Phys. Rev. **D63**, 091102 (2001);
CDF: Phys. Rev. Lett. **76**, 2006 (1996) and Phys. Rev. Lett. **87**, 251803 (2001).
34. **DØ**: Phys. Rev. Lett. **82**, 29 (1999).
35. **DØ**: Phys. Rev. Lett. **78**, 2070 (1997).
36. A. Djouadi *et al.*, Phys. Rev. **D71**, 095006 (2000) and Phys. Rev. **D63**, 115005 (2001).
37. **CDF**: Phys. Rev. Lett. **84**, 5704 (2000).
38. **DØ**: Phys. Rev. Lett. **76**, 2222 (1996).
39. **DØ**: Phys. Rev. Lett. **88**, 171802 (2002).
40. **CDF**: Phys. Rev. **D63**, 091101 (2001).
41. **DØ**: Phys. Rev. **D60**, 031101 (1999).
42. **CDF**: Phys. Rev. Lett. **83**, 2133 (1999) and Phys. Rev. Lett. **87**, 251803 (2001);
DØ: Phys. Rev. **D62**, 071701 (2000) and Phys. Rev. Lett. **83**, 4476 (1999).
43. **CDF**: `hep-ex/0305010`.
44. **CDF**: Phys. Rev. **D59**, 092002 (1999).
45. **DØ**: Phys. Rev. Lett. **78**, 2070 (1997).
46. **CDF**: Phys. Rev. Lett. **81**, 1791 (1998).
47. **CDF**: Phys. Rev. Lett. **85**, 1378 (2000).

48. **CDF**: Phys. Rev. Lett. **81**, 1791 (1998).
49. Andrzej J. Buras, hep-ph/9806471 and references therein.
50. A. Dedes, H.K. Dreiner, U. Nierste and P. Richardson, hep-ph/0207026.
51. **CDF**: Phys. Rev. Lett. **57**, 3811 (1998).
52. Prelim. results from **CDF** and **DØ** were reported by M.Schmitt at Lepton-Photon, 2003, at FNAL.
53. R. Arnowitt, B.Dutta, T.Kamon and M.Tanaka, Phys. Lett. **B538**, 121 (2002).
54. G.L.Kane, C.Kolda and J.E.Lennon, hep-ph/0310042.
55. M. Kuze and Y. Sirois, Prog. in Part. Nucl. Phys. **50**, 1 (2003).
56. **H1**: Eur. Phys. J. **C20**, 639 (2001);
H1: Phys. Lett. **B568**, 35 (2003).

SUPERSYMMETRIC MODEL ASSUMPTIONS

The exclusion of particle masses within a mass range (m_1, m_2) will be denoted with the notation "none m_1-m_2" in the VALUE column of the following Listings.

Most of the results shown below, unless stated otherwise, are based on the Minimal Supersymmetric Standard Model (MSSM), as described in the Note on Supersymmetry. Unless otherwise indicated, this includes the assumption of common gaugino and scalar masses at the scale of Grand Unification (GUT), and use of the resulting relations in the spectrum and decay branching ratios. It is also assumed that R-parity (R) is conserved. Unless otherwise indicated, the results also assume that:

1) The $\widetilde{\chi}_1^0$ is the lighest supersymmetric particle (LSP)
2) $m_{\widetilde{f}_L} = m_{\widetilde{f}_R}$, where $\widetilde{f}_{L,R}$ refer to the scalar partners of left- and right-handed fermions.

Limits involving different assumptions are identified in the Comments or in the Footnotes. We summarize here the notations used in this Chapter to characterize some of the most common deviations from the MSSM (for further details, see the Note on Supersymmetry).

Theories with R-parity violation ($\not{R}$) are characterised by a superpotential of the form: $\lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \lambda''_{ijk} u^c_i d^c_j d^c_k$, where i, j, k are generation indices. The presence of any of these couplings is often identified in the following by the symbols $LL\overline{E}$, $LQ\overline{D}$, and $\overline{UDD}$. Mass limits in the presence of $\not{R}$ will often refer to "direct" and "indirect" decays. Direct refers to $\not{R}$ decays of the particle in consideration. Indirect refers to cases where $\not{R}$ appears in the decays of the LSP.

In several models, most notably in theories with so-called Gauge Mediated Supersymmetry Breaking (GMSB), the gravitino ($\widetilde{G}$) is the LSP. It is usually much lighter than any other massive marticle in the spectrum, and $m_{\widetilde{G}}$ is then neglected in all decay processes involving gravitinos. In these scenarios, particles other than the neutralino are sometimes considered as the next-to-lighest supersymmetric particle (NLSP), and are assumed to decay to their even-R partner plus $\widetilde{G}$. If the lifetime is short enough for the decay to take place within the detector, $\widetilde{G}$ is assumed to be undetected and to give rise to missing energy ($\not{E}$) or missing transverse energy ($\not{E}_T$) signatures.

When needed, specific assumptions on the eigenstate content of $\widetilde{\chi}^0$ and $\widetilde{\chi}^\pm$ states are indicated, using the notation $\widetilde{\gamma}$ (photino), $\widetilde{H}$ (higgsino), $\widetilde{W}$ (wino), and $\widetilde{Z}$ (zino) to signal that the limit of pure states was used. The terms gaugino is also used, to generically indicate wino-like charginos and zino-like neutralinos.

$\widetilde{\chi}^0_1$ (Lightest Neutralino) MASS LIMIT

$\widetilde{\chi}^0_1$ is often assumed to be the lightest supersymmetric particle (LSP). See also the $\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_4$ section below.

We have divided the $\widetilde{\chi}_1^0$ listings below into five sections:

1) Accelerator limits for stable $\widetilde{\chi}_1^0$,
2) Bounds on $\widetilde{\chi}_1^0$ from dark matter searches,
3) Bounds on $\widetilde{\chi}_1^0$ elastic cross sections from dark matter searches,
4) Other bounds on $\widetilde{\chi}_1^0$ from astrophysics and cosmology, and
5) Bounds on unstable $\widetilde{\chi}_1^0$.

Accelerator limits for stable $\widetilde{\chi}_1^0$

Unless otherwise stated, results in this section assume spectra, production rates, decay modes, and branching ratios as evaluated in the MSSM, with gaugino and sfermion mass unification at the GUT scale. These papers generally study production of $\widetilde{\chi}_i^0 \widetilde{\chi}_j^0$ ($i \geq 1$, $j \geq 2$), $\widetilde{\chi}_1^+ \widetilde{\chi}_1^-$, and (in the case of hadronic collisions) $\widetilde{\chi}_1^+ \widetilde{\chi}_2^0$ pairs. The mass limits on $\widetilde{\chi}_1^0$ are either direct, or follow indirectly from the constraints set by the non-observation of $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_2^0$ states on the gaugino and higgsino MSSM parameters M_2 and μ. In some cases, information is used from the nonobservation of slepton decays.

Obsolete limits obtained from e^+e^- collisions up to $\sqrt{s}$=184 GeV have been removed from this compilation and can be found in the 2000 Edition (The European Physical Journal **C15** 1 (2000)) of this Review. $\Delta m_0 = m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>39.2	95	[1] ABDALLAH	03M	DLPH	all tanβ, $m_{\widetilde{\nu}}$ >500 GeV
>46	95	[2] ABDALLAH	03M	DLPH	all tanβ, all Δm_0, all m_0
>37	95	[3] BARATE	01	ALEP	all tanβ, all m_0
>31.6	95	[4] ABBIENDI	00H	OPAL	all tanβ, all Δm_0 >5 GeV, all m_0
>32.5	95	[5] ACCIARRI	00D	L3	tan$\beta > 0.7$, $\Delta m_0 > 3$ GeV, all m_0
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[6] ABBOTT	98C	D0	$p\overline{p} \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0$
>41	95	[7] ABE	98J	CDF	$p\overline{p} \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0$

[1] ABDALLAH 03M uses data from $\sqrt{s} = 192$–208 GeV. A limit on the mass of $\widetilde{\chi}_1^0$ is derived from direct searches for neutralinos combined with the chargino search. Neutralinos are searched in the production of $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^0\widetilde{\chi}_3^0$, as well as $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$ and $\widetilde{\chi}_2^0\widetilde{\chi}_4^0$ giving rise to cascade decays, and $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$, followed by the decay $\widetilde{\chi}_2^0 \rightarrow \widetilde{\tau}\tau$. The results hold for the parameter space defined by values of $M_2 < 1$ TeV, $|\mu| \leq 2$ TeV with the $\widetilde{\chi}_1^0$ as LSP. The limit is obtained for tan$\beta = 1$ and large m_0, where$\widetilde{\chi}_2^0\widetilde{\chi}_4^0$ and chargino pair production are important. If the constraint from Higgs searches is also imposed, the limit improves to 49.0 GeV in the M_h^{max} scenario with m_t=174.3 GeV. These limits update the results of ABREU 00J.

[2] ABDALLAH 03M uses data from $\sqrt{s} = 192$–208 GeV. An indirect limit on the mass of $\widetilde{\chi}_1^0$ is derived by constraining the MSSM parameter space by the results from direct searches for neutralinos (including cascade decays and $\widetilde{\tau}\tau$ final states), for charginos (for all Δm_+) and for sleptons, stop and sbottom. The results hold for the full parameter

space defined by values of $M_2 < 1$ TeV, $|\mu| \leq 2$ TeV with the $\widetilde{\chi}^0_1$ as LSP. Constraints from the Higgs search in the M_h^{max} scenario assuming m_t=174.3 GeV are included. The limit is obtained for tan$\beta \geq 5$ when stau mixing leads to mass degeneracy between $\widetilde{\tau}_1$ and $\widetilde{\chi}^0_1$ and the limit is based on $\widetilde{\chi}^0_2$ production followed by its decay to $\widetilde{\tau}_1\tau$. In the pathological scenario where m_0 and $|\mu|$ are large, so that the $\widetilde{\chi}^0_2$ production cross section is negligible, and where there is mixing in the stau sector but not in stop nor sbottom, the limit is based on charginos with soft decay products and an ISR photon. The limit then degrades to 39 GeV. See Figs 40–42 for the dependence of the limit on tanβ and $m_{\widetilde{\nu}}$. These limits update the results of ABREU 00W.

[3] BARATE 01 data collected at 189 to 202 GeV. Updates earlier analyses of sleptons and squarks from BARATE 99Q, and of charginos and neutralinos from BARATE 98X and BARATE 99P. The limit is based on the direct search for charginos and neutralinos and the constraints from the slepton search and Z^0 width measurements, as discussed in BARATE 99P, assuming a negligible mixing in the stau sector. The limit improves to 48 GeV under the assumption of MSUGRA with unification of the Higgs and sfermion masses, when direct constraints on the Higgs mass from BARATE 01C are used and $m_{\widetilde{\tau}} - m_{\widetilde{\chi}^0_1} > 5$ GeV to avoid degeneracy at large tanβ. These limits include and update the results of BARATE 99P.

[4] ABBIENDI 00H data collected at $\sqrt{s}$=189 GeV. The results hold over the full parameter space defined by $0 \leq M_2 \leq 2$ TeV, $|\mu| \leq 500$ GeV, $m_0 \leq 500$ GeV, $A=\pm M_2$, $\pm m_0$, and 0. The minimum mass limit is reached for tanβ=1. The results of ABBIENDI 99F are used to constrain regions of parameter space dominated by radiative $\widetilde{\chi}^0_2 \to \widetilde{\chi}^0_1\gamma$ decays. The limit improves to 48.5 GeV for m_0=500 GeV and tanβ=35. See their Table and Figs 4–5 for the tanβ and m_0 dependence of the limits. Updates ABBIENDI 99G.

[5] ACCIARRI 00D data collected at $\sqrt{s}$=189 GeV. The results hold over the full parameter space defined by $0.7 \leq \tan\beta \leq 60$, $0 \leq M_2 \leq 2$ TeV, $m_0 \leq 500$ GeV, $|\mu| \leq 2$ TeV The minimum mass limit is reached for tanβ=1 and large m_0. The results of slepton searches from ACCIARRI 99W are used to help set constraints in the region of small m_0. The limit improves to 48 GeV for $m_0 \gtrsim 200$ GeV and tan$\beta \gtrsim 10$. See their Figs. 6–8 for the tanβ and m_0 dependence of the limits. Updates ACCIARRI 98F.

[6] ABBOTT 98C searches for trilepton final states (ℓ=e,μ). See footnote to ABBOTT 98C in the Chargino Section for details on the assumptions. Assuming a negligible decay rate of $\widetilde{\chi}^\pm_1$ and $\widetilde{\chi}^0_2$ to quarks, they obtain $m_{\widetilde{\chi}^0_2} \gtrsim 51$ GeV.

[7] ABE 98J searches for trilepton final states (ℓ=e,μ). See footnote to ABE 98J in the Chargino Section for details on the assumptions. The quoted result corresponds to the best limit within the selected range of parameters, obtained for $m_{\widetilde{q}} > m_{\widetilde{g}}$, tan$\beta$=2, and μ=−600 GeV.

Bounds on $\widetilde{\chi}^0_1$ from dark matter searches

These papers generally exclude regions in the $M_2-\mu$ parameter plane assuming that $\widetilde{\chi}^0_1$ is the dominant form of dark matter in the galactic halo. These limits are based on the lack of detection in laboratory experiments or by the absence of a signal in underground neutrino detectors. The latter signal is expected if $\widetilde{\chi}^0_1$ accumulates in the Sun or the Earth and annihilates into high-energy ν's.

VALUE	*DOCUMENT ID*	*TECN*

• • • We do not use the following data for averages, fits, limits, etc. • • •

	[8] AMBROSIO	99	MCRO
	[9] LOSECCO	95	RVUE
	[10] MORI	93	KAMI
	[11] BOTTINO	92	COSM
	[12] BOTTINO	91	RVUE
	[13] GELMINI	91	COSM
	[14] KAMIONKOW.	91	RVUE
	[15] MORI	91B	KAMI
none 4–15 GeV	[16] OLIVE	88	COSM

[8] AMBROSIO 99 set new neutrino flux limits which can be used to limit the parameter space in supersymmetric models based on neutralino annihilation in the Sun and the Earth.

[9] LOSECCO 95 reanalyzed the IMB data and places lower limit on $m_{\widetilde{\chi}^0_1}$ of 18 GeV if the LSP is a photino and 10 GeV if the LSP is a higgsino based on LSP annihilation in the sun producing high-energy neutrinos and the limits on neutrino fluxes from the IMB detector.

[10] MORI 93 excludes some region in M_2–μ parameter space depending on tanβ and lightest scalar Higgs mass for neutralino dark matter $m_{\widetilde{\chi}^0} > m_W$, using limits on upgoing muons produced by energetic neutrinos from neutralino annihilation in the Sun and the Earth.

[11] BOTTINO 92 excludes some region M_2-μ parameter space assuming that the lightest neutralino is the dark matter, using upgoing muons at Kamiokande, direct searches by Ge detectors, and by LEP experiments. The analysis includes top radiative corrections on Higgs parameters and employs two different hypotheses for nucleon-Higgs coupling. Effects of rescaling in the local neutralino density according to the neutralino relic abundance are taken into account.

[12] BOTTINO 91 excluded a region in $M_2-\mu$ plane using upgoing muon data from Kamioka experiment, assuming that the dark matter surrounding us is composed of neutralinos and that the Higgs boson is not too heavy.

[13] GELMINI 91 exclude a region in $M_2 - \mu$ plane using dark matter searches.

[14] KAMIONKOWSKI 91 excludes a region in the M_2–μ plane using IMB limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the sun, assuming that the dark matter is composed of neutralinos and that $m_{H^0_1} \lesssim$ 50 GeV. See Fig. 8 in the paper.

[15] MORI 91B exclude a part of the region in the M_2–μ plane with $m_{\widetilde{\chi}^0_1} \lesssim$ 80 GeV using a limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the earth, assuming that the dark matter surrounding us is composed of neutralinos and that $m_{H^0_1} \lesssim$ 80 GeV.

[16] OLIVE 88 result assumes that photinos make up the dark matter in the galactic halo. Limit is based on annihilations in the sun and is due to an absence of high energy neutrinos detected in underground experiments. The limit is model dependent.

$\widetilde{\chi}^0_1$-*p* elastic cross section

Experimental results on the $\widetilde{\chi}^0_1$-p elastic cross section are evaluated at $m_{\widetilde{\chi}^0_1}$=100 GeV. The experimental results on the cross section are often mass dependent. Therefore, the mass and cross section results are also given where the limit is strongest, when appropriate. Results are quoted separately for spin-dependent interactions (based on an effective 4-Fermi Lagrangian of the form $\overline{\chi}\gamma^\mu\gamma^5\chi\overline{q}\gamma_\mu\gamma^5 q$) and spin-independent interactions ($\overline{\chi}\chi\overline{q}q$). For calculational details see GRIEST 88B, ELLIS 88D, BARBIERI 89C, DREES 93B, ARNOWITT 96, BERGSTROM 96, and BAER 97 in addition to the theory papers listed in the Tables. For a description of the theoretical assumptions and experimental techniques underlying most of the listed papers, see the review on "Dark matter" in this "Review of Particle Properties," and references therein. Most of the following papers use galactic halo and nuclear interaction assumptions from (LEWIN 96).

Spin-dependent interactions

VALUE (pb)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$ 0.8	[17] AHMED	03	NAIA	NaI Spin Dep.
$<$ 40	[18] TAKEDA	03	BOLO	NaF Spin Dep.
$<$ 10	[19] ANGLOHER	02	CRES	Saphire
8×10^{-7} to 2×10^{-5}	[20] ELLIS	01C	THEO	$\tan\beta \leq 10$
$<$ 3.8	[21] BERNABEI	00D	DAMA	Xe
$<$ 15	[22] COLLAR	00	SMPL	F
$<$ 0.8	SPOONER	00	UKDM	NaI
$<$ 4.8	[23] BELLI	99C	DAMA	F
$<$100	[24] OOTANI	99	BOLO	LiF
$<$ 0.6	BERNABEI	98C	DAMA	Xe
$<$ 5	[23] BERNABEI	97	DAMA	F

[17] The strongest upper limit is 0.75 pb and occurs at $m_\chi \approx 70$ GeV.

[18] The strongest upper limit is 30 pb and occurs at $m_\chi \approx 20$ GeV.

[19] The strongest upper limit is 8 pb and occurs at $m_\chi \simeq 30$ GeV.

[20] ELLIS 01C calculates the χ-p elastic scattering cross section in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry. In models with nonuniversal Higgs masses, the upper limit to the cross section is 6×10^{-4}.

[21] The strongest upper limit is 3 pb and occurs at $m_\chi \simeq 60$ GeV. The limits are for inelastic scattering $X^0 + {}^{129}\text{Xe} \rightarrow X^0 + {}^{129}\text{Xe}^*$ (39.58 keV).

[22] The strongest upper limit is 9 pb and occurs at $m_\chi \simeq 30$ GeV.

[23] The strongest upper limit is 4.4 pb and occurs at $m_\chi \simeq 60$ GeV.

[24] The strongest upper limit is about 35 pb and occurs at $m_\chi \simeq 15$ GeV.

Spin-independent interactions

VALUE (pb)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 2 \times 10^{-5}$	[25] AHMED	03	NAIA	NaI Spin Indep.
$< 1.4 \times 10^{-5}$	[26] KLAPDOR-K...	03	HDMS	Ge
$< 6 \times 10^{-6}$	[27] ABRAMS	02	CDMS	Ge
$< 1.4 \times 10^{-6}$	[28] BENOIT	02	EDEL	Ge
10^{-12} to 7×10^{-6}	KIM	02B	THEO	
$< 3 \times 10^{-5}$	[29] MORALES	02B	CSME	Ge
$<10^{-5}$	[30] MORALES	02C	IGEX	Ge
$<10^{-6}$	BALTZ	01	THEO	
$< 3 \times 10^{-5}$	[31] BAUDIS	01	HDMS	Ge
$< 4.5 \times 10^{-6}$	BENOIT	01	EDEL	Ge
$< 7 \times 10^{-6}$	[32] BOTTINO	01	THEO	
$<10^{-8}$	[33] CORSETTI	01	THEO	$\tan\beta \leq 25$
5×10^{-10} to 1.5×10^{-8}	[34] ELLIS	01C	THEO	$\tan\beta \leq 10$
$< 4 \times 10^{-6}$	[33] GOMEZ	01	THEO	

2×10^{-10} to 10^{-7}	[33] LAHANAS	01	THEO	
$< 3 \times 10^{-6}$	ABUSAIDI	00	CDMS	Ge, Si
$< 6 \times 10^{-7}$	[35] ACCOMANDO	00	THEO	
	[36] BERNABEI	00	DAMA	NaI
2.5×10^{-9} to 3.5×10^{-8}	[37] FENG	00	THEO	$\tan\beta=10$
$< 1.5 \times 10^{-5}$	MORALES	00	IGEX	Ge
$< 4 \times 10^{-5}$	SPOONER	00	UKDM	NaI
$< 7 \times 10^{-6}$	BAUDIS	99	HDMO	^{76}Ge
	[38] BERNABEI	99	DAMA	NaI
	[39] BERNABEI	98	DAMA	NaI
$< 7 \times 10^{-6}$	BERNABEI	98C	DAMA	Xe

[25] The strongest upper limit is 1.8×10^{-5} pb and occurs at $m_\chi \approx 80$ GeV.

[26] The strongest upper limit is 7×10^{-6} pb and occurs at $m_\chi \simeq 30$ GeV.

[27] ABRAMS 02 is incompatible with the DAMA most likely value at the 99.9% CL. The strongest upper limit is 3×10^{-6} pb and occurs at $m_\chi \simeq 30$ GeV.

[28] BENOIT 02 excludes the central result of DAMA at the 99.8%CL.

[29] The strongest upper limit is 2×10^{-5} pb and occurs at $m_\chi \simeq 40$ GeV.

[30] The strongest upper limit is 7×10^{-6} pb and occurs at $m_\chi \simeq 46$ GeV.

[31] The strongest upper limit is 1.8×10^{-5} pb and occurs at $m_\chi \simeq 32$ GeV

[32] BOTTINO 01 calculates the χ-p elastic scattering cross section in the framework of the following supersymmetric models: N=1 supergravity with the radiative breaking of the electroweak gauge symmetry, N=1 supergravity with nonuniversal scalar masses and an effective MSSM model at the electroweak scale.

[33] Calculates the χ-p elastic scattering cross section in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry.

[34] ELLIS 01C calculates the χ-p elastic scattering cross section in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry. ELLIS 02B find a range 2×10^{-8}–1.5×10^{-7} at $\tan\beta=50$. In models with nonuniversal Higgs masses, the upper limit to the cross section is 4×10^{-7}.

[35] ACCOMANDO 00 calculate the χ-p elastic scattering cross section in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry. The limit is relaxed by at least an order of magnitude when models with nonuniversal scalar masses are considered. A subset of the authors in ARNOWITT 02 updated the limit to $< 9 \times 10^{-8}$ ($\tan\beta < 55$).

[36] BERNABEI 00 search for annual modulation of the WIMP signal. The data favor the hypothesis of annual modulation at 4σ and are consistent, for a particular model framework quoted there, with $m_{X^0}=44^{+12}_{-\ 9}$ GeV and a spin-independent X^0-proton cross section of $(5.4 \pm 1.0) \times 10^{-6}$ pb. See also BERNABEI 01 and BERNABEI 00C.

[37] FENG 00 calculate the χ-p elastic scattering cross section in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry with a particular emphasis on focus point models. At $\tan\beta=50$, the range is 8×10^{-8}–4×10^{-7}.

[38] BERNABEI 99 search for annual modulation of the WIMP signal. The data favor the hypothesis of annual modulation at 99.6%CL and are consistent, for the particular model framework considered there, with $m_{X^0}=59^{+17}_{-14}$ GeV and spin-independent X^0-proton cross section of $(7.0^{+0.4}_{-1.2}) \times 10^{-6}$ pb ($1\,\sigma$ errors).

[39] BERNABEI 98 search for annual modulation of the WIMP signal. The data are consistent, for the particular model framework considered there, with $m_{X^0}=59^{+36}_{-19}$ GeV and spin-independent X^0-proton cross section of $(1.0^{+0.1}_{-0.4}) \times 10^{-5}$ pb ($1\,\sigma$ errors).

Other bounds on $\widetilde{\chi}_1^0$ from astrophysics and cosmology

Most of these papers generally exclude regions in the $M_2-\mu$ parameter plane by requiring that the $\widetilde{\chi}_1^0$ contribution to the overall cosmological density is less than some maximal value to avoid overclosure of the Universe. Those not based on the cosmological density are indicated. Many of these papers also include LEP and/or other bounds.

VALUE	DOCUMENT ID		TECN	COMMENT
>46 GeV	[40] ELLIS	00	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[41] BAER	03	COSM	
> 6 GeV	[42] BOTTINO	03	COSM	
	[41] CHATTOPAD...	03	COSM	
	[43] ELLIS	03	COSM	
	[44] ELLIS	03B	COSM	
	[41] ELLIS	03C	COSM	
	[45] ELLIS	03D	COSM	
> 18 GeV	[42] HOOPER	03	COSM	Ω_χ = 0.05–0.3
	[41] LAHANAS	03	COSM	
	[46] BAER	02	COSM	
	[47] ELLIS	02	COSM	
	[48] LAHANAS	02	COSM	
	[49] BARGER	01C	COSM	
	[46] DJOUADI	01	COSM	
	[50] ELLIS	01B	COSM	
	[46] ROSZKOWSKI	01	COSM	
	[43] BOEHM	00B	COSM	
	[51] FENG	00	COSM	
	[52] LAHANAS	00	COSM	
< 600 GeV	[53] ELLIS	98B	COSM	
	[54] EDSJO	97	COSM	Co-annihilation
	[55] BAER	96	COSM	
	[56] BEREZINSKY	95	COSM	
	[57] FALK	95	COSM	*CP*-violating phases
	[58] DREES	93	COSM	Minimal supergravity
	[59] FALK	93	COSM	Sfermion mixing
	[58] KELLEY	93	COSM	Minimal supergravity
	[60] MIZUTA	93	COSM	Co-annihilation
	[61] LOPEZ	92	COSM	Minimal supergravity, m_0=A=0
	[62] MCDONALD	92	COSM	
	[63] GRIEST	91	COSM	
	[64] NOJIRI	91	COSM	Minimal supergravity
	[65] OLIVE	91	COSM	
	[66] ROSZKOWSKI	91	COSM	
	[67] GRIEST	90	COSM	
	[65] OLIVE	89	COSM	
none 100 eV – 15 GeV	SREDNICKI	88	COSM	$\widetilde{\gamma}$; $m_{\widetilde{f}}$=100 GeV
none 100 eV–5 GeV	ELLIS	84	COSM	$\widetilde{\gamma}$; for $m_{\widetilde{f}}$=100 GeV
	GOLDBERG	83	COSM	$\widetilde{\gamma}$
	[68] KRAUSS	83	COSM	$\widetilde{\gamma}$
	VYSOTSKII	83	COSM	$\widetilde{\gamma}$

[40] ELLIS 00 updates ELLIS 98. Uses LEP $e^+ e^-$ data at $\sqrt{s}$=202 and 204 GeV to improve bound on neutralino mass to 51 GeV when scalar mass universality is assumed and 46 GeV when Higgs mass universality is relaxed. Limits on tanβ improve to > 2.7 ($\mu > 0$), > 2.2 ($\mu < 0$) when scalar mass universality is assumed and > 1.9 (both signs of μ) when Higgs mass universality is relaxed.

[41] BAER 03, CHATTOPADHYAY 03, ELLIS 03C and LAHANAS 03 place constraints on the SUSY parameter space in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry based on WMAP results for the cold dark matter density.

[42] BOTTINO 03 (see also BOTTINO 03A) and HOOPER 03 do not assume gaugino or scalar mass unification.

[43] BOEHM 00B and ELLIS 03 place constraints on the SUSY parameter space in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry. Includes the effect of χ-$\widetilde{t}$ co-annihilations.

[44] BEREZINSKY 95 and ELLIS 03B places constraints on the SUSY parameter space in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry but non-Universal Higgs masses.

[45] ELLIS 03D places constraints on the SUSY parameter space in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry including supersymmetry breaking relations between A and B parameters.

[46] DJOUADI 01, ROSZKOWSKI 01, and BAER 02 place constraints on the SUSY parameter space in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry.

[47] ELLIS 02 places constraints on the soft supersymmetry breaking masses in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry.

[48] LAHANAS 02 places constraints on the SUSY parameter space in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry. Focuses on the role of pseudo-scalar Higgs exchange.

[49] BARGER 01C use the cosmic relic density inferred from recent CMB measurements to constrain the parameter space in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry.

[50] ELLIS 01B places constraints on the SUSY parameter space in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry. Focuses on models with large tanβ.

[51] FENG 00 explores cosmologically allowed regions of MSSM parameter space with multi-TeV masses.

[52] LAHANAS 00 use the new cosmological data which favor a cosmological constant and its implications on the relic density to constrain the parameter space in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry.

[53] ELLIS 98B assumes a universal scalar mass and radiative supersymmetry breaking with universal gaugino masses. The upper limit to the LSP mass is increased due to the inclusion of $\chi - \widetilde{\tau}_R$ coannihilations.

[54] EDSJO 97 included all coannihilation processes between neutralinos and charginos for any neutralino mass and composition.

[55] Notes the location of the neutralino Z resonance and h resonance annihilation corridors in minimal supergravity models with radiative electroweak breaking.

[56] BEREZINSKY 95 and ELLIS 02C places constraints on the SUSY parameter space in the framework of N=1 supergravity models with radiative breaking of the electroweak gauge symmetry but non-Universal Higgs masses.

[57] Mass of the bino (=LSP) is limited to $m_{\widetilde{B}} \lesssim 350$ GeV for $m_t = 174$ GeV.

[58] DREES 93, KELLEY 93 compute the cosmic relic density of the LSP in the framework of minimal N=1 supergravity models with radiative breaking of the electroweak gauge symmetry.

[59] FALK 93 relax the upper limit to the LSP mass by considering sfermion mixing in the MSSM.
[60] MIZUTA 93 include coannihilations to compute the relic density of Higgsino dark matter.
[61] LOPEZ 92 calculate the relic LSP density in a minimal SUSY GUT model.
[62] MCDONALD 92 calculate the relic LSP density in the MSSM including exact tree-level annihilation cross sections for all two-body final states.
[63] GRIEST 91 improve relic density calculations to account for coannihilations, pole effects, and threshold effects.
[64] NOJIRI 91 uses minimal supergravity mass relations between squarks and sleptons to narrow cosmologically allowed parameter space.
[65] Mass of the bino (=LSP) is limited to $m_{\widetilde{B}} \lesssim$ 350 GeV for $m_t \leq$ 200 GeV. Mass of the higgsino (=LSP) is limited to $m_{\widetilde{H}} \lesssim$ 1 TeV for $m_t \leq$ 200 GeV.
[66] ROSZKOWSKI 91 calculates LSP relic density in mixed gaugino/higgsino region.
[67] Mass of the bino (=LSP) is limited to $m_{\widetilde{B}} \lesssim$ 550 GeV. Mass of the higgsino (=LSP) is limited to $m_{\widetilde{H}} \lesssim$ 3.2 TeV.
[68] KRAUSS 83 finds $m_{\widetilde{\gamma}}$ not 30 eV to 2.5 GeV. KRAUSS 83 takes into account the gravitino decay. Find that limits depend strongly on reheated temperature. For example a new allowed region $m_{\widetilde{\gamma}}$ = 4–20 MeV exists if $m_{\text{gravitino}}$ <40 TeV. See figure 2.

Unstable $\widetilde{\chi}^0_1$ (Lightest Neutralino) MASS LIMIT

Unless otherwise stated, results in this section assume spectra and production rates as evaluated in the MSSM. Unless otherwise stated, the goldstino or gravitino mass $m_{\widetilde{G}}$ is assumed to be negligible relative to all other masses. In the following, $\widetilde{G}$ is assumed to be undetected and to give rise to a missing energy ($\not{E}$) signature.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>89	95	[69] ABDALLAH	03D	DLPH	$e^+e^- \to \widetilde{\chi}^0_1\widetilde{\chi}^0_1$, GMSB, $m(\widetilde{G}) <$ 1 eV
		[70] HEISTER	03C	ALEP	$e^+e^- \to \widetilde{B}\widetilde{B}$, $(\widetilde{B} \to \gamma\widetilde{G})$
		[71] HEISTER	03C	ALEP	$e^+e^- \to \widetilde{G}\widetilde{\chi}^0_1$, $(\widetilde{\chi}^0_1 \to \widetilde{G}\gamma)$
>39.9	95	[72] ACHARD	02	L3	$\not{R}$, MSUGRA
>92	95	[73] HEISTER	02R	ALEP	short lifetime
>54	95	[73] HEISTER	02R	ALEP	any lifetime
>85	95	[74] ABBIENDI	01	OPAL	$e^+e^- \to \widetilde{\chi}^0_1\widetilde{\chi}^0_1$, GMSB, tan$\beta$=2
>76	95	[74] ABBIENDI	01	OPAL	$e^+e^- \to \widetilde{\chi}^0_1\widetilde{\chi}^0_1$, GMSB, tan$\beta$=20
none 10–32	95	[75] ABREU	01D	DLPH	$\not{R}(\overline{UDD})$, all m_0, 0.5 ≤ tanβ ≤ 30
>32.5	95	[76] ACCIARRI	01	L3	$\not{R}$, all m_0, 0.7 ≤ tanβ ≤ 40
		[77] ADAMS	01	NTEV	$\widetilde{\chi}^0 \to \mu\mu\nu$, $\not{R}$, $LL\overline{E}$
		[78] ABBIENDI,G	00D	OPAL	$e^+e^- \to \widetilde{G}\widetilde{\chi}^0_1$ $(\widetilde{\chi}^0_1 \to \gamma\widetilde{G})$
none 45–88.3	95	[79] ABBIENDI,G	00D	OPAL	$e^+e^- \to \widetilde{B}\widetilde{B}$, $(\widetilde{B} \to \gamma\widetilde{G})$
none 10–30	95	[80] ABREU	00U	DLPH	$\not{R}$ ($LL\overline{E}$), all m_0, 1 ≤ tanβ ≤ 30
		[81] ABREU	00Z	DLPH	$e^+e^- \to \widetilde{G}\widetilde{\chi}^0_1$ $(\widetilde{\chi}^0_1 \to \widetilde{G}\gamma)$
>83.5	95	[82] ABREU	00Z	DLPH	$e^+e^- \to \widetilde{B}\widetilde{B}$ $(\widetilde{B} \to \widetilde{G}\gamma)$

>29	95	[83] ABBIENDI	99T	OPAL	$e^+e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_1$, $\not{R}$, m_0=500 GeV, tan$\beta > 1.2$
>65	95	[84] ABE	99I	CDF	$p\overline{p} \to \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}=\widetilde{\chi}^0_{1,2}$,$\widetilde{\chi}^\pm_1$, $\widetilde{\chi}^0_1 \to \gamma \widetilde{G}$
		[85] ACCIARRI	99R	L3	$e^+e^- \to \widetilde{G}\widetilde{\chi}^0_1$, $\widetilde{\chi}^0_1 \to \widetilde{G}\gamma$
>88.2	95	[86] ACCIARRI	99R	L3	$e^+e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_1$, $\widetilde{\chi}^0_1 \to \widetilde{G}\gamma$
>29	95	[87] BARATE	99E	ALEP	$\not{R}$, $LQ\overline{D}$, tanβ=1.41, m_0=500 GeV
>77	95	[88] ABBOTT	98	D0	$p\overline{p} \to \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}=\widetilde{\chi}^0_{1,2}$,$\widetilde{\chi}^\pm_1$, $\widetilde{\chi}^0_1 \to \gamma \widetilde{G}$
		[89] ABREU	98	DLPH	$e^+e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_1 \to \gamma \widetilde{G}$)
>23	95	[90] BARATE	98S	ALEP	$\not{R}$, $LL\overline{E}$
		[91] ELLIS	97	THEO	$e^+e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_1$, $\widetilde{\chi}^0_1 \to \gamma \widetilde{G}$
		[92] CABIBBO	81	COSM	

[69] ABDALLAH 03D use data from $\sqrt{s}$= 161-208 GeV. They look for 4-tau + $\not{E}$ final states, expected in GMSB when the $\widetilde{\tau}_1$ is the NLSP, and 4-lepton + $\not{E}$ final states, expected in the co-NLSP scenario, and assuming a short-lived $\widetilde{\chi}^0_1$ ($m(\widetilde{G}) < 1$ eV). Limits are computed in the plane (m($\widetilde{\tau}_1$),m($\widetilde{\chi}^0_1$)) from a scan of the GMSB parameters space, after combining these results with the search for slepton pair production from the same paper to cover prompt decays and for the case of $\widetilde{\chi}^0_1$ NLSP from ABREU 00Z. The limit above is reached for a single generation of messengers and when the $\widetilde{\tau}_1$ is the NLSP. Stronger limits are obtained when more messenger generations are assumed or when the other sleptons are co-NLSP, see their Fig. 10. Supersedes the results of ABREU 01G.

[70] HEISTER 03C use the data from $\sqrt{s}$= 189-209 GeV to search for $\gamma\not{E}_T$ final states with non-pointing photons and $\gamma\gamma$ $\not{E}_T$ events. Interpreted in the framework of Minimal GMSB, a lower bound on the $\widetilde{\chi}^0_1$ mass is obtained as function of its lifetime. For a laboratory lifetime of less than 3 ns, the limit at 95% CL is 98.8 GeV. For other lifetimes, see their Fig. 5. These results are interpreted in a more general GMSB framework in HEISTER 02R.

[71] HEISTER 03C use the data from $\sqrt{s}$= 189-209 GeV to search for $\gamma\not{E}_T$ final states. They obtained an upper bound on the cross section for the process $e^+e^- \to \widetilde{G}\widetilde{\chi}^0_1$, followed by the prompt decay $\widetilde{\chi}^0_1 \to \gamma\widetilde{G}$, shown in their Fig. 4. These results supersede BARATE 98H.

[72] ACHARD 02 searches for the production of sparticles in the case of $\not{R}$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The MSUGRA limit results from a scan over the MSSM parameter space with the assumption of gaugino and scalar mass unification at the GUT scale, imposing simultaneously the exclusions from neutralino, chargino, sleptons, and squarks analyses. The limit holds for $\overline{UDD}$ couplings and increases to 40.2 GeV for $LL\overline{E}$ couplings. For L3 limits from $LQ\overline{D}$ couplings, see ACCIARRI 01.

[73] HEISTER 02R search for signals of GMSB in the 189–209 GeV data. For the $\widetilde{\chi}^0_1$ NLSP scenario, they looked for topologies consisting of $\gamma\gamma\not{E}$ or a single γ not pointing to the interaction vertex. For the $\widetilde{\ell}$ NLSP case, the topologies consist of $\ell\ell\not{E}$ or $4\ell\not{E}$ (from $\widetilde{\chi}^0_1\widetilde{\chi}^0_1$) production), including leptons with large impact parameters, kinks, or stable particles. Limits are derived from a scan over the GMSB parameters (see their Table 5 for the ranges). The limits are valid whichever is the NLSP. The absolute mass bound on the $\widetilde{\chi}^0_1$ for any lifetime includes indirect limits from the chargino search, and from the slepton search HEISTER 02E preformed within the MSUGRA framework. A bound for any NLSP and any lifetime of 77 GeV has also been derived by using the constraints from the neutral Higgs search in HEISTER 02. Limits on the universal SUSY mass scale Λ are also derived in the paper. Supersedes the results from BARATE 00G.

[74] ABBIENDI 01 looked for final states with $\gamma\gamma\not{E}$, $\ell\ell\not{E}$, with possibly additional activity and four leptons + $\not{E}$ to search for prompt decays of $\widetilde{\chi}^0_1$ or $\widetilde{\ell}_1$ in GMSB. They derive limits in the plane ($m_{\widetilde{\chi}^0_1}$,$m_{\widetilde{\tau}_1}$), see Fig. 6, allowing either the $\widetilde{\chi}^0_1$ or a $\widetilde{\ell}_1$ to be the NLSP. Two scenarios are considered: tanβ=2 with the 3 sleptons degenerate in mass and tanβ=20 where the $\widetilde{\tau}_1$ is lighter than the other sleptons. Data taken at $\sqrt{s}$=189 GeV.

[75] ABREU 01D searches for multi-jet events, expected in the case of prompt decays from R-parity violating $\overline{UDD}$ couplings, using data from $\sqrt{s}$=189 GeV. Combined with the search for charginos, limits are obtained in the M_2 versus μ plane and a limit on the neutralino mass is derived from a scan over the parameters m_0 and tanβ. The weakest limit for $\widetilde{\chi}^0_1$ is reached for high m_0 and tanβ=1.

[76] ACCIARRI 01 searches for multi-lepton and/or multi-jet final states from $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings at $\sqrt{s}$=189 GeV. The search is performed for direct and indirect decays of neutralinos, charginos, and scalar leptons, with the $\widetilde{\chi}^0_1$ or a $\widetilde{\ell}$ as LSP and assuming one coupling to be nonzero at a time. Mass limits are derived using simultaneously the constraints from the neutralino, chargino, and slepton analyses; and the Z^0 width measurements from ACCIARRI 00C in a scan of the parameter space assuming MSUGRA with gaugino and scalar mass universality. Updates and supersedes the results from ACCIARRI 99I.

[77] ADAMS 01 looked for neutral particles with mass > 2.2 GeV, produced by 900 GeV protons incident on a Beryllium oxide target and decaying through weak interactions into $\mu\mu$, μe, or $\mu\pi$ final states in the decay channel of the NuTeV detector (E815) at Fermilab. The number of observed events is 3 $\mu\mu$, 0 μe, and 0 $\mu\pi$ with an expected background of 0.069 ± 0.010, 0.13 ± 0.02, and 0.14 ± 0.02, respectively. The $\mu\mu$ events are consistent with the $\not{R}$ decay of a neutralino with mass around 5 GeV. However, they share several aspects with ν-interaction backgroundes. An upper limit on the differential production cross section of neutralinos in $p\,p$ interactions as function of the decay length is given in Fig. 3.

[78] ABBIENDI,G 00D obtained an upper limit on the cross section for the process $e^+ e^- \rightarrow \widetilde{G}\,\widetilde{\chi}^0_1$ followed by the prompt decay $\widetilde{\chi}^0_1 \rightarrow \gamma\,\widetilde{G}$ shown in Fig. 11. Data taken at $\sqrt{s}$=189 GeV. These limits include and update the results of ABBIENDI 99F.

[79] ABBIENDI,G 00D looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$=189 GeV. The limit is for pure bino $\widetilde{B}$ NLSP and assumes $m_{\widetilde{e}_R} = 1.35 m_{\widetilde{\chi}^0_1}$ and $m_{\widetilde{e}_L} = 2.7 m_{\widetilde{\chi}^0_1}$. See Fig. 14 for the cross-section limits as function of $m_{\widetilde{\chi}^0_1}$. These limits include and update the results of ABBIENDI 99F.

[80] ABREU 00U searches for the production of charginos and neutralinos in the case of R-parity violation with $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling to be nonzero at the time and giving rise to direct or indirect decays. Limits are obtained in the M_2 versus μ plane and a limit on the neutralino mass is derived from a scan over the parameters m_0 and tanβ. The weakest limit for $\widetilde{\chi}^0_1$ is reached for high m_0 and tanβ=1. Supersedes the results of ABREU 00I.

[81] ABREU 00Z looks for $\gamma\not{E}$ final states using data from $\sqrt{s}$= 183–189 GeV. Assuming the decay $\widetilde{\chi}^0_1 \rightarrow \widetilde{G}\gamma$, limits on cross section are derived, see their Fig. 7.

[82] ABREU 00Z looks for diphoton $+\not{E}$ final states using data from $\sqrt{s}$= 130–189 GeV. The limit is derived for a pure bino $\widetilde{B}$ assuming the prompt decay $\widetilde{B} \rightarrow \widetilde{G}\gamma$ and $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R} = 2 m_{\widetilde{B}}$. For long-lived neutralinos, cross-section limits are displayed in their Fig. 9. These results include and update limits from ABREU 99D.

[83] ABBIENDI 99T searches for the production of neutralinos in the case of R-parity violation with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero and giving rise to direct or indirect decays. Mixed decays (where one particle has a direct, the other an indirect decay) are also considered for the

$\overline{UDD}$ couplings. Upper limits on the cross section are derived which, combined with the constraint from the Z^0 width, allow to exclude regions in the M_2 versus μ plane for any coupling. Limits on the neutralino mass are obtained for non-zero $LL\overline{E}$ couplings $> 10^{-5}$. The limit disappears for $\tan\beta < 1.2$ and it improves to 50 GeV for $\tan\beta > 20$.

[84] ABE 99I looked for chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\widetilde{G}$. The limit assumes the gaugino mass unification, and holds for $1 < \tan\beta < 25$, $M_2 < 200$ GeV, and all μ. ABE 99I is an expanded version of ABE 98L.

[85] ACCIARRI 99R searches for $\gamma \not\!\!E$ final states using data from $\sqrt{s}$=189 GeV. From limits on cross section times branching ratio, mass limits are derived in a no-scale SUGRA model, see their Fig. 5. Supersedes the results of ACCIARRI 98V.

[86] ACCIARRI 99R searches for $\gamma \not\!\!E$ final states using data from $\sqrt{s}$=189 GeV. From a scan over the GMSB parameter space, a limit on the mass is derived under the assumption that the neutralino is the NLSP. Supersedes the results of ACCIARRI 98V.

[87] BARATE 99E looked for the decay of gauginos via R-violating couplings $LQ\overline{D}$. The bound is significantly reduced for smaller values of m_0. Data collected at $\sqrt{s}$=130–172 GeV.

[88] ABBOTT 98 studied the chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\widetilde{G}$. The limit assumes the gaugino mass unification.

[89] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. Upper bounds on $\gamma\gamma \not\!\!E$ cross section are obtained. Similar limits on $\gamma \not\!\!E$ are also given, relevant for $e^+ e^- \rightarrow \widetilde{\chi}^0_1 \widetilde{G}$ production.

[90] BARATE 98S looked for the decay of gauginos via R-violating coupling $LL\overline{E}$. The bound improves to 25 GeV if the chargino decays into neutralino which further decays into lepton pairs. Data collected at $\sqrt{s}$=130–172 GeV.

[91] ELLIS 97 reanalyzed the LEP2 ($\sqrt{s}$=161 GeV) limits of $\sigma(\gamma\gamma+E_{\text{miss}}) < 0.2$ pb to exclude $m_{\widetilde{\chi}^0_1} < 63$ GeV if $m_{\widetilde{e}_L}=m_{\widetilde{e}_R} < 150$ GeV and $\widetilde{\chi}^0_1$ decays to $\gamma\widetilde{G}$ inside detector.

[92] CABIBBO 81 consider $\widetilde{\gamma} \rightarrow \gamma+$ goldstino. Photino must be either light enough ($<$30 eV) to satisfy cosmology bound, or heavy enough ($>$0.3 MeV) to have disappeared at early universe.

$\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_4$ (Neutralinos) MASS LIMITS

Neutralinos are unknown mixtures of photinos, z-inos, and neutral higgsinos (the supersymmetric partners of photons and of Z and Higgs bosons). The limits here apply only to $\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, and $\widetilde{\chi}^0_4$. $\widetilde{\chi}^0_1$ is the lightest supersymmetric particle (LSP); see $\widetilde{\chi}^0_1$ Mass Limits. It is not possible to quote rigorous mass limits because they are extremely model dependent; i.e. they depend on branching ratios of various $\widetilde{\chi}^0$ decay modes, on the masses of decay products ($\widetilde{e}$, $\widetilde{\gamma}$, $\widetilde{q}$, $\widetilde{g}$), and on the $\widetilde{e}$ mass exchanged in $e^+ e^- \rightarrow \widetilde{\chi}^0_i \widetilde{\chi}^0_j$. Limits arise either from direct searches, or from the MSSM constraints set on the gaugino and higgsino mass parameters M_2 and μ through searches for lighter charginos and neutralinos. Often limits are given as contour plots in the $m_{\widetilde{\chi}^0} - m_{\widetilde{e}}$ plane vs other parameters. When specific assumptions are made, e.g, the neutralino is a pure photino ($\widetilde{\gamma}$), pure z-ino ($\widetilde{Z}$), or pure neutral higgsino ($\widetilde{H}^0$), the neutralinos will be labelled as such.

Limits obtained from $e^+ e^-$ collisions at energies up to 136 GeV, as well as other limits from different techniques, are now superseded and have not been included in this compilation. They can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
$>$ 55.9	95	[93] ABBIENDI	00H	OPAL	$\widetilde{\chi}^0_2$, $\tan\beta$=1.5, Δm >10 GeV, all m_0
$>$106	95	[93] ABBIENDI	00H	OPAL	$\widetilde{\chi}^0_3$, $\tan\beta$=1.5, Δm >10 GeV, all m_0
> 62.4	95	[94] ABREU	00W	DLPH	$\widetilde{\chi}^0_2$, $1 \leq \tan\beta \leq 40$, all Δm_0, all m_0
> 99.9	95	[94] ABREU	00W	DLPH	$\widetilde{\chi}^0_3$, $1 \leq \tan\beta \leq 40$, all Δm_0, all m_0
>116.0	95	[94] ABREU	00W	DLPH	$\widetilde{\chi}^0_4$, $1 \leq \tan\beta \leq 40$, all Δm_0, all m_0
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>$ 80.0	95	[95] ACHARD	02	L3	$\widetilde{\chi}^0_2$, $\not{R}$, MSUGRA
$>$107.2	95	[95] ACHARD	02	L3	$\widetilde{\chi}^0_3$, $\not{R}$, MSUGRA
		[96] ABREU	01B	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^0_i \widetilde{\chi}^0_j$
$>$ 68.0	95	[97] ACCIARRI	01	L3	$\widetilde{\chi}^0_2$, $\not{R}$, all m_0, $0.7 \leq \tan\beta \leq 40$
$>$ 99.0	95	[97] ACCIARRI	01	L3	$\widetilde{\chi}^0_3$, $\not{R}$, all m_0, $0.7 \leq \tan\beta \leq 40$
$>$ 50	95	[98] ABREU	00U	DLPH	$\widetilde{\chi}^0_2$, $\not{R}$ ($LL\overline{E}$), all Δm_0, $1 \leq \tan\beta \leq 30$
	95	[99] ABREU	00Z	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_2$ ($\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 \gamma$)
		[100] ABBIENDI	99F	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$)
		[101] ABBIENDI	99F	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_2$ ($\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$)
		[102] ACCIARRI	99R	L3	$e^+e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_{2,1}$, $\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 \gamma$
		[103] ABBOTT	98C	D0	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2$
$>$ 82.2	95	[104] ABE	98J	CDF	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2$
$>$ 92	95	[105] ACCIARRI	98F	L3	$\widetilde{H}^0_2$, $\tan\beta$=1.41, M_2 < 500 GeV
		[106] ACCIARRI	98V	L3	$e^+e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_{1,2}$ ($\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$)
$>$ 53	95	[107] BARATE	98H	ALEP	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$ ($\widetilde{\gamma} \rightarrow \gamma \widetilde{H}^0$)
$>$ 74	95	[108] BARATE	98J	ALEP	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$ ($\widetilde{\gamma} \rightarrow \gamma \widetilde{H}^0$)
		[109] ABACHI	96	D0	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2$
		[110] ABE	96K	CDF	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2$

[93] ABBIENDI 00H used the results of direct searches in the $e^+e^- \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_{2,3}$ channels, as well as the indirect limits from $\widetilde{\chi}^0_1$ and $\widetilde{\chi}^\pm_1$ searches, in the framework of the MSSM with gaugino and sfermion mass unification at the GUT scale. See the footnote to ABBIENDI 00H in the chargino Section for further details on the assumptions. Data collected at $\sqrt{s}$=189 GeV. The limits improve to 86.2 GeV ($\widetilde{\chi}^0_2$) and 124 GeV ($\widetilde{\chi}^0_3$) for $\tan\beta$=35. See their Table 6 for more details on the $\tan\beta$ and m_0 dependence of the limits. Quoted values consistent with erratum published in ABBIENDI 00Y. Updates ABBIENDI 99G.

[94] ABREU 00W combines data collected at $\sqrt{s}$=189 GeV with results from lower energies. The mass limit is obtained by constraining the MSSM parameter space with gaugino and sfermion mass universality at the GUT scale, using the results of negative direct searches for neutralinos (including cascade decays and $\widetilde{\tau}\tau$ final states) from ABREU 01, for charginos from ABREU 00J and ABREU 00T (for all Δm_+), and for charged sleptons

from ABREU 01B. The results hold for the full parameter space defined by all values of M_2 and $|\mu| \leq 2$ TeV with the $\widetilde{\chi}_1^0$ as LSP.

[95] ACHARD 02 searches for the production of sparticles in the case of $\not{R}$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The MSUGRA limit results from a scan over the MSSM parameter space with the assumption of gaugino and scalar mass unification at the GUT scale, imposing simultaneously the exclusions from neutralino, chargino, sleptons, and squarks analyses. The limit of $\widetilde{\chi}_2^0$ holds for $\overline{UDD}$ couplings and increases to 84.0 GeV for $LL\overline{E}$ couplings. The same $\widetilde{\chi}_3^0$ limit holds for both $LL\overline{E}$ and $\overline{UDD}$ couplings. For L3 limits from $LQ\overline{D}$ couplings, see ACCIARRI 01.

[96] ABREU 01B used data from $\sqrt{s}$=189 GeV to search for the production of $\widetilde{\chi}_i^0 \widetilde{\chi}_j^0$. They looked for di-jet and di-lepton pairs with $\not{E}$ for events from $\widetilde{\chi}_i^0 \widetilde{\chi}_j^0$ with the decay $\widetilde{\chi}_j^0 \to f\overline{f}\widetilde{\chi}_1^0$; multi-jet and multi-lepton pairs with or without additional photons to cover the cascade decays $\widetilde{\chi}_j^0 \to f\overline{f}\widetilde{\chi}_2^0$, followed by $\widetilde{\chi}_j^0 \to f\overline{f}\widetilde{\chi}_1^0$ or $\widetilde{\chi}_j^0 \to \gamma\widetilde{\chi}_1^0$; multi-tau final states from $\widetilde{\chi}_2^0 \to \widetilde{\tau}\tau$ with $\widetilde{\tau} \to \tau\widetilde{\chi}_1^0$. See Figs. 9 and 10 for limits on the (μ,M_2) plane for tanβ=1.0 and different values of m_0.

[97] ACCIARRI 01 searches for multi-lepton and/or multi-jet final states from $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings at $\sqrt{s}$=189 GeV. The search is performed for direct and indirect decays of neutralinos, charginos, and scalar leptons, with the $\widetilde{\chi}_1^0$ or a $\widetilde{\ell}$ as LSP and assuming one coupling to be nonzero at a time. Mass limits are derived using simultaneously the constraints from the neutralino, chargino, and slepton analyses; and the Z^0 width measurements from ACCIARRI 00C in a scan of the parameter space assuming MSUGRA with gaugino and scalar mass universality. Updates and supersedes the results from ACCIARRI 99I.

[98] ABREU 00U searches for the production of charginos and neutralinos in the case of R-parity violation with $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling to be nonzero at the time and giving rise to direct or indirect decays. LImits are obtained in the M_2 versus μ plane and a limit on the neutralino mass is derived from a scan over the parameters m_0 and tanβ.

[99] ABREU 00Z looks for diphoton $+\not{E}$ final states using data from $\sqrt{s}$= 130–189 GeV. They obtain an upper bound on the cross section, see their Fig. 10 for limits in the ($m_{\widetilde{\chi}_2^0}$,$m_{\widetilde{\chi}_1^0}$) plane. Updates ABREU 99D.

[100] ABBIENDI 99F looked for $\gamma\not{E}$ final states at $\sqrt{s}$=183 GeV. They obtained an upper bound on the cross section for the production $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_1^0$ followed by the prompt decay $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ of 0.075–0.80 pb in the region $m_{\widetilde{\chi}_2^0}+m_{\widetilde{\chi}_1^0} > m_Z$, $m_{\widetilde{\chi}_2^0}$=91–183 GeV, and $\Delta m_0 > 5$ GeV. See Fig. 7 for explicit limits in the ($m_{\widetilde{\chi}_2^0}$,$m_{\widetilde{\chi}_1^0}$) plane.

[101] ABBIENDI 99F looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$=183 GeV. They obtained an upper bound on the cross section for the production $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_2^0$ followed by the prompt decay $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ of 0.08–0.37 pb for $m_{\widetilde{\chi}_2^0}$=45–81.5 GeV, and $\Delta m_0 > 5$ GeV. See Fig. 11 for explicit limits in the ($m_{\widetilde{\chi}_2^0}$,$m_{\widetilde{\chi}_1^0}$) plane.

[102] ACCIARRI 99R searches for $\gamma\not{E}$ and $\gamma\gamma\not{E}$ final states using data from $\sqrt{s}$=189 GeV. Limits on the cross section for the processes $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_{2,1}^0$ with the decay $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\gamma$ are derived, as shown in their Figs. 4 and 7. Supersedes the results of ACCIARRI 98V.

[103] ABBOTT 98C searches for trilepton final states (ℓ=e,μ). See footnote to ABBOTT 98C in the Chargino Section for details on the assumptions. Assuming a negligible decay rate of $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_2^0$ to quarks, they obtain $m_{\widetilde{\chi}_2^0} \gtrsim 103$ GeV.

[104] ABE 98J searches for trilepton final states (ℓ=e,μ). See footnote to ABE 98J in the Chargino Section for details on the assumptions. The quoted result for $m_{\widetilde{\chi}_2^0}$ corresponds to the best limit within the selected range of parameters, obtained for $m_{\widetilde{q}} > m_{\widetilde{g}}$, $\tan\beta$=2, and μ=-600 GeV.

[105] ACCIARRI 98F is obtained from direct searches in the $e^+e^- \rightarrow \widetilde{\chi}_{1,2}^0 \widetilde{\chi}_2^0$ production channels, and indirectly from $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_1^0$ searches within the MSSM. See footnote to ACCIARRI 98F in the chargino Section for further details on the assumptions. Data taken at $\sqrt{s}$ = 130–172 GeV.

[106] ACCIARRI 98V looked for $\gamma(\gamma)\not{E}$ final states at $\sqrt{s}$=183 GeV. They obtained an upper bound on the cross section for the production $e^+e^- \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_{1,2}^0$ followed by the prompt decay $\widetilde{\chi}_2^0 \rightarrow \gamma\widetilde{\chi}_1^0$. See Figs. 4a and 6a for explicit limits in the ($m_{\widetilde{\chi}_2^0}$,$m_{\widetilde{\chi}_1^0}$) plane.

[107] BARATE 98H looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$ = 161,172 GeV. They obtained an upper bound on the cross section for the production $e^+e^- \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_2^0$ followed by the prompt decay $\widetilde{\chi}_2^0 \rightarrow \gamma\widetilde{\chi}_1^0$ of 0.4–0.8 pb for $m_{\widetilde{\chi}_2^0}$ = 10–80 GeV. The bound above is for the specific case of $\widetilde{\chi}_1^0 = \widetilde{H}^0$ and $\widetilde{\chi}_2^0 = \widetilde{\gamma}$ and $m_{\widetilde{e}_R}$ = 100 GeV. See Fig. 6 and 7 for explicit limits in the ($\widetilde{\chi}_2^0$,$\widetilde{\chi}_1^0$) plane and in the ($\widetilde{\chi}_2^0$,$\widetilde{e}_R$) plane.

[108] BARATE 98J looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$ = 161–183 GeV. They obtained an upper bound on the cross section for the production $e^+e^- \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_2^0$ followed by the prompt decay $\widetilde{\chi}_2^0 \rightarrow \gamma\widetilde{\chi}_1^0$ of 0.08–0.24 pb for $m_{\widetilde{\chi}_2^0} < 91$ GeV. The bound above is for the specific case of $\widetilde{\chi}_1^0 = \widetilde{H}^0$ and $\widetilde{\chi}_2^0 = \widetilde{\gamma}$ and $m_{\widetilde{e}_R}$ = 100 GeV.

[109] ABACHI 96 searches for 3-lepton final states. Efficiencies are calculated using mass relations and branching ratios in the Minimal Supergravity scenario. Results are presented as lower bounds on $\sigma(\widetilde{\chi}_1^\pm \widetilde{\chi}_2^0) \times$ B($\widetilde{\chi}_1^\pm \rightarrow \ell\nu_\ell\widetilde{\chi}_1^0$) $\times$ B($\widetilde{\chi}_2^0 \rightarrow \ell^+\ell^-\widetilde{\chi}_1^0$) as a function of $m_{\widetilde{\chi}_1^0}$. Limits range from 3.1 pb ($m_{\widetilde{\chi}_1^0}$ = 45 GeV) to 0.6 pb ($m_{\widetilde{\chi}_1^0}$ = 100 GeV).

[110] ABE 96K looked for trilepton events from chargino-neutralino production. They obtained lower bounds on $m_{\widetilde{\chi}_2^0}$ as a function of μ. The lower bounds are in the 45–50 GeV range for gaugino-dominant $\widetilde{\chi}_2^0$ with negative μ, if $\tan\beta$ <10. See paper for more details of the assumptions.

$\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_2^\pm$ (Charginos) MASS LIMITS

Charginos are unknown mixtures of w-inos and charged higgsinos (the supersymmetric partners of W and Higgs bosons). A lower mass limit for the lightest chargino ($\widetilde{\chi}_1^\pm$) of approximately 45 GeV, independent of the field composition and of the decay mode, has been obtained by the LEP experiments from the analysis of the Z width and decays. These results, as well as other now superseded limits from e^+e^- collisions at energies below 136 GeV, and from hadronic collisions, can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review.

Unless otherwise stated, results in this section assume spectra, production rates, decay modes and branching ratios as evaluated in the MSSM, with gaugino and sfermion mass unification at the GUT scale. These papers generally study production of $\widetilde{\chi}_1^0 \widetilde{\chi}_2^0$,

$\widetilde{\chi}_1^+ \widetilde{\chi}_1^-$ and (in the case of hadronic collisions) $\widetilde{\chi}_1^+ \widetilde{\chi}_2^0$ pairs, including the effects of cascade decays. The mass limits on $\widetilde{\chi}_1^\pm$ are either direct, or follow indirectly from the constraints set by the non-observation of $\widetilde{\chi}_2^0$ states on the gaugino and higgsino MSSM parameters M_2 and μ. For generic values of the MSSM parameters, limits from high-energy $e^+ e^-$ collisions coincide with the highest value of the mass allowed by phase-space, namely $m_{\widetilde{\chi}_1^\pm} \lesssim \sqrt{s}/2$. At the time of this writing, preliminary and unpublished results from the 2000 run of LEP2 at $\sqrt{s}$ up to $\simeq$ 209 GeV give therefore a lower mass limit of approximately 104 GeV valid for general MSSM models. The limits become however weaker in special regions of the MSSM parameter space where the detection efficiencies or production cross sections are suppressed. For example, this may happen when: (i) the mass differences $\Delta m_+ = m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$ or $\Delta m_\nu = m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\nu}}$ are very small, and the detection efficiency is reduced; (ii) the electron sneutrino mass is small, and the $\widetilde{\chi}_1^\pm$ production rate is suppressed due to a destructive interference between s and t channel exchange diagrams. The regions of MSSM parameter space where the following limits are valid are indicated in the comment lines or in the footnotes.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
$>$ 89	95	[111] ABBIENDI	03H	OPAL	$0.5 \leq \Delta m_+ \leq 5$ GeV,higgsino-like, $\tan\beta$=1.5
$>$ 97.1	95	[112] ABDALLAH	03M	DLPH	$\widetilde{\chi}_1^\pm$, $\Delta m_+ \geq 3$ GeV, $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^\pm}$
$>$ 75	95	[112] ABDALLAH	03M	DLPH	$\widetilde{\chi}_1^\pm$,higgsino,all Δm_+,$m_{\widetilde{f}} > m_{\widetilde{\chi}^\pm}$
$>$ 70	95	[112] ABDALLAH	03M	DLPH	$\widetilde{\chi}_1^\pm$, all Δm_+, $m_{\widetilde{\nu}}$ >500 GeV, $M_2 \leq 2M_1 \leq 10M_2$
> 94	95	[113] ABDALLAH	03M	DLPH	$\widetilde{\chi}_1^\pm$, $\tan\beta \leq 40$, Δm_+ >3 GeV,all m_0
$>$ 88	95	[114] HEISTER	02J	ALEP	$\widetilde{\chi}_1^\pm$, all Δm_+, large m_0
$>$ 71.7	95	[115] ABBIENDI	00H	OPAL	$\tan\beta$=35, Δm_+ >5 GeV, all m_0
$>$ 67.7	95	[116] ACCIARRI	00D	L3	$\tan\beta > 0.7$, all Δm_+, all m_0
$>$ 69.4	95	[117] ACCIARRI	00K	L3	$e^+ e^- \rightarrow \widetilde{\chi}^\pm \widetilde{\chi}^\mp$, all Δm_+, heavy scalars
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>100	95	[118] ABDALLAH	03D	DLPH	$e^+e^- \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_1^\mp$ ($\widetilde{\chi}_1^\pm \rightarrow \widetilde{\tau}_1 \nu_\tau$,$\widetilde{\tau}_1 \rightarrow \tau \widetilde{G}$)
>103	95	[119] HEISTER	03G	ALEP	$R\!\!\!/$ decays, $m_0 > 500$ GeV
>102.7	95	[120] ACHARD	02	L3	$R\!\!\!/$, MSUGRA
		[121] GHODBANE	02	THEO	
$>$ 94.3	95	[122] ABREU	01C	DLPH	$\widetilde{\chi}^\pm \rightarrow \tau J$
$>$ 94	95	[123] ABREU	01D	DLPH	$R\!\!\!/(\overline{UDD})$, all Δm_0, $0.5 \leq \tan\beta \leq$ 30
$>$ 93.8	95	[124] ACCIARRI	01	L3	$R\!\!\!/$, all m_0, $0.7 \leq \tan\beta \leq 40$
>100	95	[125] BARATE	01B	ALEP	$R\!\!\!/$ decays, $m_0 > 500$ GeV
$>$ 94	95	[126] ABREU	00U	DLPH	$R\!\!\!/$ ($LL\overline{E}$), all Δm_0, $1 \leq \tan\beta \leq 30$
$>$ 91.8	95	[127] ABREU	00V	DLPH	$e^+ e^- \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_1^\pm$ ($\widetilde{\chi}_1^\pm \rightarrow \widetilde{\tau}_1 \nu_\tau$, $\widetilde{\tau}_1 \rightarrow \tau \widetilde{G}$)
		[128] CHO	00B	THEO	EW analysis
$>$ 76	95	[129] ABBIENDI	99T	OPAL	$R\!\!\!/$, m_0=500 GeV

>120	95	[130] ABE	99I	CDF	$p\overline{p} \to \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}$=$\widetilde{\chi}^0_{1,2}$,$\widetilde{\chi}^{\pm}_1$, $\widetilde{\chi}^0_1 \to \gamma\widetilde{G}$
> 51	95	[131] MALTONI	99B	THEO	EW analysis, $\Delta m_+ \sim 1$ GeV
>150	95	[132] ABBOTT	98	D0	$p\overline{p} \to \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}$=$\widetilde{\chi}^0_{1,2}$,$\widetilde{\chi}^{\pm}_1$, $\widetilde{\chi}^0_1 \to \gamma\widetilde{G}$
		[133] ABBOTT	98C	D0	$p\overline{p} \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_2$
> 81.5	95	[134] ABE	98J	CDF	$p\overline{p} \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_2$
		[135] ACKERSTAFF	98K	OPAL	$\widetilde{\chi}^+ \to \ell^+ \not{E}$
> 65.7	95	[136] ACKERSTAFF	98L	OPAL	$\Delta m_+ > 3$ GeV, Δm_ν >2 GeV
		[137] ACKERSTAFF	98V	OPAL	light gluino
		[138] CARENA	97	THEO	$g_\mu - 2$
		[139] KALINOWSKI	97	THEO	$W \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_1$
		[140] ABE	96K	CDF	$p\overline{p} \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_2$

[111] ABBIENDI 03H used e^+e^- data at $\sqrt{s}$ = 188-209 GeV to search for chargino pair production in the case of small Δm_+ They select events with an energetic photon, large $\not{E}$ and little hadronic or leptonic activity. The bound applies to higgsino-like charginos with zero lifetime and a 100% branching ratio $\widetilde{\chi}^{\pm}_1 \to \widetilde{\chi}^0_1 W^*$. The mass limit for gaugino-like charginos, in case of non-universal gaugino masses, is of 92 GeV for $m_{\widetilde{\nu}}$ = 1000 GeV and is lowered to 74 GeV for $m_{\widetilde{\nu}} \geq 100$ GeV. Limits in the plane $(m_{\widetilde{\chi}^{\pm}_1}, \Delta m_+)$ are shown in Fig. 7. Exclusion regions are also derived for the AMSB scenario in the ($m_{3/2}$, tanβ) plane, see their Fig. 9.

[112] ABDALLAH 03M searches for the production of charginos using data from $\sqrt{s}$= 192 to 208 GeV to investigate topologies with multiple leptons, jets plus leptons, multi-jets, or isolated photons. The first limit holds for tan$\beta \geq$1 and is obtained at Δm_+ =3 GeV in the higgsino region. For $\Delta m_+ \geq$10 (5) GeV and large m_0, the limit improves to 102.7 (101.7) GeV. For the region of small Δm_+, all data from $\sqrt{s}$= 130 to 208 GeV are used to investigate final states with heavy stable charged particles, decay vertices inside the detector and soft topologies with a photon from initial state radiation. The second limit is obtained in the higgsino region, assuming gaugino mass universality at the GUT scale and 1 < tanβ < 50. For the case of non-universality of gaugino masses, the parameter space is scanned in the domain 1 < tanβ < 50 and, for $\Delta m_+ < 3$ GeV, for values of M_1, M_2 and μ such that $M_2 \leq 2M_1 \leq 10M_2$ and $|\mu| \geq M_2$. The third limit is obtained in the gaugino region. See Fig. 36 for the dependence of the low Δm_+ limits on Δm_+. These limits include and update the results of ABREU 00J and ABREU 00T.

[113] ABDALLAH 03M uses data from $\sqrt{s}$ = 192–208 GeV to obtain limits in the framework of the MSSM with gaugino and sfermion mass universality at the GUT scale. An indirect limit on the mass of charginos is derived by constraining the MSSM parameter space by the results from direct searches for neutralinos (including cascade decays), for charginos and for sleptons. These limits are valid for values of M_2 < 1 TeV, $|\mu| \leq$ 2 TeV with the $\widetilde{\chi}^0_1$ as LSP. Constraints from the Higgs search in the M_h^{max} scenario assuming m_t=174.3 GeV are included. The quoted limit applies if there is no mixing in the third family or when $m_{\widetilde{\tau}_1} - m_{\widetilde{\chi}^0_1}$ >6 GeV. If mixing is included the limit degrades to 90 GeV. See Fig. 43 for the mass limits as a function of tanβ. These limits update the results of ABREU 00W.

[114] HEISTER 02J search for chargino production with small Δm_+ in final states with a hard isolated initial state radiation photon and few low-momentum particles, using 189–208 GeV data. This search is sensitive in the intermediate Δm_+ region. Combined with searches for $\not{E}$ topologies and for stable charged particles, the above bound is obtained for m_0 larger than few hundred GeV, 1<tanβ < 300 and holds for any chargino field contents. For light scalars, the general limit reduces to the one from the Z^0, but under the

assumption of gaugino and sfermion mass unification the above bound is recovered. See Figs. 4–6 for the more general dependence of the limits on Δm_+. Updates BARATE 98X.

[115] ABBIENDI 00H data collected at $\sqrt{s}$=189 GeV. The results hold over the full parameter space defined by $0 \leq M_2 \leq 2$ TeV, $|\mu| \leq 500$ GeV, $m_0 \leq 500$ GeV, $A=\pm M_2$, $\pm m_0$, and 0. The results of slepton searches from ABBIENDI 00G were used to help set constraints in the region of small m_0. The limit improves to 78 GeV for tanβ=1.5. See their Table 5 and Fig. 4 for the tanβ and M_2 dependence of the limits. Updates ABBIENDI 99G.

[116] ACCIARRI 00D data collected at $\sqrt{s}$=189 GeV. The results hold over the full parameter space defined by $0.7 \leq \tan\beta \leq 60$, $0 \leq M_2 \leq 2$ TeV, $|\mu| \leq 2$ TeV $m_0 \leq 500$ GeV. The results of slepton searches from ACCIARRI 99W are used to help set constraints in the region of small m_0. See their Figs. 5 for the tanβ and M_2 dependence on the limits. See the text for the impact of a large B($\widetilde{\chi}^\pm \rightarrow \tau \widetilde{\nu}_\tau$) on the result. The region of small Δm_+ is excluded by the analysis of ACCIARRI 00K. Updates ACCIARRI 98F.

[117] ACCIARRI 00K searches for the production of charginos with small Δm_+ using data from $\sqrt{s}$=189 GeV. They investigate soft final states with a photon from initial state radiation. The results are combined with the limits on prompt decays from ACCIARRI 00D and from heavy stable charged particles from ACCIARRI 99L (see Heavy Charged Lepton Searches). The production and decay branching ratios are evaluated within the MSSM, assuming heavy sfermions. The parameter space is scanned in the domain $1<\tan\beta<50$, $0.3 < M_1/M_2 < 50$, and $0< |\mu| <2$ TeV. The limit is obtained in the higgsino region and improves to 78.6 GeV for gaugino-like charginos. The limit is unchanged for light scalar quarks. For light $\widetilde{\tau}$ or $\widetilde{\nu}_\tau$, the limit is unchanged in the gaugino-like region and is lowered by 0.8 GeV in the higgsino-like case. For light $\widetilde{\mu}$ or $\widetilde{\nu}_\mu$, the limit is unchanged in the higgsino-like region and is lowered by 0.9 GeV in the gaugino-like region. No direct mass limits are obtained for light $\widetilde{e}$ or $\widetilde{\nu}_e$.

[118] ABDALLAH 03D use data from $\sqrt{s}$= 183-208 GeV. They look for final states with two acoplanar leptons, expected in GMSB when the $\widetilde{\tau}_1$ is the NLSP and assuming a short-lived $\widetilde{\chi}_1^\pm$. Limits are obtained in the plane (m($\widetilde{\tau}$),m($\widetilde{\chi}_1^\pm$)) for different domains of m($\widetilde{G}$), after combining these results with the search for slepton pair production from the same paper. The limit above is valid if the $\widetilde{\tau}_1$ is the NLSP for all values of m($\widetilde{G}$) provided $m(\widetilde{\chi}_1^\pm) - m(\widetilde{\tau}_1) \geq 0.3$ GeV. For larger m($\widetilde{G}$) $>$ 100 eV the limit improves to 102 GeV, see their Fig. 11. In the co-NLSP scenario, the limits are 96 and 102 GeV for all m($\widetilde{G}$) and m($\widetilde{G}$) $>$ 100 eV, respectively. Supersedes the results of ABREU 01G.

[119] HEISTER 03G searches for the production of charginos prompt decays. in the case of $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–209 GeV. The search is performed for indirect decays, assuming one coupling at a time to be non-zero. The limit holds for $\tan\beta = 1.41$. Excluded regions in the (μ, M_2) plane are shown in their Fig. 3.

[120] ACHARD 02 searches for the production of sparticles in the case of $\not{R}$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The MSUGRA limit results from a scan over the MSSM parameter space with the assumption of gaugino and scalar mass unification at the GUT scale, imposing simultaneously the exclusions from neutralino, chargino, sleptons, and squarks analyses. The limit of $\widetilde{\chi}_1^\pm$ holds for $\overline{UDD}$ couplings and increases to 103.0 GeV for $LL\overline{E}$ couplings. For L3 limits from $LQ\overline{D}$ couplings, see ACCIARRI 01.

[121] GHODBANE 02 reanalyzes DELPHI data at $\sqrt{s}$=189 GeV in the presence of complex phases for the MSSM parameters.

[122] ABREU 01C looked for τ pairs with $\not{E}$ at $\sqrt{s}$=183–189 GeV to search for the associated production of charginos, followed by the decay $\widetilde{\chi}^\pm \rightarrow \tau J$, J being an invisible massless particle. See Fig. 6 for the regions excluded in the (μ, M_2) plane.

[123] ABREU 01D searches for multi-jet events, expected in the case of prompt decays from R-parity violating $\overline{UDD}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with 6 or 10 jets, originating from direct or indirect decays. Limits are obtained in

the M_2 versus μ plane and a limit on the chargino mass is derived from a scan over the parameters m_0 and $\tan\beta$.

[124] ACCIARRI 01 searches for multi-lepton and/or multi-jet final states from $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings at $\sqrt{s}$=189 GeV. The search is performed for direct and indirect decays of neutralinos, charginos, and scalar leptons, with the $\widetilde{\chi}^0_1$ or a $\widetilde{\ell}$ as LSP and assuming one coupling to be nonzero at a time. Mass limits are derived using simultaneously the constraints from the neutralino, chargino, and slepton analyses; and the Z^0 width measurements from ACCIARRI 00C in a scan of the parameter space assuming MSUGRA with gaugino and scalar mass universality. Updates and supersedes the results from ACCIARRI 99I.

[125] BARATE 01B searches for the production of charginos in the case of $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings at $\sqrt{s}$=189–202 GeV. The search is performed for indirect decays, assuming one coupling at a time to be nonzero. Updates BARATE 00H.

[126] ABREU 00U searches for the production of charginos and neutralinos in the case of R-parity violation with $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling to be nonzero at the time and giving rise to direct or indirect decays. LImits are obtained in the M_2 versus μ plane and a limit on the neutralino mass is derived from a scan over the parameters m_0 and $\tan\beta$. Supersedes the results of ABREU 00I.

[127] ABREU 00V use data from $\sqrt{s}$= 183–189 GeV. They look for final states with two acoplanar leptons, expected in GMSB when the $\widetilde{\tau}_1$ is the NLSP and assuming a short-lived $\widetilde{\chi}^\pm_1$. Limits are obtained in the plane ($m_{\widetilde{\tau}}$,$m_{\widetilde{\chi}^\pm_1}$) for different domains of $m_{\widetilde{G}}$, after combining these results with the search for slepton pair production in the SUGRA framework from ABREU 01 to cover prompt decays and on stable particle searches from ABREU 00Q. The limit above is valid for all values of $m_{\widetilde{G}}$.

[128] CHO 00B studied constraints on the MSSM spectrum from precision EW observables. Global fits favour charginos with masses at the lower bounds allowed by direct searches. Allowing for variations of the squark and slepton masses does not improve the fits.

[129] ABBIENDI 99T searches for the production of neutralinos in the case of R-parity violation with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero and giving rise to direct or indirect decays. Mixed decays (where one particle has a direct, the other an indirect decay) are also considered for the $\overline{UDD}$ couplings. Upper limits on the cross section are derived which, combined with the constraint from the Z^0 width, allow to exclude regions in the M_2 versus μ plane for any coupling. Limits on the chargino mass are obtained for non-zero $LL\overline{E}$ couplings $> 10^{-5}$ and assuming decays via a W^*.

[130] ABE 99I looked for chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\widetilde{G}$. The limit assumes the gaugino mass unification, and holds for 1 <$\tan\beta$ < 25, M_2 < 200 GeV, and all μ. ABE 99I is an expanded version of ABE 98L.

[131] MALTONI 99B studied the effect of light chargino-neutralino to the electroweak precision data with a particular focus on the case where they are nearly degenerate ($\Delta m_+ \sim 1$ GeV) which is difficult to exclude from direct collider searches. The quoted limit is for higgsino-like case while the bound improves to 56 GeV for wino-like case. The values of the limits presented here are obtained in an update to MALTONI 99B, as described in MALTONI 00.

[132] ABBOTT 98 studied the chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\widetilde{G}$. The limit assumes the gaugino mass unification.

[133] ABBOTT 98C searches for trilepton final states (ℓ=e,μ). Efficiencies are calculated using mass relations in the Minimal Supergravity scenario, exploring the domain of parameter space defined by $m_{\widetilde{\chi}^\pm_1}$=$m_{\widetilde{\chi}^0_2}$ and $m_{\widetilde{\chi}^\pm_1}$=$2m_{\widetilde{\chi}^0_1}$. Results are presented in Fig. 1 as upper

bounds on $\sigma(p\overline{p} \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0)\times$B($3\ell$). Assuming equal branching ratio for all possible leptonic decays, limits range from 2.6 pb ($m_{\widetilde{\chi}_1^{\pm}}$=45 GeV) to 0.4 pb ($m_{\widetilde{\chi}_1^{\pm}}$=124 GeV) at 95%CL. Assuming a negligible decay rate of $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$ to quarks, this corresponds to $m_{\widetilde{\chi}_1^{\pm}} > 103$ GeV.

[134] ABE 98J searches for trilepton final states (ℓ=e,μ). Efficiencies are calculated using mass relations in the Minimal Supergravity scenario, exploring the domain of parameter space defined by 1.1 <tanβ < 8, $-1000 < \mu$(GeV)< -200, and $m_{\widetilde{q}}/m_{\widetilde{g}}$=1–2. In this region $m_{\widetilde{\chi}_1^{\pm}} \sim m_{\widetilde{\chi}_2^0}$ and $m_{\widetilde{\chi}_1^{\pm}} \sim 2m_{\widetilde{\chi}_1^0}$. Results are presented in Fig. 1 as upper bounds on $\sigma(p\overline{p} \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0)\times$B($3\ell$). Limits range from 0.8 pb ($m_{\widetilde{\chi}_1^{\pm}}$=50 GeV) to 0.23 pb ($m_{\widetilde{\chi}_1^{\pm}}$=100 GeV) at 95%CL. The gaugino mass unification hypothesis and the assumed mass relation between squarks and gluinos define the value of the leptonic branching ratios. The quoted result corresponds to the best limit within the selected range of parameters, obtained for $m_{\widetilde{q}} > m_{\widetilde{g}}$, tan$\beta$=2, and μ=-600 GeV. Mass limits for different values of tanβ and μ are given in Fig. 2.

[135] ACKERSTAFF 98K looked for dilepton+$\not\!\!E_T$ final states at $\sqrt{s}$=130–172 GeV. Limits on $\sigma(e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-)\times$B$^2(\ell)$, with B($\ell$)=B($\chi^+ \to \ell^+\nu_\ell\chi_1^0$) (B($\ell$)=B($\chi^+ \to \ell^+\widetilde{\nu}_\ell$)), are given in Fig. 16 (Fig. 17).

[136] ACKERSTAFF 98L limit is obtained for $0 < M_2 < 1500$, $|\mu| < 500$ and tan$\beta > 1$, but remains valid outside this domain. The dependence on the trilinear-coupling parameter A is studied, and found negligible. The limit holds for the smallest value of m_0 consistent with scalar lepton constraints (ACKERSTAFF 97H) and for all values of m_0 where the condition $\Delta m_{\widetilde{\nu}} > 2.0$ GeV is satisfied. $\Delta m_\nu > 10$ GeV if $\widetilde{\chi}^{\pm} \to \ell\widetilde{\nu}_\ell$. The limit improves to 84.5 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$=130–172 GeV.

[137] ACKERSTAFF 98V excludes the light gluino with universal gaugino mass where charginos, neutralinos decay as $\widetilde{\chi}_1^{\pm}$,$\widetilde{\chi}_2^0 \to q\overline{q}\widetilde{g}$ from total hadronic cross sections at $\sqrt{s}$=130–172 GeV. See paper for the case of nonuniversal gaugino mass.

[138] CARENA 97 studied the constraints on chargino and sneutrino masses from muon $g-2$. The bound can be important for large tanβ.

[139] KALINOWSKI 97 studies the constraints on the chargino-neutralino parameter space from limits on $\Gamma(W \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^0)$ achievable at LEP2. This is relevant when $\widetilde{\chi}_1^{\pm}$ is "invisible," i.e., if $\widetilde{\chi}_1^{\pm}$ dominantly decays into $\widetilde{\nu}_\ell\ell^{\pm}$ with little energy for the lepton. Small otherwise allowed regions could be excluded.

[140] ABE 96K looked for trilepton events from chargino-neutralino production. The bound on $m_{\widetilde{\chi}_1^{\pm}}$ can reach up to 47 GeV for specific choices of parameters. The limits on the combined production cross section times 3-lepton branching ratios range between 1.4 and 0.4 pb, for $45 < m_{\widetilde{\chi}_1^{\pm}}(GeV)<100$. See the paper for more details on the parameter dependence of the results.

Long-lived $\widetilde{\chi}^{\pm}$ (Chargino) MASS LIMITS

Limits on charginos which leave the detector before decaying.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>102	95	[141] ABBIENDI	03L	OPAL	$m_{\widetilde{\nu}}$ >500 GeV
none 2–93.0	95	[142] ABREU	00T	DLPH	$\widetilde{H}^{\pm}$ or $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^{\pm}}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 83	95	[143] BARATE	97K	ALEP	
> 28.2	95	ADACHI	90C	TOPZ	

[141] ABBIENDI 03L used e^+e^- data at $\sqrt{s}$ = 130-209 GeV to select events with two high momentum tracks with anomalous dE/dx. The excluded cross section is compared to the theoretical expectation as a function of the heavy particle mass in their Fig. 3. The bounds are valid for colorless fermions with lifetime longer than 10^{-6} s. Supersedes the results from ACKERSTAFF 98P.

[142] ABREU 00T searches for the production of heavy stable charged particles, identified by their ionization or Cherenkov radiation, using data from $\sqrt{s}$= 130 to 189 GeV. These limits include and update the results of ABREU 98P.

[143] BARATE 97K uses e^+e^- data collected at $\sqrt{s}$ = 130–172 GeV. Limit valid for $\tan\beta = \sqrt{2}$ and $m_{\widetilde{\nu}} > 100$ GeV. The limit improves to 86 GeV for $m_{\widetilde{\nu}} > 250$ GeV.

$\widetilde{\nu}$ (Sneutrino) MASS LIMIT

The limits may depend on the number, $N(\widetilde{\nu})$, of sneutrinos assumed to be degenerate in mass. Only $\widetilde{\nu}_L$ (not $\widetilde{\nu}_R$) is assumed to exist. It is possible that $\widetilde{\nu}$ could be the lightest supersymmetric particle (LSP).

We report here, but do not include in the Listings, the limits obtained from the final, but unpublished, fit of the final results obtained by the LEP Collaborations on the invisible width of the Z boson ($\Delta\Gamma_{\text{inv.}} < 2.0$ MeV, LEP 03): $m_{\widetilde{\nu}} > 43.7$ GeV ($N(\widetilde{\nu})$=1) and $m_{\widetilde{\nu}} > 44.7$ GeV ($N(\widetilde{\nu})$=3) .

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 94	95	[144] ABDALLAH	03M	DLPH	$1 \leq \tan\beta \leq 40$, $m_{\widetilde{e}_R} - m_{\widetilde{\chi}^0_1} > 10$ GeV
> 84	95	[145] HEISTER	02N	ALEP	$\widetilde{\nu}_e$, any Δm
> 37.1	95	[146] ADRIANI	93M	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
> 41	95	[147] DECAMP	92	ALEP	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=3
> 36	95	ABREU	91F	DLPH	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
> 31.2	95	[148] ALEXANDER	91F	OPAL	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[149] ABDALLAH	03F	DLPH	$\widetilde{\nu}_{\mu,\tau}$, $\not{R}$ $LL\overline{E}$ decays
		[150] ACOSTA	03E	CDF	$\widetilde{\nu}$, $\not{R}$, $LQ\overline{D}$ production and $LL\overline{E}$ decays
> 88	95	[151] HEISTER	03G	ALEP	$\widetilde{\nu}_e$, $\not{R}$ decays, μ=−200 GeV, $\tan\beta$=2
> 65	95	[151] HEISTER	03G	ALEP	$\widetilde{\nu}_{\mu,\tau}$, $\not{R}$ decays
		[152] ABAZOV	02H	D0	$\not{R}$, λ'_{211}
> 95	95	[153] ACHARD	02	L3	$\widetilde{\nu}_e$, $\not{R}$ decays, μ=−200 GeV, $\tan\beta=\sqrt{2}$
> 65	95	[153] ACHARD	02	L3	$\widetilde{\nu}_{\nu,\tau}$, $\not{R}$ decays
>149	95	[153] ACHARD	02	L3	$\widetilde{\nu}$, $\not{R}$ decays, MSUGRA
		[154] HEISTER	02F	ALEP	$e\gamma \to \widetilde{\nu}_{\mu,\tau}\ell_k$, $\not{R}$ $LL\overline{E}$
		[155] ABBIENDI	00	OPAL	$\widetilde{\nu}_{e,\mu}$, $\not{R}$, $LL\overline{E}$ or $LQ\overline{D}$ decays
none 100–264	95	[156] ABBIENDI	00R	OPAL	$\widetilde{\nu}_{\mu,\tau}$, $\not{R}$, (s+t)-channel
none 100–200	95	[157] ABBIENDI	00R	OPAL	$\widetilde{\nu}_{\tau}$, $\not{R}$, s-channel
		[158] ABREU	00S	DLPH	$\widetilde{\nu}_{\ell}$, $\not{R}$, (s+t)-channel
> 76.5	95	[159] ABREU	00U	DLPH	$\widetilde{\nu}_{\ell}$, $\not{R}$ ($LL\overline{E}$)
none 50–210	95	[160] ACCIARRI	00P	L3	$\widetilde{\nu}_{\mu,\tau}$, $\not{R}$, s-channel

none 50–210	95	[161] BARATE	00I	ALEP	$\widetilde{\nu}_{\mu,\tau}$, $\not R$, $(s+t)$-channel
none 90–210	95	[162] BARATE	00I	ALEP	$\widetilde{\nu}_{\tau}$, $\not R$, s-channel
none 100–160	95	[163] ABBIENDI	99	OPAL	$\widetilde{\nu}_e$, $\not R$, t-channel
$\neq m_Z$	95	[164] ACCIARRI	97U	L3	$\widetilde{\nu}_{\tau}$, $\not R$, s-channel
none 125–180	95	[164] ACCIARRI	97U	L3	$\widetilde{\nu}_{\tau}$, $\not R$, s-channel
		[165] CARENA	97	THEO	$g_{\mu} - 2$
$>$ 46.0	95	[166] BUSKULIC	95E	ALEP	$N(\widetilde{\nu})$=1, $\widetilde{\nu} \rightarrow \nu\nu\ell\overline{\ell}'$
none 20–25000		[167] BECK	94	COSM	Stable $\widetilde{\nu}$, dark matter
$<$600		[168] FALK	94	COSM	$\widetilde{\nu}$ LSP, cosmic abundance
none 3–90	90	[169] SATO	91	KAMI	Stable $\widetilde{\nu}_e$ or $\widetilde{\nu}_{\mu}$, dark matter
none 4–90	90	[169] SATO	91	KAMI	Stable $\widetilde{\nu}_{\tau}$, dark matter

[144] ABDALLAH 03M uses data from $\sqrt{s}$ = 192–208 GeV to obtain limits in the framework of the MSSM with gaugino and sfermion mass universality at the GUT scale. An indirect limit on the mass is derived by constraining the MSSM parameter space by the results from direct searches for neutralinos (including cascade decays) and for sleptons. These limits are valid for values of $M_2 < 1$ TeV, $|\mu| \leq 1$ TeV with the $\widetilde{\chi}^0_1$ as LSP. The quoted limit is obtained when there is no mixing in the third family. See Fig. 43 for the mass limits as a function of tanβ. These limits update the results of ABREU 00W.

[145] HEISTER 02N derives a bound on $m_{\widetilde{\nu}_e}$ by exploiting the mass relation between the $\widetilde{\nu}_e$ and $\widetilde{e}$, based on the assumption of universal GUT scale gaugino and scalar masses $m_{1/2}$ and m_0 and the search described in the $\widetilde{e}$ section. In the MSUGRA framework with radiative electroweak symmetry breaking, the limit improves to $m_{\widetilde{\nu}_e}$ >130 GeV, assuming a trilinear coupling A_0=0 at the GUT scale. See Figs. 5 and 7 for the dependence of the limits on tanβ.

[146] ADRIANI 93M limit from $\Delta\Gamma(Z)$(invisible)$<$ 16.2 MeV.

[147] DECAMP 92 limit is from Γ(invisible)/$\Gamma(\ell\ell)$ = 5.91 ± 0.15 (N_{ν} = 2.97 ± 0.07).

[148] ALEXANDER 91F limit is for one species of $\widetilde{\nu}$ and is derived from Γ(invisible, new)/$\Gamma(\ell\ell)$ $<$ 0.38.

[149] ABDALLAH 03F looked for events of the type $e^+e^- \rightarrow \widetilde{\nu} \rightarrow \widetilde{\chi}^0\nu$, $\widetilde{\chi}^{\pm}\ell^{\mp}$ followed by $\not R$ decays of the $\widetilde{\chi}^0$ via λ_{1j1} (j = 2,3) couplings in the data at $\sqrt{s}$= 183-208 GeV. From a scan over the SUGRA parameters, they derive upper limits on the λ_{1j1} couplings as a function of the sneutrino mass, see their Figs. 5-8.

[150] ACOSTA 03E search for $e\mu$, $e\tau$ and $\mu\tau$ final states, and sets limits on the product of production cross-section and decay branching ratio for a $\widetilde{\nu}$ in RPV models (see Fig. 3).

[151] HEISTER 03G searches for the production of sneutrinos in the case of $\not R$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–209 GeV. The search is performed for direct and indirect decays, assuming one coupling at a time to be non-zero. The limit holds for indirect $\overline{\nu}$ decays via $\overline{UDD}$ couplings and $\Delta m >$ 10 GeV. Stronger limits are reached for ($\overline{\nu}_e$,$\overline{\nu}_{\mu,\tau}$) for $LL\overline{E}$ direct (100,90) GeV or indirect (98,89) GeV and for $LQ\overline{D}$ direct (–,79) GeV or indirect (91,78) GeV couplings. For $LL\overline{E}$ indirect decays, use is made of the bound $m(\widetilde{\chi}^0_1) >$ 23 GeV from BARATE 98S. Supersedes the results from BARATE 01B.

[152] ABAZOV 02H looked in 94 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with at least 2 muons and 2 jets for s-channel production of $\widetilde{\mu}$ or $\widetilde{\nu}$ and subsequent decay via $\not R$ couplings $LQ\overline{D}$. A scan over the MSUGRA parameters is performed to exclude regions of the (m_0,$m_{1/2}$) plane, examples being shown in Fig. 2.

[153] ACHARD 02 searches for the associated production of sneutrinos in the case of $\not R$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit holds for direct decays via $LL\overline{E}$ couplings. Stronger limits are reached for ($\widetilde{\nu}_e$,$\widetilde{\nu}_{\mu,\tau}$) for $LL\overline{E}$ indirect (99,78) GeV and for $\overline{UDD}$ direct or indirect (99,70) GeV decays. The

MSUGRA limit results from a scan over the MSSM parameter space with the assumption of gaugino and scalar mass unification at the GUT scale, imposing simultaneously the exclusions from neutralino, chargino, sleptons, and squarks analyses. The limit holds for $\overline{UDD}$ couplings and increases to 152.7 GeV for $LL\overline{E}$ couplings.

[154] HEISTER 02F searched for single sneutrino production via $e\gamma \rightarrow \widetilde{\nu}_j \ell_k$ mediated by $\not{R}$ $LL\overline{E}$ couplings, decaying directly or indirectly via a $\widetilde{\chi}_1^0$ and assuming a single coupling to be nonzero at a time. Final states with three leptons and possible $\not{E}_T$ due to neutrinos were selected in the 189–209 GeV data. Limits on the couplings λ_{1jk} as function of the sneutrino mass are shown in Figs. 10–14. The couplings λ_{232} and λ_{233} are not accessible and λ_{121} and λ_{131} are measured with better accuracy in sneutrino resonant production. For all tested couplings, except λ_{133}, the limits are significantly improved compared to the low-energy limits.

[155] ABBIENDI 00 searches for the production of sneutrinos in the case of R-parity violation with $LL\overline{E}$ or $LQ\overline{D}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero and giving rise to direct or indirect decays. For non-zero $LL\overline{E}$ couplings, they obtain limits on the electron sneutrino mass of 88 GeV for direct decays and of 87 GeV for indirect decays with a low mass χ_1^0. For non-zero $LQ\overline{D}$ couplings, the limits are 86 GeV for indirect decays of $\widetilde{\nu}_e$ with a low mass χ_1^0 and 80 GeV for direct decays of $\widetilde{\nu}_e$. There exists a region of small Δm, of varying size, for which no limit is obtained, see Fig. 20. It is assumed that $\tan\beta$=1.5 and μ=$-$200 GeV. For muon sneutrinos, direct decays via $LL\overline{E}$ couplings lead to a 66 GeV mass limit and via $LQ\overline{D}$ couplings to a 58 GeV limit.

[156] ABBIENDI 00R studied the effect of s- and t-channel τ or μ sneutrino exchange in $e^+ e^- \rightarrow e^+ e^-$ at $\sqrt{s}$=130–189 GeV, via the R-parity violating coupling $\lambda_{1i1} L_1 L_i e_1$ (i=2 or 3). The limits quoted here hold for λ_{1i1} >0.13, and supersede the results of ABBIENDI 99. See Fig. 11 for limits on $m_{\widetilde{\nu}}$ versus coupling.

[157] ABBIENDI 00R studied the effect of s-channel τ sneutrino exchange in $e^+ e^- \rightarrow \mu^+ \mu^-$ at $\sqrt{s}$=130–189 GeV, in presence of the R-parity violating couplings $\lambda_{i3i} L_i L_3 e_i$ (i=1 and 2), with λ_{131}=λ_{232}. The limits quoted here hold for $\lambda_{131} > 0.09$, and supersede the results of ABBIENDI 99. See Fig. 12 for limits on $m_{\widetilde{\nu}}$ versus coupling.

[158] ABREU 00S searches for anomalies in the production cross sections and forward-backward asymmetries of the $\ell^+ \ell^- (\gamma)$ final states (ℓ=e,μ,τ) from $e^+ e^-$ collisions at $\sqrt{s}$=130–189 GeV. Limits are set on the s- and t-channel exchange of sneutrinos in the presence of $\not{R}$ with $\lambda LL\overline{E}$ couplings. For points between the energies at which data were taken, information is obtained from events in which a photon was radiated. Exclusion limits in the (λ,$m_{\widetilde{\nu}}$) plane are given in Fig. 5. These limits include and update the results of ABREU 99A.

[159] ABREU 00U searches for the pair production of sneutrinos with a decay involving R-parity violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons, assuming one coupling to be nonzero at the time and giving rise to direct or indirect decays. The limits, valid for each individual flavor, are determined by the indirect decays and assume a neutralino mass limit of 30 GeV, also derived in ABREU 00U. Better limits for specific flavors and for specific $\not{R}$ couplings can be obtained and are discussed in the paper. Supersedes the results of ABREU 00I.

[160] ACCIARRI 00P use the dilepton total cross sections and asymmetries at $\sqrt{s}$=m_Z and $\sqrt{s}$=130–189 GeV data to set limits on the effect of $\not{R}$ $LL\overline{E}$ couplings giving rise to μ or τ sneutrino exchange. See their Fig. 5 for limits on the sneutrino mass versus couplings.

[161] BARATE 00I studied the effect of s-channel and t-channel τ or μ sneutrino exchange in $e^+ e^- \rightarrow e^+ e^-$ at $\sqrt{s}$= 130–183 GeV, via the R-parity violating coupling $\lambda_{1i1} L_1 L_i e_1^c$ (i=2 or 3). The limits quoted here hold for $\lambda_{1i1} > 0.1$. See their Fig. 15 for limits as a function of the coupling.

[162] BARATE 00I studied the effect of s-channel τ sneutrino exchange in $e^+ e^- \rightarrow \mu^+ \mu^-$ at $\sqrt{s}$= 130–183 GeV, in presence of the R-parity violating coupling $\lambda_{i3i} L_i L_3 e_i^c$ (i=1

and 2). The limits quoted here hold for $\sqrt{|\lambda_{131}\lambda_{232}|} > 0.2$. See their Fig. 16 for limits as a function of the coupling.

163 ABBIENDI 99 studied the effect of t-channel electron sneutrino exchange in $e^+e^- \to \tau^+\tau^-$ at $\sqrt{s}$=130–183 GeV, in presence of the R-parity violating couplings $\lambda_{131} L_1 L_3 e^c_1$. The limits quoted here hold for $\lambda_{131} > 0.6$.

164 ACCIARRI 97U studied the effect of the s-channel tau-sneutrino exchange in $e^+e^- \to e^+e^-$ at $\sqrt{s}$=m_Z and $\sqrt{s}$=130–172 GeV, via the R-parity violating coupling $\lambda_{131} L_1 L_i e^c_1$. The limits quoted here hold for $\lambda_{131} > 0.05$. Similar limits were studied in $e^+e^- \to \mu^+\mu^-$ together with $\lambda_{232} L_2 L_3 e^c_2$ coupling.

165 CARENA 97 studied the constraints on chargino and sneutrino masses from muon $g-2$. The bound can be important for large tanβ.

166 BUSKULIC 95E looked for $Z \to \widetilde{\nu}\overline{\widetilde{\nu}}$, where $\widetilde{\nu} \to \nu\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

167 BECK 94 limit can be inferred from limit on Dirac neutrino using $\sigma(\widetilde{\nu}) = 4\sigma(\nu)$. Also private communication with H.V. Klapdor-Kleingrothaus.

168 FALK 94 puts an upper bound on $m_{\widetilde{\nu}}$ when $\widetilde{\nu}$ is LSP by requiring its relic density does not overclose the Universe.

169 SATO 91 search for high-energy neutrinos from the sun produced by annihilation of sneutrinos in the sun. Sneutrinos are assumed to be stable and to constitute dark matter in our galaxy. SATO 91 follow the analysis of NG 87, OLIVE 88, and GAISSER 86.

CHARGED SLEPTONS

This section contains limits on charged scalar leptons ($\widetilde{\ell}$, with ℓ=e,μ,τ). Studies of width and decays of the Z boson (use is made here of $\Delta\Gamma_{\text{inv}} < 2.0$ MeV, LEP 00) conclusively rule out $m_{\widetilde{\ell}_R} < 40$ GeV (41 GeV for $\widetilde{\ell}_L$) , independently of decay modes, for each individual slepton. The limits improve to 43 GeV (43.5 GeV for $\widetilde{\ell}_L$) assuming all 3 flavors to be degenerate. Limits on higher mass sleptons depend on model assumptions and on the mass splitting $\Delta m= m_{\widetilde{\ell}} - m_{\widetilde{\chi}^0_1}$. The mass and composition of $\widetilde{\chi}^0_1$ may affect the selectron production rate in e^+e^- collisions through t-channel exchange diagrams. Production rates are also affected by the potentially large mixing angle of the lightest mass eigenstate $\widetilde{\ell}_1$=$\widetilde{\ell}_R$ sinθ_ℓ + $\widetilde{\ell}_L$ cosθ_ℓ. It is generally assumed that only $\widetilde{\tau}$ may have significant mixing. The coupling to the Z vanishes for θ_ℓ=0.82. In the high-energy limit of e^+e collisions the interference between γ and Z exchange leads to a minimal cross section for θ_ℓ=0.91, a value which is sometimes used in the following entries relative to data taken at LEP2. When limits on $m_{\widetilde{\ell}_R}$ are quoted, it is understood that limits on $m_{\widetilde{\ell}_L}$ are usually at least as strong.

Possibly open decays involving gauginos other than $\widetilde{\chi}^0_1$ will affect the detection efficiencies. Unless otherwise stated, the limits presented here result from the study of $\widetilde{\ell}^+\widetilde{\ell}^-$ production, with production rates and decay properties derived from the MSSM. Limits made obsolete by the recent analyses of e^+e^- collisions at high energies can be found in previous Editions of this Review.

For decays with final state gravitinos ($\widetilde{G}$), $m_{\widetilde{G}}$ is assumed to be negligible relative to all other masses.

$\widetilde{e}$ (Selectron) MASS LIMIT

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 97.5	95	[170] ABBIENDI	04	OPAL	$\widetilde{e}_R$,$\Delta m >$ 11 GeV, $\lvert\mu\rvert >$100 GeV, tanβ=1.5
> 94.4	95	[171] ACHARD	04	L3	$\widetilde{e}_R$,$\Delta m >$ 10 GeV, $\lvert\mu\rvert >$200 GeV, tan$\beta \geq$ 2
> 71.3	95	[171] ACHARD	04	L3	$\widetilde{e}_R$, all Δm
none 30–94	95	[172] ABDALLAH	03M	DLPH	$\Delta m >$15 GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$
> 94	95	[173] ABDALLAH	03M	DLPH	$\widetilde{e}_R$,1 $\leq$ tan$\beta \leq$ 40, $\Delta m >$10 GeV
> 95	95	[174] HEISTER	02E	ALEP	$\Delta m >$ 15 GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$
> 73	95	[175] HEISTER	02N	ALEP	$\widetilde{e}_R$, any Δm
>107	95	[175] HEISTER	02N	ALEP	$\widetilde{e}_L$, any Δm
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 93	95	[176] HEISTER	03G	ALEP	$\widetilde{e}_R$,$\not{R}$ decays,μ=−200 GeV, tanβ=2
> 69	95	[177] ACHARD	02	L3	$\widetilde{e}_R$, $\not{R}$ decays, μ=−200 GeV, tanβ=$\sqrt{2}$
> 92	95	[178] BARATE	01	ALEP	$\Delta m >$ 10 GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$
> 72	95	[179] ABBIENDI	00	OPAL	$\widetilde{e}^+_R \widetilde{e}^-_R$, $\not{R}$, light $\widetilde{\chi}^0_1$
> 77	95	[180] ABBIENDI	00J	OPAL	$\Delta m >$5 GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$
> 83	95	[181] ABREU	00U	DLPH	$\widetilde{e}_R$, $\not{R}$ ($LL\overline{E}$)
> 67	95	[182] ABREU	00V	DLPH	$\widetilde{e}_R \widetilde{e}_R$ ($\widetilde{e}_R \rightarrow e\widetilde{G}$), $m_{\widetilde{G}} >$10 eV
> 85	95	[183] BARATE	00G	ALEP	$\widetilde{\ell}_R \rightarrow \ell\widetilde{G}$, any $\tau(\widetilde{\ell}_R)$
> 29.5	95	[184] ACCIARRI	99I	L3	$\widetilde{e}_R$, $\not{R}$, tan$\beta \geq$ 2
> 56	95	[185] ACCIARRI	98F	L3	$\Delta m >$ 5 GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$, tan$\beta \geq$ 1.41
> 77	95	[186] BARATE	98K	ALEP	Any Δm, $\widetilde{e}^+_R \widetilde{e}^-_R$, $\widetilde{e}_R \rightarrow e\gamma\widetilde{G}$
> 77	95	[187] BREITWEG	98	ZEUS	$m_{\widetilde{q}}$=$m_{\widetilde{e}}$, $m(\widetilde{\chi}^0_1)$= 40 GeV
> 63	95	[188] AID	96C	H1	$m_{\widetilde{q}}$=$m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$=35 GeV

[170] ABBIENDI 04 search for $\widetilde{e}_R \widetilde{e}_R$ production in acoplanar di-electron final states in the 183–208 GeV data. See Fig. 13 for the dependence of the limits on $m_{\widetilde{\chi}^0_1}$ and for the limit at tanβ=35 This limit supersedes ABBIENDI 00G.

[171] ACHARD 04 search for $\widetilde{e}_R \widetilde{e}_L$ and $\widetilde{e}_R \widetilde{e}_R$ production in single- and acoplanar di-electron final states in the 192–209 GeV data. Absolute limits on $m_{\widetilde{e}_R}$ are derived from a scan over the MSSM parameter space with universal GUT scale gaugino and scalar masses $m_{1/2}$ and m_0, $1 \leq$ tan$\beta \leq 60$ and $-2 \leq \mu \leq 2$ TeV. See Fig. 4 for the dependence of the limits on $m_{\widetilde{\chi}^0_1}$. This limit supersedes ACCIARRI 99W.

[172] ABDALLAH 03M looked for acoplanar dielectron $+\not{E}$ final states at $\sqrt{s}$ = 189–208 GeV. The limit assumes μ=−200 GeV and tanβ=1.5 in the calculation of the production cross section and B($\widetilde{e} \rightarrow e\widetilde{\chi}^0_1$). See Fig. 15 for limits in the ($m_{\widetilde{e}_R}$, $m_{\widetilde{\chi}^0_1}$) plane. These limits include and update the results of ABREU 01

[173] ABDALLAH 03M uses data from $\sqrt{s}$ = 192–208 GeV to obtain limits in the framework of the MSSM with gaugino and sfermion mass universality at the GUT scale. An indirect limit on the mass is derived by constraining the MSSM parameter space by the results from direct searches for neutralinos (including cascade decays) and for sleptons. These limits are valid for values of $M_2 <$ 1 TeV, $\lvert\mu\rvert \leq$ 1 TeV with the $\widetilde{\chi}^0_1$ as LSP. The quoted

limit is obtained when there is no mixing in the third family. See Fig. 43 for the mass limits as a function of tanβ. These limits update the results of ABREU 00W.

[174] HEISTER 02E looked for acoplanar dielectron + $\not\!\!E_T$ final states from $e^+ e^-$ interactions between 183 and 209 GeV. The mass limit assumes $\mu < -200$ GeV and tanβ=2 for the production cross section and B($\tilde{e} \to e\tilde{\chi}_1^0$)=1. See their Fig. 4 for the dependence of the limit on Δm. These limits include and update the results of BARATE 01.

[175] HEISTER 02N search for $\tilde{e}_R \tilde{e}_L$ and $\tilde{e}_R \tilde{e}_R$ production in single- and acoplanar di-electron final states in the 183–208 GeV data. Absolute limits on $m_{\tilde{e}_R}$ are derived from a scan over the MSSM parameter space with universal GUT scale gaugino and scalar masses $m_{1/2}$ and m_0, $1 \leq$ tan$\beta \leq 50$ and $-10 \leq \mu \leq 10$ TeV. The region of small $|\mu|$, where cascade decays are important, is covered by a search for $\tilde{\chi}_1^0 \tilde{\chi}_3^0$ in final states with leptons and possibly photons. Limits on $m_{\tilde{e}_L}$ are derived by exploiting the mass relation between the $\tilde{e}_L$ and $\tilde{e}_R$, based on universal m_0 and $m_{1/2}$. When the constraint from the mass limit of the lightest Higgs from HEISTER 02 is included, the bounds improve to $m_{\tilde{e}_R}$ >77(75) GeV and $m_{\tilde{e}_L}$ >115(115) GeV for a top mass of 175(180) GeV. In the MSUGRA framework with radiative electroweak symmetry breaking, the limits improve further to $m_{\tilde{e}_R}$ >95 GeV and $m_{\tilde{e}_L}$ >152 GeV, assuming a trilinear coupling A_0=0 at the GUT scale. See Figs. 4, 5, 7 for the dependence of the limits on tanβ.

[176] HEISTER 03G searches for the production of selectrons in the case of $\not\!\!R$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s}$ = 189–209 GeV. The search is performed for direct and indirect decays, assuming one coupling at a time to be non-zero. The limit holds for indirect decays mediated by $LQ\overline{D}$ couplings with $\Delta m > 10$ GeV. Limits are also given for $LL\overline{E}$ direct ($m_{\tilde{e},R} > 96$ GeV) and indirect decays ($m_{\tilde{e},R} > 96$ GeV for $m(\tilde{\chi}_1^0) > 23$ GeV from BARATE 98S) and for $\overline{UDD}$ indirect decays ($m_{\tilde{e},R} > 94$ GeV with $\Delta m > 10$ GeV). Supersedes the results from BARATE 01B.

[177] ACHARD 02 searches for the production of selectrons in the case of $\not\!\!R$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit holds for direct decays via $LL\overline{E}$ couplings. Stronger limits are reached for $LL\overline{E}$ indirect (79 GeV) and for $\overline{UDD}$ direct or indirect (96 GeV) decays.

[178] BARATE 01 looked for acoplanar dielectron + $\not\!\!E_T$ final states at 189 to 202 GeV. The limit assumes μ=−200 GeV and tanβ=2 for the production cross section and 100% branching ratio for $\tilde{e} \to e\tilde{\chi}_1^0$. See their Fig. 1 for the dependence of the limit on Δm. These limits include and update the results of BARATE 99Q.

[179] ABBIENDI 00 searches for the production of selectrons in the case of R-parity violation with $LL\overline{E}$ or $LQ\overline{D}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero and giving rise to direct or indirect decays. For non-zero $LL\overline{E}$ couplings, they obtain limits on the selectron mass of 84 GeV both for direct decays and for indirect decays with a low mass $\tilde{\chi}_1^0$. For non-zero $LQ\overline{D}$ couplings, the limits are 72 GeV for indirect decays of $\tilde{e}_R$ with a low mass $\tilde{\chi}_1^0$ and 76 GeV for direct decays of $\tilde{e}_L$. It is assumed that tanβ=1.5 and μ=−200 GeV.

[180] ABBIENDI 00J looked for acoplanar dielectron + $\not\!\!E_T$ final states at $\sqrt{s}$= 161–183 GeV. The limit assumes $\mu < -100$ GeV and tanβ=1.5 for the production cross section and decay branching ratios, evaluated within the MSSM, and zero efficiency for decays other than $\tilde{e} \to e\tilde{\chi}_1^0$. See their Fig. 12 for the dependence of the limit on Δm and tanβ.

[181] ABREU 00U studies decays induced by R-parity violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons, assuming one coupling at the time to be nonzero and giving rise to indirect decays. The limits assume a neutralino mass limit of 30 GeV, also derived in ABREU 00U. Updates ABREU 00I.

[182] ABREU 00V use data from $\sqrt{s}$= 130–189 GeV to search for tracks with large impact parameter or visible decay vertices. Limits are obtained as a function of $m_{\tilde{G}}$, from a scan

of the GMSB parameters space, after combining these results with the search for slepton pair production in the SUGRA framework from ABREU 01 to cover prompt decays and on stable particle searches from ABREU 00Q. For limits at different $m_{\widetilde{G}}$, see their Fig. 12.

[183] BARATE 00G combines the search for acoplanar dileptons, leptons with large impact parameters, kinks, and stable heavy-charged tracks, assuming 3 flavors of degenerate sleptons, produced in the s channel. Data collected at $\sqrt{s}$=189 GeV.

[184] ACCIARRI 99I establish indirect limits on $m_{\widetilde{e}_R}$ from the regions excluded in the M_2 versus m_0 plane by their chargino and neutralino searches at $\sqrt{s}$=130–183 GeV. The situations where the $\widetilde{\chi}^0_1$ is the LSP (indirect decays) and where a $\widetilde{\ell}$ is the LSP (direct decays) were both considered. The weakest limit, quoted above, comes from direct decays with $\overline{UDD}$ couplings; $LL\overline{E}$ couplings or indirect decays lead to a stronger limit.

[185] ACCIARRI 98F looked for acoplanar dielectron+$\not\!\!E_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes μ=−200 GeV, and zero efficiency for decays other than $\widetilde{e}_R \rightarrow e\widetilde{\chi}^0_1$. See their Fig. 6 for the dependence of the limit on Δm.

[186] BARATE 98K looked for $e^+e^-\gamma\gamma + \not\!\!E$ final states at $\sqrt{s}$= 161–184 GeV. The limit assumes μ=−200 GeV and tanβ=2 for the evaluation of the production cross section. See Fig. 4 for limits on the ($m_{\widetilde{e}_R}$,$m_{\widetilde{\chi}^0_1}$) plane and for the effect of cascade decays.

[187] BREITWEG 98 used positron+jet events with missing energy and momentum to look for $e^+ q \rightarrow \widetilde{e}\widetilde{q}$ via gaugino-like neutralino exchange with decays into $(e\widetilde{\chi}^0_1)(q\widetilde{\chi}^0_1)$. See paper for dependences in $m(\widetilde{q})$, $m(\widetilde{\chi}^0_1)$.

[188] AID 96C used positron+jet events with missing energy and momentum to look for $e^+ q \rightarrow \widetilde{e}\widetilde{q}$ via neutralino exchange with decays into $(e\widetilde{\chi}^0_1)(q\widetilde{\chi}^0_1)$. See the paper for dependences on $m_{\widetilde{q}}$, $m_{\widetilde{\chi}^0_1}$.

$\widetilde{\mu}$ (Smuon) MASS LIMIT

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>91.0	95	[189] ABBIENDI	04	OPAL	Δm > 3 GeV, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$, $\vert\mu\vert$ > 100 GeV, tanβ=1.5
>86.7	95	[190] ACHARD	04	L3	Δm > 10 GeV, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$ $\vert\mu\vert$ >200 GeV, tan$\beta \geq 2$
none 30–88	95	[191] ABDALLAH	03M	DLPH	Δm >5 GeV, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$
>94	95	[192] ABDALLAH	03M	DLPH	$\widetilde{\mu}_R$,1 ≤ tanβ ≤ 40, Δm >10 GeV
>88	95	[193] HEISTER	02E	ALEP	Δm > 15 GeV, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>81	95	[194] HEISTER	03G	ALEP	$\widetilde{\mu}_L$,$\not\!\!R$ decays
		[195] ABAZOV	02H	D0	$\not\!\!R$, λ'_{211}
>61	95	[196] ACHARD	02	L3	$\widetilde{\mu}_R$, $\not\!\!R$ decays
>85	95	[197] BARATE	01	ALEP	Δm > 10 GeV, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$
>50	95	[198] ABBIENDI	00	OPAL	$\widetilde{\mu}^+_R\widetilde{\mu}^-_R$, $\not\!\!R$, Δm > 5 GeV
>65	95	[199] ABBIENDI	00J	OPAL	Δm >2 GeV, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$
>83	95	[200] ABREU	00U	DLPH	$\widetilde{\mu}_R$, $\not\!\!R$ ($LL\overline{E}$)
>80	95	[201] ABREU	00V	DLPH	$\widetilde{\mu}_R\widetilde{\mu}_R$ ($\widetilde{\mu}_R \rightarrow \mu\widetilde{G}$), $m_{\widetilde{G}}$ >8 eV
>77	95	[202] BARATE	98K	ALEP	Any Δm, $\widetilde{\mu}^+_R\widetilde{\mu}^-_R$, $\widetilde{\mu}_R \rightarrow \mu\gamma\widetilde{G}$

[189] ABBIENDI 04 search for $\widetilde{\mu}_R \widetilde{\mu}_R$ production in acoplanar di-muon final states in the 183–208 GeV data. See Fig. 14 for the dependence of the limits on $m_{\widetilde{\chi}_1^0}$ and for the limit at tanβ=35. Under the assumption of 100% branching ratio for $\widetilde{\mu}_R \rightarrow \mu \widetilde{\chi}_1^0$, the limit improves to 94.0 GeV for $\Delta m >$ 4 GeV. See Fig. 11 for the dependence of the limits on m$_{\widetilde{\chi}_1^0}$ at several values of the branching ratio. This limit supersedes ABBIENDI 00G.

[190] ACHARD 04 search for $\widetilde{\mu}_R \widetilde{\mu}_R$ production in acoplanar di-muon final states in the 192–209 GeV data. Limits on $m_{\widetilde{\mu}_R}$ are derived from a scan over the MSSM parameter space with universal GUT scale gaugino and scalar masses $m_{1/2}$ and m_0, $1 \leq$ tanβ ≤ 60 and $-2 \leq \mu \leq 2$ TeV. See Fig. 4 for the dependence of the limits on $m_{\widetilde{\chi}_1^0}$. This limit supersedes ACCIARRI 99W.

[191] ABDALLAH 03M looked for acoplanar dimuon $+\not\!\!E$ final states at $\sqrt{s}$ = 189–208 GeV. The limit assumes B($\widetilde{\mu} \rightarrow \mu \widetilde{\chi}_1^0$) = 100%. See Fig. 16 for limits on the ($m_{\widetilde{\mu}_R}$, $m_{\widetilde{\chi}_1^0}$) plane. These limits include and update the results of ABREU 01.

[192] ABDALLAH 03M uses data from $\sqrt{s}$ = 192–208 GeV to obtain limits in the framework of the MSSM with gaugino and sfermion mass universality at the GUT scale. An indirect limit on the mass is derived by constraining the MSSM parameter space by the results from direct searches for neutralinos (including cascade decays) and for sleptons. These limits are valid for values of $M_2 <$ 1 TeV, $|\mu| \leq$ 1 TeV with the $\widetilde{\chi}_1^0$ as LSP. The quoted limit is obtained when there is no mixing in the third family. See Fig. 43 for the mass limits as a function of tanβ. These limits update the results of ABREU 00W.

[193] HEISTER 02E looked for acoplanar dimuon + $\not\!\!E_T$ final states from $e^+ e^-$ interactions between 183 and 209 GeV. The mass limit assumes B($\widetilde{\mu} \rightarrow \mu \widetilde{\chi}_1^0$)=1. See their Fig. 4 for the dependence of the limit on Δm. These limits include and update the results of BARATE 01.

[194] HEISTER 03G searches for the production of smuons in the case of $\not\!R$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s}$ = 189–209 GeV. The search is performed for direct and indirect decays, assuming one coupling at a time to be non-zero. The limit holds for direct decays mediated by $\not\!R$ $LQ\overline{D}$ couplings and improves to 90 GeV for indirect decays (for $\Delta m >$ 10 GeV). Limits are also given for $LL\overline{E}$ direct ($m_{\widetilde{\mu}R} >$ 87 GeV) and indirect decays ($m_{\widetilde{\mu}R} >$ 96 GeV for $m(\widetilde{\chi}_1^0) >$ 23 GeV from BARATE 98S) and for $\overline{UDD}$ indirect decays ($m_{\widetilde{\mu}R} >$ 85 GeV for $\Delta m >$ 10 GeV). Supersedes the results from BARATE 01B.

[195] ABAZOV 02H looked in 94 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with at least 2 muons and 2 jets for s-channel production of $\widetilde{\mu}$ or $\widetilde{\nu}$ and subsequent decay via $\not\!R$ couplings $LQ\overline{D}$. A scan over the MSUGRA parameters is performed to exclude regions of the (m_0,$m_{1/2}$) plane, examples being shown in Fig. 2.

[196] ACHARD 02 searches for the production of smuons in the case of $\not\!R$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit holds for direct decays via $LL\overline{E}$ couplings. Stronger limits are reached for $LL\overline{E}$ indirect (87 GeV) and for $\overline{UDD}$ direct or indirect (86 GeV) decays.

[197] BARATE 01 looked for acoplanar dimuon + $\not\!\!E_T$ final states at 189 to 202 GeV. The limit assumes 100% branching ratio for $\widetilde{\mu} \rightarrow \mu \widetilde{\chi}_1^0$. See their Fig. 1 for the dependence of the limit on Δm. These limits include and update the results of BARATE 99Q.

[198] ABBIENDI 00 searches for the production of smuons in the case of R-parity violation with $LL\overline{E}$ or $LQ\overline{D}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero and giving rise to direct or indirect decays. For non-zero $LL\overline{E}$ couplings, they obtain limits on the smuon mass of 66 GeV for direct decays and of 74 GeV for indirect decays with a low mass $\widetilde{\chi}_1^0$. For non-zero $LQ\overline{D}$ couplings, the limits are 50 GeV

for indirect decays of $\widetilde{\mu}_R$ with a low mass $\widetilde{\chi}^0_1$ and 64 GeV for direct decays of $\widetilde{\mu}_L$. It is assumed that tanβ=1.5 and μ=−200 GeV.

[199] ABBIENDI 00J looked for acoplanar dimuon + $\not\!\!E_T$ final states at $\sqrt{s}$= 161–183 GeV. The limit assumes B($\widetilde{\mu} \rightarrow \mu\widetilde{\chi}^0_1$)=1. Using decay branching ratios derived from the MSSM, a lower limit of 65 GeV is obtained for $\mu < -100$ GeV and tanβ=1.5. See their Figs. 10 and 13 for the dependence of the limit on the branching ratio and on Δm.

[200] ABREU 00U studies decays induced by R-parity violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons, assuming one coupling at the time to be nonzero and giving rise to indirect decays. The limits, valid for each individual flavor, assume a neutralino mass limit of 30 GeV, also derived in ABREU 00U. Updates ABREU 00I.

[201] ABREU 00V use data from $\sqrt{s}$= 130–189 GeV to search for tracks with large impact parameter or visible decay vertices. Limits are obtained as function of $m_{\widetilde{G}}$, after combining these results with the search for slepton pair production in the SUGRA framework from ABREU 01 to cover prompt decays and on stable particle searches from ABREU 00Q. For limits at different $m_{\widetilde{G}}$, see their Fig. 12.

[202] BARATE 98K looked for $\mu^+\mu^-\gamma\gamma + \not\!\!E$ final states at $\sqrt{s}$= 161–184 GeV. See Fig. 4 for limits on the ($m_{\widetilde{\mu}_R}$,$m_{\widetilde{\chi}^0_1}$) plane and for the effect of cascade decays.

$\widetilde{\tau}$ (Stau) MASS LIMIT

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>85.2	95	[203] ABBIENDI	04	OPAL	Δm > 6 GeV, θ_τ=π/2, $\lvert\mu\rvert$ > 100 GeV, tanβ=1.5
>78.3	95	[204] ACHARD	04	L3	Δm > 15 GeV, θ_τ=π/2, $\lvert\mu\rvert$ >200 GeV, tan$\beta \geq 2$
>81.9	95	[205] ABDALLAH	03M	DLPH	Δm >15 GeV, all θ_τ
none m_τ− 26.3	95	[205] ABDALLAH	03M	DLPH	Δm >m_τ, all θ_τ
>79	95	[206] HEISTER	02E	ALEP	Δm > 15 GeV, θ_τ=π/2
>76	95	[206] HEISTER	02E	ALEP	Δm > 15 GeV, θ_τ=0.91
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>82.5	95	[207] ABDALLAH	03D	DLPH	$\widetilde{\tau}_R \rightarrow \tau\widetilde{G}$, all $\tau(\widetilde{\tau}_R)$
>70	95	[208] HEISTER	03G	ALEP	$\widetilde{\tau}_R$,$\not\!R$ decay
>61	95	[209] ACHARD	02	L3	$\widetilde{\tau}_R$, $\not\!R$ decays
>77	95	[210] HEISTER	02R	ALEP	τ_1, any lifetime
>70	95	[211] BARATE	01	ALEP	Δm > 10 GeV, θ_τ=π/2
>68	95	[211] BARATE	01	ALEP	Δm > 10 GeV, θ_τ=0.91
>66	95	[212] ABBIENDI	00	OPAL	$\widetilde{\tau}^+_R\widetilde{\tau}^-_R$, $\not\!R$, light $\widetilde{\chi}^0_1$
>64	95	[213] ABBIENDI	00J	OPAL	Δm >10 GeV, $\widetilde{\tau}^+_R\widetilde{\tau}^-_R$
>83	95	[214] ABREU	00U	DLPH	$\widetilde{\tau}_R$, $\not\!R$ ($LL\overline{E}$)
>84	95	[215] ABREU	00V	DLPH	$\widetilde{\ell}_R\widetilde{\ell}_R$ ($\widetilde{\ell}_R \rightarrow \ell\widetilde{G}$), $m_{\widetilde{G}}$ >9 eV
>73	95	[216] ABREU	00V	DLPH	$\widetilde{\tau}_1\widetilde{\tau}_1$ ($\widetilde{\tau}_1 \rightarrow \tau\widetilde{G}$), all $\tau(\widetilde{\tau}_1)$
>52	95	[217] BARATE	98K	ALEP	Any Δm, θ_τ=π/2, $\widetilde{\tau}_R \rightarrow \tau\gamma\widetilde{G}$

[203] ABBIENDI 04 search for $\widetilde{\tau}\widetilde{\tau}$ production in acoplanar di-tau final states in the 183–208 GeV data. See Fig. 15 for the dependence of the limits on $m_{\widetilde{\chi}^0_1}$ and for the limit at tanβ=35. Under the assumption of 100% branching ratio for $\widetilde{\tau}_R \rightarrow \tau\,\widetilde{\chi}^0_1$, the limit improves to 89.8 GeV for $\Delta m > 8$ GeV. See Fig. 12 for the dependence of the limits on m$_{\widetilde{\chi}^0_1}$ at several values of the branching ratio and for their dependence on θ_τ. This limit supersedes ABBIENDI 00G.

[204] ACHARD 04 search for $\widetilde{\tau}\widetilde{\tau}$ production in acoplanar di-tau final states in the 192–209 GeV data. Limits on $m_{\widetilde{\tau}_R}$ are derived from a scan over the MSSM parameter space with universal GUT scale gaugino and scalar masses $m_{1/2}$ and m_0, $1 \leq \tan\beta \leq 60$ and $-2 \leq \mu \leq 2$ TeV. See Fig. 4 for the dependence of the limits on $m_{\widetilde{\chi}^0_1}$.

[205] ABDALLAH 03M looked for acoplanar ditaus $+\not{E}$ final states at $\sqrt{s}$ = 130–208 GeV. A dedicated search was made for low mass $\widetilde{\tau}$s decoupling from the Z^0. The limit assumes B($\widetilde{\tau} \rightarrow \tau\widetilde{\chi}^0_1$) = 100%. See Fig. 20 for limits on the ($m_{\widetilde{\tau}}$,$m_{\widetilde{\chi}^0_1}$) plane and as function of the $\widetilde{\chi}^0_1$ mass and of the branching ratio. The limit in the low-mass region improves to 29.6 and 31.1 GeV for $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$, respectively, at $\Delta m > m_\tau$. The limit in the high-mass region improves to 84.7 GeV for $\widetilde{\tau}_R$ and $\Delta m >$ 15 GeV. These limits include and update the results of ABREU 01.

[206] HEISTER 02E looked for acoplanar ditau + $\not{E}_T$ final states from e^+e^- interactions between 183 and 209 GeV. The mass limit assumes B($\widetilde{\tau} \rightarrow \tau\widetilde{\chi}^0_1$)=1. See their Fig. 4 for the dependence of the limit on Δm. These limits include and update the results of BARATE 01.

[207] ABDALLAH 03D use data from $\sqrt{s}$= 130-208 GeV to search for tracks with large impact parameter or visible decay vertices and for heavy charged stable particles. Limits are obtained as function of m($\widetilde{G}$), after combining these results with the search for slepton pair production in the SUGRA framework from ABDALLAH 03M to cover prompt decays. The above limit is reached for the stau decaying promptly, m($\widetilde{G}$) < 6 eV, and is computed for stau mixing yielding the minimal cross section. Stronger limits are obtained for longer lifetimes, See their Fig. 9. Supersedes the results of ABREU 01G.

[208] HEISTER 03G searches for the production of stau in the case of $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s}$ = 189–209 GeV. The search is performed for direct and indirect decays, assuming one coupling at a time to be non-zero. The limit holds for indirect decays mediated by $\not{R}$ $\overline{UDD}$ couplings with $\Delta m >$ 10 GeV. Limits are also given for $LL\overline{E}$ direct ($m_{\widetilde{\tau}_R}$ > 87 GeV) and indirect decays ($m_{\widetilde{\tau}_R}$ > 95 GeV for $m(\widetilde{\chi}^0_1) >$ 23 GeV from BARATE 98S) and for $LQ\overline{D}$ indirect decays ($m_{\widetilde{\tau}_R}$ > 76 GeV). Supersedes the results from BARATE 01B.

[209] ACHARD 02 searches for the production of staus in the case of $\not{R}$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit holds for direct decays via $LL\overline{E}$ couplings. Stronger limits are reached for $LL\overline{E}$ indirect (86 GeV) and for $\overline{UDD}$ direct or indirect (75 GeV) decays.

[210] HEISTER 02R search for signals of GMSB in the 189–209 GeV data. For the $\widetilde{\chi}^0_1$ NLSP scenario, they looked for topologies consisting of $\gamma\gamma\not{E}$ or a single γ not pointing to the interaction vertex. For the $\widetilde{\ell}$ NLSP case, the topologies consist of $\ell\ell\not{E}$, including leptons with large impact parameters, kinks, or stable particles. Limits are derived from a scan over the GMSB parameters (see their Table 5 for the ranges). The limit remains valid whichever is the NLSP. The absolute mass bound on the $\widetilde{\chi}^0_1$ for any lifetime includes indirect limits from the slepton search HEISTER 02E preformed within the MSUGRA framework. A bound for any NLSP and any lifetime of 77 GeV has also been derived by using the constraints from the neutral Higgs search in HEISTER 02. In the co-NLSP scenario, limits $m_{\widetilde{e}_R} >$ 83 GeV (neglecting t-channel exchange) and $m_{\widetilde{\mu}_R} >$ 88 GeV are obtained independent of the lifetime. Supersedes the results from BARATE 00G.

[211] BARATE 01 looked for acoplanar ditau + $\not{E}_T$ final states at 189 to 202 GeV. A slight excess (with 1.2% probability) of events is observed relative to the expected SM background. The limit assumes 100% branching ratio for $\widetilde{\tau} \rightarrow \tau\widetilde{\chi}^0_1$. See their Fig. 1 for the dependence of the limit on Δm. These limits include and update the results of BARATE 99Q.

[212] ABBIENDI 00 searches for the production of staus in the case of R-parity violation with $LL\overline{E}$ or $LQ\overline{D}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with

multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero and giving rise to direct or indirect decays. For non-zero $LL\overline{E}$ couplings, they obtain limits on the stau mass of 66 GeV both for direct decays and for indirect decays with a low mass χ^0_1. For non-zero $LQ\overline{D}$ couplings, the limits are 66 GeV for indirect decays of $\widetilde{\tau}_R$ with a low mass χ^0_1 and 63 GeV for direct decays of $\widetilde{\tau}_L$. It is assumed that tanβ=1.5 and μ=−200 GeV.

213 ABBIENDI 00J looked for acoplanar ditau + $\not{E}_T$ final states at $\sqrt{s}$= 161–183 GeV. The limit assumes B($\widetilde{\tau} \rightarrow \tau\widetilde{\chi}^0_1$)=1. Using decay branching ratios derived from the MSSM, a lower limit of 60 GeV at Δm >9 GeV is obtained for $\mu < -100$ GeV and tanβ=1.5. See their Figs. 11 and 14 for the dependence of the limit on the branching ratio and on Δm.

214 ABREU 00U studies decays induced by R-parity violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons, assuming one coupling at the time to be nonzero and giving rise to indirect decays. The limits, valid for each individual flavor, assume a neutralino mass limit of 30 GeV, also derived in ABREU 00U. Updates ABREU 00I.

215 ABREU 00V use data from $\sqrt{s}$= 130–189 GeV to search for tracks with large impact parameter or visible decay vertices. Limits are obtained as function of $m_{\widetilde{G}}$, after combining these results with the search for slepton pair production in the SUGRA framework from ABREU 01 to cover prompt decays and on stable particle searches from ABREU 00Q. The above limit assumes the degeneracy of stau and smuon. For limits at different $m_{\widetilde{G}}$, see their Fig. 12.

216 ABREU 00V use data from $\sqrt{s}$= 130–189 GeV to search for tracks with large impact parameter or visible decay vertices. Limits are obtained as function of $m_{\widetilde{G}}$, after combining these results with the search for slepton pair production in the SUGRA framework from ABREU 01 to cover prompt decays and on stable particle searches from ABREU 00Q. The above limit is reached for the stau mixing yielding the minimal cross section and decaying promptly. Stronger limits are obtained for longer lifetimes or for $\widetilde{\tau}_R$; see their Fig. 11. For $10 \leq m_{\widetilde{G}} \leq 310$ eV, the whole range $2 \leq m_{\widetilde{\tau}_1} \leq 80$ GeV is excluded. Supersedes the results of ABREU 99C and ABREU 99F.

217 BARATE 98K looked for $\tau^+\tau^-\gamma\gamma + \not{E}$ final states at $\sqrt{s}$= 161–184 GeV. See Fig. 4 for limits on the ($m_{\widetilde{\tau}_R}$,$m_{\widetilde{\chi}^0_1}$) plane and for the effect of cascade decays.

Degenerate Charged Sleptons

Unless stated otherwise in the comment lines or in the footnotes, the following limits assume 3 families of degenerate charged sleptons.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>93	95	[218] BARATE	01	ALEP	$\Delta m > 10$ GeV, $\widetilde{\ell}^+_R\widetilde{\ell}^-_R$
>70	95	[218] BARATE	01	ALEP	all Δm, $\widetilde{\ell}^+_R\widetilde{\ell}^-_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>88	95	[219] ABDALLAH	03D	DLPH	$\widetilde{\ell}_R \rightarrow \ell\widetilde{G}$, all $\tau(\widetilde{\ell}_R)$
>82.7	95	[220] ACHARD	02	L3	$\widetilde{\ell}_R$, $\not{R}$ decays, MSUGRA
>83	95	[221] ABBIENDI	01	OPAL	$e^+e^- \rightarrow \widetilde{\ell}_1\widetilde{\ell}_1$, GMSB, tan$\beta$=2
		[222] ABREU	01	DLPH	$\widetilde{\ell} \rightarrow \ell\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_2 \rightarrow \gamma\widetilde{\chi}^0_1$, ℓ=e,μ
>68.8	95	[223] ACCIARRI	01	L3	$\widetilde{\ell}_R$, $\not{R}$, 0.7 ≤ tanβ ≤ 40
>84	95	[224,225] ABREU	00V	DLPH	$\widetilde{\ell}_R\widetilde{\ell}_R$ ($\widetilde{\ell}_R \rightarrow \ell\widetilde{G}$), $m_{\widetilde{G}}$ >9 eV

[218] BARATE 01 looked for acoplanar dilepton + $\not\!\!E_T$ and single electron (for $\widetilde{e}_R \widetilde{e}_L$) final states at 189 to 202 GeV. The limit assumes $\mu=-200$ GeV and $\tan\beta=2$ for the production cross section and decay branching ratios, evaluated within the MSSM, and zero efficiency for decays other than $\widetilde{\ell} \rightarrow \ell \widetilde{\chi}^0_1$. The slepton masses are determined from the GUT relations without stau mixing. See their Fig. 1 for the dependence of the limit on Δm.

[219] ABDALLAH 03D use data from $\sqrt{s}=$ 130-208 GeV to search for tracks with large impact parameter or visible decay vertices and for heavy charged stable particles. Limits are obtained as function of m($\widetilde{G}$), after combining these results with the search for slepton pair production in the SUGRA framework from ABDALLAH 03M to cover prompt decays The above limit is reached for prompt decays and assumes the degeneracy of the sleptons. For limits at different m($\widetilde{G}$), see their Fig. 9. Supersedes the results of ABREU 01G.

[220] ACHARD 02 searches for the production of sparticles in the case of $\not\!R$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The MSUGRA limit results from a scan over the MSSM parameter space with the assumption of gaugino and scalar mass unification at the GUT scale and no mixing in the slepton sector, imposing simultaneously the exclusions from neutralino, chargino, sleptons, and squarks analyses. The limit holds for $LL\overline{E}$ couplings and increases to 88.7 GeV for $\overline{UDD}$ couplings. For L3 limits from $LQ\overline{D}$ couplings, see ACCIARRI 01.

[221] ABBIENDI 01 looked for final states with $\gamma\gamma\not\!\!E$, $\ell\ell\not\!\!E$, with possibly additional activity and four leptons + $\not\!\!E$ to search for prompt decays of $\widetilde{\chi}^0_1$ or $\widetilde{\ell}_1$ in GMSB. They derive limits in the plane ($m_{\widetilde{\chi}^0_1}$,$m_{\widetilde{\tau}_1}$), see Fig. 6, allowing either the $\widetilde{\chi}^0_1$ or a $\widetilde{\ell}_1$ to be the NLSP. Two scenarios are considered: $\tan\beta$=2 with the 3 sleptons degenerate in mass and $\tan\beta$=20 where the $\widetilde{\tau}_1$ is lighter than the other sleptons. Data taken at $\sqrt{s}$=189 GeV. For $\tan\beta$=20, the obtained limits are $m_{\widetilde{\tau}_1} > 69$ GeV and $m_{\widetilde{e}_1,\widetilde{\mu}_1} > 88$ GeV.

[222] ABREU 01 looked for acoplanar dilepton + diphoton + $\not\!\!E$ final states from $\widetilde{\ell}$ cascade decays at $\sqrt{s}$=130–189 GeV. See Fig. 9 for limits on the (μ,M_2) plane for $m_{\widetilde{\ell}}$=80 GeV, $\tan\beta$=1.0, and assuming degeneracy of $\widetilde{\mu}$ and $\widetilde{e}$.

[223] ACCIARRI 01 searches for multi-lepton and/or multi-jet final states from $\not\!R$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$, or $\overline{UDD}$ couplings at $\sqrt{s}$=189 GeV. The search is performed for direct and indirect decays of neutralinos, charginos, and scalar leptons, with the $\widetilde{\chi}^0_1$ or a $\widetilde{\ell}$ as LSP and assuming one coupling to be nonzero at a time. Mass limits are derived using simultaneously the constraints from the neutralino, chargino, and slepton analyses; and the Z^0 width measurements from ACCIARRI 00C in a scan of the parameter space assuming MSUGRA with gaugino and scalar mass universality. Updates and supersedes the results from ACCIARRI 99I.

[224] ABREU 00V use data from $\sqrt{s}$= 130–189 GeV to search for tracks with large impact parameter or visible decay vertices. Limits are obtained as function of $m_{\widetilde{G}}$, after combining these results with the search for slepton pair production in the SUGRA framework from ABREU 01 to cover prompt decays and on stable particle searches from ABREU 00Q. For limits at different $m_{\widetilde{G}}$, see their Fig. 12.

[225] The above limit assumes the degeneracy of stau and smuon.

Long-lived $\widetilde{\ell}$ (Slepton) MASS LIMIT

Limits on scalar leptons which leave detector before decaying. Limits from Z decays are independent of lepton flavor. Limits from continuum e^+e^- annihilation are also independent of flavor for smuons and staus. Selectron limits from e^+e^- collisions in the continuum depend on MSSM parameters because of the additional neutralino exchange contribution.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>98	95	[226] ABBIENDI	03L	OPAL	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
none 2–87.5	95	[227] ABREU	00Q	DLPH	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
>81.2	95	[228] ACCIARRI	99H	L3	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
>81	95	[229] BARATE	98K	ALEP	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$

[226] ABBIENDI 03L used e^+e^- data at $\sqrt{s}$ = 130–209 GeV to select events with two high momentum tracks with anomalous dE/dx. The excluded cross section is compared to the theoretical expectation as a function of the heavy particle mass in their Fig. 3. The limit improves to 98.5 GeV for $\widetilde{\mu}_L$ and $\widetilde{\tau}_L$. The bounds are valid for colorless spin 0 particles with lifetimes longer than 10^{-6} s. Supersedes the results from ACKERSTAFF 98P.

[227] ABREU 00Q searches for the production of pairs of heavy, charged stable particles in e^+e^- annihilation at $\sqrt{s}$= 130–189 GeV. The upper bound improves to 88 GeV for $\widetilde{\mu}_L$, $\widetilde{\tau}_L$. These limits include and update the results of ABREU 98P.

[228] ACCIARRI 99H searched for production of pairs of back-to-back heavy charged particles at $\sqrt{s}$=130–183 GeV. The upper bound improves to 82.2 GeV for $\widetilde{\mu}_L$, $\widetilde{\tau}_L$.

[229] The BARATE 98K mass limit improves to 82 GeV for $\widetilde{\mu}_L$,$\widetilde{\tau}_L$. Data collected at $\sqrt{s}$=161–184 GeV.

$\widetilde{q}$ (Squark) MASS LIMIT

For $m_{\widetilde{q}}$ > 60–70 GeV, it is expected that squarks would undergo a cascade decay via a number of neutralinos and/or charginos rather than undergo a direct decay to photinos as assumed by some papers. Limits obtained when direct decay is assumed are usually higher than limits when cascade decays are included.

Limits from e^+e^- collisions depend on the mixing angle of the lightest mass eigenstate $\widetilde{q}_1$=$\widetilde{q}_R\sin\theta_q$+$\widetilde{q}_L\cos\theta_q$. It is usually assumed that only the sbottom and stop squarks have non-trivial mixing angles (see the stop and sbottom sections). Here, unless otherwise noted, squarks are always taken to be either left/right degenerate, or purely of left or right type. Data from Z decays have set squark mass limits above 40 GeV, in the case of $\widetilde{q} \rightarrow q\widetilde{\chi}_1$ decays if Δm=$m_{\widetilde{q}} - m_{\widetilde{\chi}^0_1} \gtrsim$ 5 GeV. For smaller values of Δm, current constraints on the invisible width of the Z ($\Delta\Gamma_{\rm inv} <$ 2.0 MeV, LEP 00) exclude $m_{\widetilde{u}_{L,R}}$ <44 GeV, $m_{\widetilde{d}_R}$ <33 GeV, $m_{\widetilde{d}_L}$ <44 GeV and, assuming all squarks degenerate, $m_{\widetilde{q}}$ <45 GeV.

Limits made obsolete by the most recent analyses of e^+e^-, $p\overline{p}$, and $e\,p$ collisions can be found in previous Editions of this *Review*.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 99.5	95	[230] ACHARD	04	L3	Δm > 10 GeV, $e^+e^- \rightarrow \widetilde{q}_{L,R}\overline{\widetilde{q}}_{L,R}$
> 97	95	[230] ACHARD	04	L3	Δm > 10 GeV, $e^+e^- \rightarrow \widetilde{q}_R\overline{\widetilde{q}}_R$
>138	95	[231] ABBOTT	01D	D0	$\ell\ell$+jets+$\not{E}_T$, tanβ < 10, m_0 < 300 GeV, μ < 0, A_0=0
>255	95	[231] ABBOTT	01D	D0	tanβ=2, $m_{\widetilde{g}}$=$m_{\widetilde{q}}$, μ <0, A_0=0, $\ell\ell$+jets+$\not{E}_T$
> 97	95	[232] BARATE	01	ALEP	$e^+e^- \rightarrow \widetilde{q}\overline{\widetilde{q}}$, Δm > 6 GeV
>250	95	[233] ABBOTT	99L	D0	tanβ=2, μ <0, A=0, jets+$\not{E}_T$
>224	95	[234] ABE	96D	CDF	$m_{\widetilde{g}} \leq m_{\widetilde{q}}$; with cascade decays, $\ell\ell$+jets+$\not{E}_T$

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[235] ADLOFF	03	H1	$e^{\pm}p \to \widetilde{q}$, $\not{R}$, $LQ\overline{D}$
>276	95	[236] CHEKANOV	03B	ZEUS	$\widetilde{d} \to e^{-}u,\nu d$,$\not{R}$,$LQ\overline{D}$,$\lambda >$0.1
>260	95	[236] CHEKANOV	03B	ZEUS	$\widetilde{u} \to e^{+}d$,$\not{R}$,$LQ\overline{D}$,$\lambda >$0.1
> 82.5	95	[237] HEISTER	03G	ALEP	$\widetilde{u}_R$,$\not{R}$ decay
> 77	95	[237] HEISTER	03G	ALEP	$\widetilde{d}_R$,$\not{R}$ decay
>240	95	[238] ABAZOV	02F	D0	$\widetilde{q}$, $\not{R}$ λ'_{2jk} indirect decays, tanβ=2, any $m_{\widetilde{g}}$
>265	95	[238] ABAZOV	02F	D0	$\widetilde{q}$, $\not{R}$ λ'_{2jk} indirect decays, tanβ=2, $m_{\widetilde{q}}$=$m_{\widetilde{g}}$
		[239] ABAZOV	02G	D0	$p\overline{p} \to \widetilde{g}\widetilde{g}$, $\widetilde{g}\widetilde{q}$
none 80–121	95	[240] ABBIENDI	02	OPAL	$e\gamma \to \widetilde{u}_L$, $\not{R}$ $LQ\overline{D}$, λ=0.3
none 80–158	95	[240] ABBIENDI	02	OPAL	$e\gamma \to \widetilde{d}_R$, $\not{R}$ $LQ\overline{D}$, λ=0.3
none 80–185	95	[241] ABBIENDI	02B	OPAL	$e\gamma \to \widetilde{u}_L$, $\not{R}$ $LQ\overline{D}$, λ=0.3
none 80–196	95	[241] ABBIENDI	02B	OPAL	$e\gamma \to \widetilde{d}_R$, $\not{R}$ $LQ\overline{D}$, λ=0.3
> 79	95	[242] ACHARD	02	L3	$\widetilde{u}_R$, $\not{R}$ decays
> 55	95	[242] ACHARD	02	L3	$\widetilde{d}_R$, $\not{R}$ decays
>263	95	[243] CHEKANOV	02	ZEUS	$\widetilde{u}_L \to \mu q$, $\not{R}$, $LQ\overline{D}$, λ=0.3
>258	95	[243] CHEKANOV	02	ZEUS	$\widetilde{u}_L \to \tau q$, $\not{R}$, $LQ\overline{D}$, λ=0.3
>260	95	[244] ADLOFF	01B	H1	$e^{+}p \to \widetilde{q}$, $\not{R}$ $LQ\overline{D}$, λ=0.3
> 82	95	[245] BARATE	01B	ALEP	$\widetilde{u}_R$, $\not{R}$ decays
> 68	95	[245] BARATE	01B	ALEP	$\widetilde{d}_R$, $\not{R}$ decays
none 150–204	95	[246] BREITWEG	01	ZEUS	$e^{+}p \to \widetilde{d}_R$, $\not{R}$ $LQ\overline{D}$, λ=0.3
>200	95	[247] ABBOTT	00C	D0	$\widetilde{u}_L$, $\not{R}$, λ'_{2jk} decays
>180	95	[247] ABBOTT	00C	D0	$\widetilde{d}_R$, $\not{R}$, λ'_{2jk} decays
>390	95	[248] ACCIARRI	00P	L3	$e^{+}e^{-} \to q\overline{q}$, $\not{R}$, λ=0.3
>148	95	[249] AFFOLDER	00K	CDF	$\widetilde{d}_L$, $\not{R}$ λ'_{ij3} decays
>200	95	[250] BARATE	00I	ALEP	$e^{+}e^{-} \to q\overline{q}$, $\not{R}$, λ=0.3
none 150–269	95	[251] BREITWEG	00E	ZEUS	$e^{+}p \to \widetilde{u}_L$, $\not{R}$, $LQ\overline{D}$, λ=0.3
>240	95	[252] ABBOTT	99	D0	$\widetilde{q} \to \widetilde{\chi}^0_2 X \to \widetilde{\chi}^0_1 \gamma X$, $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} >$ 20 GeV
>320	95	[252] ABBOTT	99	D0	$\widetilde{q} \to \widetilde{\chi}^0_1 X \to \widetilde{G}\gamma X$
>243	95	[253] ABBOTT	99K	D0	any $m_{\widetilde{g}}$, $\not{R}$, tanβ=2, $\mu <$ 0
>200	95	[254] ABE	99M	CDF	$p\overline{p} \to \widetilde{q}\widetilde{q}$, $\not{R}$
none 80–134	95	[255] ABREU	99G	DLPH	$e\gamma \to \widetilde{u}_L$, $\not{R}$ $LQ\overline{D}$, λ=0.3
none 80–161	95	[255] ABREU	99G	DLPH	$e\gamma \to \widetilde{d}_R$, $\not{R}$ $LQ\overline{D}$, λ=0.3
>225	95	[256] ABBOTT	98E	D0	$\widetilde{u}_L$, $\not{R}$, λ'_{1jk} decays
>204	95	[256] ABBOTT	98E	D0	$\widetilde{d}_R$, $\not{R}$, λ'_{1jk} decays
> 79	95	[256] ABBOTT	98E	D0	$\widetilde{d}_L$, $\not{R}$, λ'_{ijk} decays
>202	95	[257] ABE	98S	CDF	$\widetilde{u}_L$, $\not{R}$ λ'_{2jk} decays
>160	95	[257] ABE	98S	CDF	$\widetilde{d}_R$, $\not{R}$ λ'_{2jk} decays
>140	95	[258] ACKERSTAFF	98V	OPAL	$e^{+}e^{-} \to q\overline{q}$, $\not{R}$, λ=0.3
> 77	95	[259] BREITWEG	98	ZEUS	$m_{\widetilde{q}}$=$m_{\widetilde{e}}$, $m(\widetilde{\chi}^0_1)$= 40 GeV
		[260] DATTA	97	THEO	$\widetilde{\nu}$'s lighter than $\widetilde{\chi}^{\pm}_1$, $\widetilde{\chi}^0_2$

>216	95	[261] DERRICK	97	ZEUS	$e p \to \tilde{q}$, $\tilde{q} \to \mu j$ or τj, $\not{R}$
none 130–573	95	[262] HEWETT	97	THEO	$q \tilde{g} \to \tilde{q}$, $\tilde{q} \to q \tilde{g}$, with a light gluino
none 190–650	95	[263] TEREKHOV	97	THEO	$q g \to \tilde{q} \tilde{g}$, $\tilde{q} \to q \tilde{g}$, with a light gluino
> 63	95	[264] AID	96C	H1	$m_{\tilde{q}}=m_{\tilde{e}}$, $m_{\tilde{\chi}_1^0}$=35 GeV
none 330–400	95	[265] TEREKHOV	96	THEO	$u g \to \tilde{u} \tilde{g}$, $\tilde{u} \to u \tilde{g}$ with a light gluino
>176	95	[266] ABACHI	95C	D0	Any $m_{\tilde{g}}$ <300 GeV; with cascade decays
		[267] ABE	95T	CDF	$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$
> 90	90	[268] ABE	92L	CDF	Any $m_{\tilde{g}}$ <410 GeV; with cascade decay
>100		[269] ROY	92	RVUE	$p \overline{p} \to \tilde{q} \tilde{q}$; $\not{R}$
		[270] NOJIRI	91	COSM	

[230] ACHARD 04 search for the production of $\tilde{q}\tilde{q}$ of the first two generations in acoplanar di-jet final states in the 192–209 GeV data. Degeneracy of the squark masses is assumed either for both left and right squarks or for right squarks only, as well as B($\tilde{q} \to q \tilde{\chi}_1^0$) = 1 See Fig. 7 for the dependence of the limits on $m_{\tilde{\chi}_1^0}$. This limit supersedes ACCIARRI 99V.

[231] ABBOTT 01D looked in $\sim$ 108 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with ee, $\mu\mu$, or $e\mu$ acompanied by at least 2 jets and $\not{E}_T$. Excluded regions are obtained in the MSUGRA framework from a scan over the parameters 0<m_0 <300 GeV, 10<$m_{1/2}$ <110 GeV, and 1.2 <tanβ <10.

[232] BARATE 01 looked for acoplanar dijets + $\not{E}_T$ final states at 189 to 202 GeV. The limit assumes B($\tilde{q} \to q \tilde{\chi}_1^0$)=1, with $\Delta m = m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$. It applies to tan$\beta$=4, μ=−400 GeV. See their Fig. 2 for the exclusion in the ($m_{\tilde{q}}$,$m_{\tilde{g}}$) plane. These limits include and update the results of BARATE 99Q.

[233] ABBOTT 99L consider events with three or more jets and large $\not{E}_T$. Spectra and decay rates are evaluated in the framework of minimal Supergravity, assuming five flavors of degenerate squarks, and scanning the space of the universal gaugino ($m_{1/2}$) and scalar (m_0) masses. See their Figs. 2–3 for the dependence of the limit on the relative value of $m_{\tilde{q}}$ and $m_{\tilde{g}}$.

[234] ABE 96D searched for production of gluinos and five degenerate squarks in final states containing a pair of leptons, two jets, and missing E_T. The two leptons arise from the semileptonic decays of charginos produced in the cascade decays. The limit is derived for fixed tanβ = 4.0, μ = −400 GeV, and m_{H^+} = 500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario.

[235] ADLOFF 03 looked for the s-channel production of squarks via $\not{R}$ $LQ\overline{D}$ couplings in 117.2 pb^{-1} of e^+p data at $\sqrt{s}$ = 301 and 319 GeV and of e^-p data at $\sqrt{s}$ = 319 GeV. The comparison of the data with the SM differential cross section allows limits to be set on couplings for processes mediated through contact interactions. They obtain lower bounds on the value of $m_{\tilde{q}}/\lambda'$ of 710 GeV for the process $e^+\bar{u} \to \tilde{\bar{d}}^k$ (and charge conjugate), mediated by λ'_{11k}, and of 430 GeV for the process $e^+d \to \tilde{u}^j$ (and charge conjugate), mediated by λ'_{1j1}.

[236] CHEKANOV 03B used 131.5 pb^{-1} of e^+p and e^-p data taken at 300 and 318 GeV to look for narrow resonances in the eq or νq final states. Such final states may originate from $LQ\overline{D}$ couplings with non-zero λ'_{1j1} (leading to $\tilde{u}_j$) or λ'_{11k} (leading to $\tilde{d}_k$). See their Fig. 8 and explanations in the text for limits. The quoted mass bound assumes that only direct squark decays contribute.

[237] HEISTER 03G searches for the production of squarks in the case of $\not{R}$ prompt decays with $\overline{UDD}$ direct couplings at at $\sqrt{s}$ = 189–209 GeV.

[238] ABAZOV 02F looked in 77.5 pb^{-1} of $p\overline{p}$ collisions at 1.8 TeV for events with $\geq 2\mu+ \geq$ 4jets, originating from associated production of squarks followed by an indirect $\not{R}$ decay (of the $\widetilde{\chi}^0_1$) via $LQ\overline{D}$ couplings of the type λ'_{2jk} where j=1,2 and k=1,2,3. Bounds are obtained in the MSUGRA scenario by a scan in the range $0 \leq M_0 \leq 400$ GeV, $60 \leq m_{1/2} \leq 120$ GeV for fixed values A_0=0, μ <0, and tanβ=2 or 6. The bounds are weaker for tanβ=6. See Figs. 2,3 for the exclusion contours in $m_{1/2}$ versus m_0 for tanβ=2 and 6, respectively.

[239] ABAZOV 02G search for associated production of gluinos and squarks in 92.7 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV, using events with one electron, $\geq$ 4 jets, and large $\not{E}_T$. The results are compared to a MSUGRA scenario with μ <0, A_0=0, and tanβ=3 and allow to exclude a region of the (m_0,$m_{1/2}$) shown in Fig. 11.

[240] ABBIENDI 02 looked for events with an electron or neutrino and a jet in e^+e^- at 189 GeV. Squarks (or leptoquarks) could originate from a $LQ\overline{D}$ coupling of an electron with a quark from the fluctuation of a virtual photon. Limits on the couplings λ'_{1jk} as a function of the squark mass are shown in Figs. 8–9, assuming that only direct squark decays contribute.

[241] ABBIENDI 02B looked for events with an electron or neutrino and a jet in e^+e^- at 189–209 GeV. Squarks (or leptoquarks) could originate from a $LQ\overline{D}$ coupling of an electron with a quark from the fluctuation of a virtual photon. Limits on the couplings λ'_{1jk} as a function of the squark mass are shown in Fig. 4, assuming that only direct squark decays contribute. The quoted limits are read off from Fig. 4. Supersedes the results of ABBIENDI 02.

[242] ACHARD 02 searches for the production of squarks in the case of $\not{R}$ prompt decays with $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit holds for indirect decays. Stronger limits are reached for ($\widetilde{u}_R$,$\widetilde{d}_R$) direct (80,56) GeV and ($\widetilde{u}_L$,$\widetilde{d}_L$) direct or indirect (87,86) GeV decays.

[243] CHEKANOV 02 search for lepton flavor violating processes $e^+p \rightarrow \ell X$, where $\ell = \mu$ or τ with high p_T, in 47.7 pb^{-1} of e^+p collisions at 300 GeV. Such final states may originate from $LQ\overline{D}$ couplings with simultaneously nonzero λ'_{1jk} and λ'_{ijk} (i=2 or 3). The quoted mass bound assumes that only direct squark decays contribute.

[244] ADLOFF 01B searches for squark exchange in 37 pb^{-1} of e^+p collisions, mediated by $\not{R}$ couplings $LQ\overline{D}$ and leading to several final states with leptons and jets from direct or indirect decays. The 7 decay topologies considered cover almost all branching fractions. Limits are derived on λ'_{1j1}, as a function of the squark mass from a scan over the parameters 70<M_2 <350 GeV, $-300 < \mu$ <300 GeV, assuming mass degeneracy for the squarks, a slepton mass of 90 GeV, and tanβ=2. Similar limits obtained under more constrained model assumptions are discussed in the paper. These results supersede AID 96.

[245] BARATE 01B searches for the production of squarks in the case of $\not{R}$ prompt decays with $LL\overline{E}$ indirect or $\overline{UDD}$ direct couplings at $\sqrt{s}$=189–202 GeV. The limit holds for direct decays mediated by $\not{R}$ $\overline{UDD}$ couplings. Limits are also given for $LL\overline{E}$ indirect decays ($m_{\widetilde{u}_R} > 90$ GeV and $m_{\widetilde{d}_R} > 89$ GeV). Supersedes the results from BARATE 00H.

[246] BREITWEG 01 searches for squark production in 47.7 pb^{-1} of e^+p collisions, mediated by $\not{R}$ couplings $LQ\overline{D}$ and leading to final states with $\widetilde{\nu}$ and $\geq$ 1 jet, complementing the e^+X final states of BREITWEG 00E. Limits are derived on $\lambda'\sqrt{\beta}$, where β is the branching fraction of the squarks into $e^+q+\overline{\nu}q$, as function of the squark mass, see their Fig. 15. The quoted mass limit assumes that only direct squark decays contribute.

[247] ABBOTT 00C searched in $\sim$ 94 pb^{-1} of $p\overline{p}$ collisions for events with $\mu\mu$+jets, originating from associated production of leptoquarks. The results can be interpreted as

limits on production of squarks followed by direct $\not{R}$ decay via $\lambda'_{2jk} L_2 Q_j d^c_k$ couplings. Bounds are obtained on the cross section for branching ratios of 1 and of 1/2, see their Fig. 4. The former yields the limit on the $\widetilde{u}_L$. The latter is combined with the bound of ABBOTT 99J from the $\mu\nu$+jets channel and of ABBOTT 98E and ABBOTT 98J from the $\nu\nu$+jets channel to yield the limit on $\widetilde{d}_R$.

248 ACCIARRI 00P studied the effect on hadronic cross sections of t-channel down-type squark exchange via R-parity violating coupling $\lambda'_{1jk} L_1 Q_j d^c_k$. The limit here refers to the case j=1,2, and holds for λ'_{1jk}=0.3. Data collected at $\sqrt{s}$=130–189 GeV, superseding the results of ACCIARRI 98J.

249 AFFOLDER 00K searched in $\sim$ 88 pb^{-1} of $p\overline{p}$ collisions for events with 2–3 jets, at least one being b-tagged, large $\not{E}_T$ and no high p_T leptons. Such $\nu\nu$+b-jets events would originate from associated production of squarks followed by direct $\not{R}$ decay via $\lambda'_{ij3} L_i Q_j d^c_3$ couplings. Bounds are obtained on the production cross section assuming zero branching ratio to charged leptons.

250 BARATE 00I studied the effect on hadronic cross sections and charge asymmetries of t-channel down-type squark exchange via R-parity violating coupling $\lambda'_{1jk} L_1 Q_j d^c_k$. The limit here refers to the case j=1,2, and holds for λ'_{1jk}=0.3. A 50 GeV limit is found for up-type squarks with k=3. Data collected at $\sqrt{s}$= 130–183 GeV.

251 BREITWEG 00E searches for squark exchange in $e^+ p$ collisions, mediated by $\not{R}$ couplings $LQ\overline{D}$ and leading to final states with an identified e^+ and $\geq$ 1 jet. The limit applies to up-type squarks of all generations, and assumes B($\widetilde{q} \rightarrow q e$)=1.

252 ABBOTT 99 searched for $\gamma \not{E}_T$ + $\geq$ 2 jet final states, and set limits on $\sigma(p\overline{p} \rightarrow \widetilde{q}$+X)·B($\widetilde{q} \rightarrow \gamma \not{E}_T$X). The quoted limits correspond to $m_{\widetilde{g}} \geq m_{\widetilde{q}}$, with B($\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 \gamma$)=1 and B($\widetilde{\chi}^0_1 \rightarrow \widetilde{G}\gamma$)=1, respectively. They improve to 310 GeV (360 GeV in the case of $\gamma \widetilde{G}$ decay) for $m_{\widetilde{g}}$=$m_{\widetilde{q}}$.

253 ABBOTT 99K uses events with an electron pair and four jets to search for the decay of the $\widetilde{\chi}^0_1$ LSP via $\not{R}$ $LQ\overline{D}$ couplings. The particle spectrum and decay branching ratios are taken in the framework of minimal supergravity. An excluded region at 95% CL is obtained in the (m_0,$m_{1/2}$) plane under the assumption that A_0=0, $\mu < 0$, tanβ=2 and any one of the couplings $\lambda'_{1jk} > 10^{-3}$ (j=1,2 and k=1,2,3) and from which the above limit is computed. For equal mass squarks and gluinos, the corresponding limit is 277 GeV. The results are essentially independent of A_0, but the limit deteriorates rapidly with increasing tanβ or μ >0.

254 ABE 99M looked in 107 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with like sign dielectrons and two or more jets from the sequential decays $\widetilde{q} \rightarrow q \widetilde{\chi}^0_1$ and $\widetilde{\chi}^0_1 \rightarrow e q \overline{q}'$, assuming $\not{R}$ coupling $L_1 Q_j D^c_k$, with j=2,3 and k=1,2,3. They assume five degenerate squark flavors, B($\widetilde{q} \rightarrow q \widetilde{\chi}^0_1$)=1, B($\widetilde{\chi}^0_1 \rightarrow e q \overline{q}'$)=0.25 for both e^+ and e^-, and $m_{\widetilde{g}} \geq$ 200 GeV. The limit is obtained for $m_{\widetilde{\chi}^0_1} \geq m_{\widetilde{q}}/2$ and improves for heavier gluinos or heavier χ^0_1.

255 ABREU 99G looked for events with an electron or neutrino and a jet in $e^+ e^-$ at 183 GeV. Squarks (or leptoquarks) could originate from a $LQ\overline{D}$ coupling of an electron with a quark from the fluctuation of a virtual photon. Limits on the couplings λ'_{1jk} as a function of the squark mass are shown in Fig. 4, assuming that only direct squark decays contribute.

256 ABBOTT 98E searched in $\sim$ 115 pb^{-1} of $p\overline{p}$ collisions for events with $e\nu$+jets, originating from associated production of squarks followed by direct $\not{R}$ decay via $\lambda'_{1jk} L_1 Q_j d^c_k$ couplings. Bounds are obtained by combining these results with the previous bound of

ABBOTT 97B from the ee+jets channel and with a reinterpretation of ABACHI 96B $\nu\nu$+jets channel.

[257] ABE 98S looked in $\sim$ 110 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with $\mu\mu$+jets originating from associated production of squarks followed by direct $\not{R}$ decay via $\lambda'_{2jk} L_2 Q_j d^c_k$ couplings. Bounds are obtained on the production cross section times the square of the branching ratio, see Fig. 2. Mass limits result from the comparison with theoretical cross sections and branching ratio equal to 1 for $\widetilde{u}_L$ and 1/2 for $\widetilde{d}_R$.

[258] ACKERSTAFF 98V and ACCIARRI 98J studied the interference of t-channel squark ($\widetilde{d}_R$) exchange via R-parity violating $\lambda'_{1jk} L_1 Q_j d^c_k$ coupling in $e^+ e^- \rightarrow q\overline{q}$. The limit is for λ'_{1jk}=0.3. See paper for related limits on $\widetilde{u}_L$ exchange. Data collected at $\sqrt{s}$=130–172 GeV.

[259] BREITWEG 98 used positron+jet events with missing energy and momentum to look for $e^+ q \rightarrow \widetilde{e}\widetilde{q}$ via gaugino-like neutralino exchange with decays into $(e\widetilde{\chi}^0_1)(q\widetilde{\chi}^0_1)$. See paper for dependences in $m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$.

[260] DATTA 97 argues that the squark mass bound by ABACHI 95C can be weakened by 10–20 GeV if one relaxes the assumption of the universal scalar mass at the GUT-scale so that the $\widetilde{\chi}^\pm_1$,$\widetilde{\chi}^0_2$ in the squark cascade decays have dominant and invisible decays to $\widetilde{\nu}$.

[261] DERRICK 97 looked for lepton-number violating final states via R-parity violating couplings $\lambda'_{ijk} L_i Q_j d_k$. When $\lambda'_{11k}\lambda'_{ijk} \neq 0$, the process $e u \rightarrow \widetilde{d}^*_k \rightarrow \ell_i u_j$ is possible. When $\lambda'_{1j1}\lambda'_{ijk} \neq 0$, the process $e\overline{d} \rightarrow \widetilde{u}^*_j \rightarrow \ell_i \overline{d}_k$ is possible. 100% branching fraction $\widetilde{q} \rightarrow \ell j$ is assumed. The limit quoted here corresponds to $\widetilde{t} \rightarrow \tau q$ decay, with λ'=0.3. For different channels, limits are slightly better. See Table 6 in their paper.

[262] HEWETT 97 reanalyzed the limits on possible resonances in di-jet mode ($\widetilde{q} \rightarrow q\widetilde{g}$) from ALITTI 93 quoted in "Limits for Excited q (q^*) from Single Production," ABE 96 in "SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$," and unpublished CDF, DØ bounds. The bound applies to the gluino mass of 5 GeV, and improves for lighter gluino. The analysis has gluinos in parton distribution function.

[263] TEREKHOV 97 improved the analysis of TEREKHOV 96 by including di-jet angular distributions in the analysis.

[264] AID 96C used positron+jet events with missing energy and momentum to look for $e^+ q \rightarrow \widetilde{e}\widetilde{q}$ via neutralino exchange with decays into $(e\widetilde{\chi}^0_1)(q\widetilde{\chi}^0_1)$. See the paper for dependences on $m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$.

[265] TEREKHOV 96 reanalyzed the limits on possible resonances in di-jet mode ($\widetilde{u} \rightarrow u\widetilde{g}$) from ABE 95N quoted in "MASS LIMITS for g_A (axigluon)." The bound applies only to the case with a light gluino.

[266] ABACHI 95C assume five degenerate squark flavors with $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$. Sleptons are assumed to be heavier than squarks. The limits are derived for fixed $\tan\beta$ = 2.0 μ = $-$250 GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space. No limit is given for m_{gluino} >547 GeV.

[267] ABE 95T looked for a cascade decay of five degenerate squarks into $\widetilde{\chi}^0_2$ which further decays into $\widetilde{\chi}^0_1$ and a photon. No signal is observed. Limits vary widely depending on the choice of parameters. For $\mu = -40$ GeV, $\tan\beta$ = 1.5, and heavy gluinos, the range 50<$m_{\widetilde{q}}$ (GeV)<110 is excluded at 90% CL. See the paper for details.

[268] ABE 92L assume five degenerate squark flavors and $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$. ABE 92L includes the effect of cascade decay, for a particular choice of parameters, $\mu = -250$ GeV, $\tan\beta$ = 2. Results are weakly sensitive to these parameters over much of parameter space. No

limit for $m_{\widetilde{q}} \leq 50$ GeV (but other experiments rule out that region). Limits are 10–20 GeV higher if B($\widetilde{q} \rightarrow q\widetilde{\gamma}$) = 1. Limit assumes GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\widetilde{\chi}^0_1} \approx m_{\widetilde{g}}/6$. This last relation implies that as $m_{\widetilde{g}}$ increases, the mass of $\widetilde{\chi}^0_1$ will eventually exceed $m_{\widetilde{q}}$ so that no decay is possible. Even before that occurs, the signal will disappear; in particular no bounds can be obtained for $m_{\widetilde{g}}$ >410 GeV. m_{H^+}=500 GeV.

[269] ROY 92 reanalyzed CDF limits on di-lepton events to obtain limits on squark production in R-parity violating models. The 100% decay $\widetilde{q} \rightarrow q\widetilde{\chi}$ where $\widetilde{\chi}$ is the LSP, and the LSP decays either into $\ell q \overline{d}$ or $\ell\ell\overline{e}$ is assumed.

[270] NOJIRI 91 argues that a heavy squark should be nearly degenerate with the gluino in minimal supergravity not to overclose the universe.

Long-lived $\widetilde{q}$ (Squark) MASS LIMIT

The following are bounds on long-lived scalar quarks, assumed to hadronise into hadrons with lifetime long enough to escape the detector prior to a possible decay. Limits may depend on the mixing angle of mass eigenstates: $\widetilde{q}_1 = \widetilde{q}_L \cos\theta_q + \widetilde{q}_R \sin\theta_q$. The coupling to the Z^0 boson vanishes for up-type squarks when θ_u=0.98, and for down type squarks when θ_d=1.17.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>95	95	[271] HEISTER	03H	ALEP	$\widetilde{u}$
>92	95	[271] HEISTER	03H	ALEP	$\widetilde{d}$
none 2–85	95	[272] ABREU	98P	DLPH	$\widetilde{u}_L$
none 2–81	95	[272] ABREU	98P	DLPH	$\widetilde{u}_R$
none 2–80	95	[272] ABREU	98P	DLPH	$\widetilde{u}$, θ_u=0.98
none 2–83	95	[272] ABREU	98P	DLPH	$\widetilde{d}_L$
none 5–40	95	[272] ABREU	98P	DLPH	$\widetilde{d}_R$
none 5–38	95	[272] ABREU	98P	DLPH	$\widetilde{d}$, θ_d=1.17

[271] HEISTER 03H use e^+e^- data at and around the Z^0 peak to look for hadronizing stable squarks. Combining their results on searches for charged and neutral R-hadrons with JANOT 03, a lower limit of 15.7 GeV on the mass is obtained. Combining this further with the results of searches for tracks with anomalous ionization in data from 183 to 208 GeV yields the quoted bounds.

[272] ABREU 98P assumes that 40% of the squarks will hadronise into a charged hadron, and 60% into a neutral hadron which deposits most of its energy in hadron calorimeter. Data collected at $\sqrt{s}$=130–183 GeV.

$\widetilde{b}$ (Sbottom) MASS LIMIT

Limits in e^+e^- depend on the mixing angle of the mass eigenstate $\widetilde{b}_1 = \widetilde{b}_L \cos\theta_b + \widetilde{b}_R \sin\theta_b$. Coupling to the Z vanishes for $\theta_b \sim 1.17$. As a consequence, no absolute constraint in the mass region $\lesssim$ 40 GeV is available in the literature at this time from e^+e^- collisions. In the Listings below, we use $\Delta m = m_{\widetilde{b}_1} - m_{\widetilde{\chi}^0_1}$.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>95	95	[273] ACHARD	04	L3	$\widetilde{b} \rightarrow b\widetilde{\chi}^0_1$,$\theta_b$=0,$\Delta m$> 15–25 GeV
>81	95	[273] ACHARD	04	L3	$\widetilde{b} \rightarrow b\widetilde{\chi}^0_1$, all θ_b, Δm >15–25 GeV
>93	95	[274] ABDALLAH	03M	DLPH	$\widetilde{b} \rightarrow b\widetilde{\chi}^0$, θ_b=0, Δm >7 GeV

>76	95	[274] ABDALLAH	03M	DLPH	$\widetilde{b} \rightarrow b\widetilde{\chi}^0$, all θ_b, Δm >7 GeV
>85.1	95	[275] ABBIENDI	02H	OPAL	$\widetilde{b} \rightarrow b\widetilde{\chi}^0_1$, all$\theta_b$, Δm >10 GeV, CDF
>89	95	[276] HEISTER	02K	ALEP	$\widetilde{b} \rightarrow b\widetilde{\chi}^0_1$, all θ_b, Δm >8 GeV, CDF
none 3.5–4.5	95	[277] SAVINOV	01	CLEO	$\widetilde{B}$ meson
none 80–145		[278] AFFOLDER	00D	CDF	$\widetilde{b} \rightarrow b\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1}$ <50 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 50–82	95	[279] ABDALLAH	03C	DLPH	$\tilde{b} \rightarrow b\tilde{g}$, stable $\tilde{g}$, all θ_b, $\Delta M >$ 10 GeV
		[280] BERGER	03	THEO	
>71.5	95	[281] HEISTER	03G	ALEP	$\widetilde{b}_L$, $\not{R}$ decay
>27.4	95	[282] HEISTER	03H	ALEP	$\widetilde{b} \rightarrow b\widetilde{g}$, stable $\widetilde{g}$ or $\widetilde{b}$
>48	95	[283] ACHARD	02	L3	$\widetilde{b}_1$, $\not{R}$ decays
		[284] BAEK	02	THEO	
		[285] BECHER	02	THEO	
		[286] CHEUNG	02B	THEO	
		[287] CHO	02	THEO	
>72	95	[288] ABREU	01D	DLPH	$\not{R}(\overline{UDD})$, all $\Delta m >$ 5 GeV, θ_b=0
		[289] BERGER	01	THEO	$p\overline{p} \rightarrow$ X+b-quark
none 52–115	95	[290] ABBOTT	99F	D0	$\widetilde{b} \rightarrow b\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1} <$ 20 GeV

[273] ACHARD 04 search for the production of $\widetilde{b}\widetilde{b}$ in acoplanar b-tagged di-jet final states in the 192–209 GeV data. See Fig. 6 for the dependence of the limits on $m_{\widetilde{\chi}^0_1}$. This limit supersedes ACCIARRI 99V.

[274] ABDALLAH 03M looked for $\widetilde{b}$ pair production in events with acoplanar jets and $\not{E}$ at $\sqrt{s}$ = 189–208 GeV. The limit improves to 87 (98) GeV for all θ_b ($\theta_b = 0$) for $\Delta m >$ 10 GeV. See Fig. 24 and Table 11 for other choices of Δm. These limits include and update the results of ABREU,P 00D.

[275] ABBIENDI 02H search for events with two acoplanar jets and $\not{p}_T$ in the 161–209 GeV data. The limit assumes 100% branching ratio and uses the exclusion at large Δm from CDF (AFFOLDER 00D). For θ_b=0, the bound improves to > 96.9 GeV. See Fig. 4 and Table 6 for the more general dependence on the limits on Δm. These results supersede ABBIENDI 99M.

[276] HEISTER 02K search for bottom squarks in final states with acoplanar jets with b tagging, using 183–209 GeV data. The mass bound uses the CDF results from AFFOLDER 00D. See Fig. 5 for the more general dependence of the limits on Δm. Updates BARATE 01.

[277] SAVINOV 01 use data taken at $\sqrt{s}$=10.52 GeV, below the $B\overline{B}$ threshold. They look for events with a pair of leptons with opposite charge and a fully reconstructed hadronic D or D^* decay. These could originate from production of a light-sbottom hadron followed by $\widetilde{B} \rightarrow D^{(*)}\ell^-\widetilde{\nu}$, in case the $\widetilde{\nu}$ is the LSP, or $\widetilde{B} \rightarrow D^{(*)}\pi\ell^-$, in case of $\not{R}$. The mass range 3.5 ≤ $M(\widetilde{B})$ ≤ 4.5 GeV was explored, assuming 100% branching ratio for either of the decays. In the $\widetilde{\nu}$ LSP scenario, the limit holds only for $M(\widetilde{\nu})$ less than about 1 GeV and for the D^* decays it is reduced to the range 3.9–4.5 GeV. For the $\not{R}$ decay, the whole range is excluded.

[278] AFFOLDER 00D search for final states with 2 or 3 jets and $\not{E}_T$, one jet with a b tag. See their Fig. 3 for the mass exclusion in the $m_{\widetilde{t}}$, $m_{\widetilde{\chi}^0_1}$ plane.

[279] ABDALLAH 03C looked for events of the type $q\bar{q}R^{\pm}R^{\pm}$, $q\bar{q}R^{\pm}R^0$ or $q\bar{q}R^0R^0$ in e^+e^- interactions at $\sqrt{s} = 189 - 208$ GeV. The $R^{\pm}$ bound states are identified by anomalous dE/dx in the tracking chambers and the R^0 by missing energy due to their reduced energy loss in the calorimeters. Excluded mass regions in the $(m(\tilde{b}), m(\tilde{g}))$ plane for

$m(\tilde{g}) > 2$ GeV are obtained for several values of the probability for the gluino to fragment into $R^{\pm}$ or R^{0}, as shown in their Fig. 19. The limit improves to 94 GeV for $\theta_{b} = 0$.

[280] BERGER 03 studies the constraints on a $\tilde{b}_1$ with mass in the 2.2–5.5 GeV region coming from radiative decays of Υ(nS) into sbottomonium. The constraints apply only if $\tilde{b}_1$ lives long enough to permit formation of the sbottomonium bound state. A small region of mass in the $m_{\tilde{b}_1} - m_{\tilde{g}}$ plane survives current experimental constraints from CLEO.

[281] HEISTER 03G searches for the production of $\tilde{b}$ pairs in the case of $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s} =$ 189–209 GeV. The limit holds for indirect decays mediated by $\not{R}$ $\overline{UDD}$ couplings. It improves to 90 GeV for indirect decays mediated by $\not{R}$ $LL\overline{E}$ couplings and to 80 GeV for indirect decays mediated by $\not{R}$ $LQ\overline{D}$ couplings. Supersedes the results from BARATE 01B.

[282] HEISTER 03H use their results on bounds on stable squarks, on stable gluinos and on squarks decaying to a stable gluino from the same paper to derive a mass limit on $\tilde{b}$, see their Fig. 13.

[283] ACHARD 02 searches for the production of squarks in the case of $\not{R}$ prompt decays with $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit is computed for the minimal cross section and holds for indirect decays and reaches 55 GeV for direct decays.

[284] BAEK 02 studies the constraints on a $\tilde{b}_1$ with mass in the 2.2–5.5 GeV region coming from precision measurements of Z^0 decays. It is noted that CP-violating couplings in the MSSM parameters relax the strong constraints otherwised derived from CP conservation.

[285] BECHER 02 studies the constraints on a $\tilde{b}_1$ with mass in the 2.2–5.5 GeV region coming from radiative B meson decays, and sets limits on the off-diagonal flavor-changing couplings $q\tilde{b}\tilde{g}$ (q=d,s).

[286] CHEUNG 02B studies the constraints on a $\tilde{b}_1$ with mass in the 2.2–5.5 GeV region and a gluino in the mass range 12–16 GeV, using precision measurements of Z^0 decays and e^+e^- annihilations at LEP2. Few detectable events are predicted in the LEP2 data for the model proposed by BERGER 01.

[287] CHO 02 studies the constraints on a $\tilde{b}_1$ with mass in the 2.2–5.5 GeV region coming from precision measurements of Z^0 decays. Strong constraints are obtained for CP-conserving MSSM couplings.

[288] ABREU 01D searches for multi-jet events, expected in the case of prompt decays from $\not{R}$ $\overline{UDD}$ couplings and indirect decays, using data from $\sqrt{s}$=189 GeV. Limits are obtained in the plane of the squark mass versus $m_{\tilde{\chi}_1^0}$. The mass limit is derived using the constraint on the neutralino mass from the same paper (see the section on unstable $\tilde{\chi}_1^0$). See Fig. 9 for other choices of Δm.

[289] BERGER 01 reanalyzed interpretation of Tevatron data on bottom-quark production. Argues that pair production of light gluinos ($m\sim$ 12–16 GeV) with subsequent 2-body decay into a light sbottom ($m\sim$ 2–5.5 GeV) and bottom can reconcile Tevatron data with predictions of perturbative QCD for the bottom production rate. The sbottom must either decay hadronically via a R-parity- and B-violating interaction, or be long-lived. Constraints on the mass spectrum are derived from the measurements of time-averaged B^0-$\overline{B}^0$ mixing.

[290] ABBOTT 99F looked for events with two jets, with or without an associated muon from b decay, and $\not{E}_T$. See Fig. 2 for the dependence of the limit on $m_{\tilde{\chi}_1^0}$. No limit for $m_{\tilde{\chi}_1^0} > 47$ GeV.

$\tilde{t}$ (Stop) MASS LIMIT

Limits depend on the decay mode. In e^+e^- collisions they also depend on the mixing angle of the mass eigenstate $\tilde{t}_1 = \tilde{t}_L\cos\theta_t + \tilde{t}_R\sin\theta_t$. The coupling to the Z vanishes when θ_t = 0.98. In the Listings below, we use $\Delta m \equiv m_{\widetilde{t}_1} - m_{\widetilde{\chi}^0_1}$ or $\Delta m \equiv m_{\widetilde{t}_1} - m_{\widetilde{\nu}}$, depending on relevant decay mode. See also bounds in "$\widetilde{q}$ (Squark) MASS LIMIT." Limits made obsolete by the most recent analyses of e^+e^- and $p\overline{p}$ collisions can be found in previous Editions of this *Review*.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 90	95	[291] ACHARD	04	L3	$\widetilde{t} \to c\widetilde{\chi}^0_1$, all θ_t, $\Delta m>$ 15–25 GeV
> 93	95	[291] ACHARD	04	L3	$\widetilde{b} \to b\ell\widetilde{\nu}$, all θ_t, $\Delta m>$15 GeV
> 88	95	[291] ACHARD	04	L3	$\widetilde{b} \to b\tau\widetilde{\nu}$, all θ_t,$\Delta m>$15 GeV
> 75	95	[292] ABDALLAH	03M	DLPH	$\widetilde{t} \to c\widetilde{\chi}^0$, θ_t=0, Δm >2 GeV
> 71	95	[292] ABDALLAH	03M	DLPH	$\widetilde{t} \to c\widetilde{\chi}^0$, all θ_t, Δm >2 GeV
> 96	95	[292] ABDALLAH	03M	DLPH	$\widetilde{t} \to c\widetilde{\chi}^0$,$\theta_t$=0,$\Delta m$ >10 GeV
> 92	95	[292] ABDALLAH	03M	DLPH	$\widetilde{t} \to c\widetilde{\chi}^0$,all θ_t,Δm >10 GeV
none 80–131	95	[293] ACOSTA	03C	CDF	$\widetilde{t} \to b\ell\widetilde{\nu}$, $m_{\widetilde{\nu}} \leq$ 63 GeV
>144	95	[294] ABAZOV	02C	D0	$\widetilde{t} \to b\ell\widetilde{\nu}$, $m_{\widetilde{\nu}}$=45 GeV
> 95.7	95	[295] ABBIENDI	02H	OPAL	$c\widetilde{\chi}^0_1$, allθ_t, Δm >10 GeV
> 92.6	95	[295] ABBIENDI	02H	OPAL	$b\ell\widetilde{\nu}$, allθ_t, Δm >10 GeV
> 91.5	95	[295] ABBIENDI	02H	OPAL	$b\tau\widetilde{\nu}$, allθ_t, Δm >10 GeV
> 63	95	[296] HEISTER	02K	ALEP	any decay, any lifetime, all θ_t
> 92	95	[296] HEISTER	02K	ALEP	$\widetilde{t} \to c\widetilde{\chi}^0_1$, all θ_t, Δm >8 GeV, CDF
> 97	95	[296] HEISTER	02K	ALEP	$\widetilde{t} \to b\ell\widetilde{\nu}$, all θ_t, Δm >8 GeV, DØ
> 78	95	[296] HEISTER	02K	ALEP	$\widetilde{t} \to b\widetilde{\chi}^0_1 W^*$, all θ_t, Δm >8 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 50–87	95	[297] ABDALLAH	03C	DLPH	$\tilde{t} \to c\tilde{g}$, stable $\tilde{g}$, all θ_t, $\Delta M >$ 10 GeV
		[298] CHAKRAB...	03	THEO	$p\overline{p} \to \widetilde{t}\widetilde{t}^*$, RPV
> 71.5	95	[299] HEISTER	03G	ALEP	$\widetilde{t}_L$,$\not{R}$ decay
> 80	95	[300] HEISTER	03H	ALEP	$\widetilde{t} \to c\widetilde{g}$, stable $\widetilde{g}$ or $\widetilde{t}$, all θ_t, all ΔM
> 77	95	[301] ACHARD	02	L3	$\widetilde{t}_1$, $\not{R}$ decays
> 74	95	[302] ABREU	01D	DLPH	$\not{R}(\overline{UDD})$, all $\Delta m >$ 5 GeV, θ_t=0
> 59	95	[302] ABREU	01D	DLPH	$\not{R}(\overline{UDD})$, all $\Delta m >$ 5 GeV, θ_t=0.98
		[303] AFFOLDER	01B	CDF	$t \to \widetilde{t}\chi^0_1$
> 76	95	[304] ABBIENDI	00	OPAL	$\not{R}$, $(\overline{UDD})$, all θ_t
> 61	95	[305] ABREU	00I	DLPH	$\not{R}$ $(LL\overline{E})$, θ_t=0.98, $\Delta m >$ 4 GeV
none 68–119	95	[306] AFFOLDER	00D	CDF	$\widetilde{t} \to c\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1}$ <40 GeV
none 84–120	95	[307] AFFOLDER	00G	CDF	$\widetilde{t}_1 \to b\ell\widetilde{\nu}$, $m_{\widetilde{\nu}}$ <45
> 59	95	[308] BARATE	00P	ALEP	Repl. by HEISTER 02K
>120	95	[309] ABE	99M	CDF	$p\overline{p} \to \widetilde{t}_1\widetilde{t}_1$, $\not{R}$
none 61–91	95	[310] ABACHI	96B	D0	$\widetilde{t} \to c\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1}$ <30 GeV
none 9–24.4	95	[311] AID	96	H1	$ep \to \widetilde{t}\widetilde{t}$, $\not{R}$ decays

>138	95	[312] AID	96	H1	$ep \to \widetilde{t}$, $\not{R}$, $\lambda\cos\theta_t > 0.03$
> 45		[313] CHO	96	RVUE	B^0-$\overline{B}^0$ and ϵ, θ_t= 0.98, $\tan\beta$ <2
none 11–41	95	[314] BUSKULIC	95E	ALEP	$\not{R}$ ($LL\overline{E}$), θ_t=0.98
none 6.0–41.2	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, Δm >2 GeV
none 5.0–46.0	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, Δm >5 GeV
none 11.2–25.5	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0.98, Δm >2 GeV
none 7.9–41.2	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0.98, Δm >5 GeV
none 7.6–28.0	95	[315] SHIRAI	94	VNS	$\widetilde{t} \to c\widetilde{\chi}^0_1$, any θ_t, Δm >10 GeV
none 10–20	95	[315] SHIRAI	94	VNS	$\widetilde{t} \to c\widetilde{\chi}^0_1$, any θ_t, Δm > 2.5 GeV

[291] ACHARD 04 search in the 192–209 GeV data for the production of $\widetilde{t}\,\widetilde{t}$ in acoplanar di-jet final states and, in case of $b\ell\widetilde{\nu}$ ($b\tau\widetilde{\nu}$) final states, two leptons (taus). The limits for θ_t=0 improve to 95, 96 and 93 GeV, respectively. All limits assume 100% branching ratio for the respective decay modes. See Fig. 6 for the dependence of the limits on $m_{\widetilde{\chi}^0_1}$. These limits supersede ACCIARRI 99V.

[292] ABDALLAH 03M looked for $\widetilde{t}$ pair production in events with acoplanar jets and $\not{E}$ at $\sqrt{s}$ = 189–208 GeV. See Fig. 23 and Table 11 for other choices of Δm. These limits include and update the results of ABREU,P 00D.

[293] ACOSTA 03C searched in 107 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for pair production of $\widetilde{t}$ followed by the decay $\widetilde{t} \to b\ell\widetilde{\nu}$. They looked for events with two isolated leptons (e or μ), at least one jet and $\not{E}_T$. The excluded mass range is reduced for larger $m_{\widetilde{\nu}}$, and no limit is set for $m_{\widetilde{\nu}} > 88.4$ GeV (see Fig. 2).

[294] ABAZOV 02C looked in 108.3pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with $e\mu\not{E}_T$, originating from associated production $\widetilde{t}\,\widetilde{t}$. Branching ratios are assumed to be 100%. The bound for the $b\ell\widetilde{\nu}$ decay weakens for large $\widetilde{\nu}$ mass (see Fig. 3), and no limit is set when $m_{\widetilde{\nu}}$ >85 GeV. See Fig. 4 for the limits in case of decays to a real $\widetilde{\chi}^\pm_1$, followed by $\widetilde{\chi}^\pm_1 \to \ell\widetilde{\nu}$, as a function of $m_{\widetilde{\chi}^\pm_1}$.

[295] ABBIENDI 02H looked for events with two acoplanar jets, $\not{p}_T$, and, in the case of $b\ell\widetilde{\nu}$ final states, two leptons, in the 161–209 GeV data. The bound for $c\widetilde{\chi}^0_1$ applies to the region where $\Delta m < m_W + m_b$, else the decay $\widetilde{t}_1 \to b\widetilde{\chi}^0_1 W^+$ becomes dominant. The limit for $b\ell\widetilde{\nu}$ assumes equal branching ratios for the three lepton flavors and for $b\tau\widetilde{\nu}$ 100% for this channel. For θ_t=0, the bounds improve to > 97.6 GeV ($c\widetilde{\chi}^0_1$), > 96.0 GeV ($b\ell\widetilde{\nu}$), and > 95.5 ($b\tau\widetilde{\nu}$). See Figs. 5–6 and Table 5 for the more general dependence of the limits on Δm. These results supersede ABBIENDI 99M.

[296] HEISTER 02K search for top squarks in final states with jets (with/without b tagging or leptons) or long-lived hadrons, using 183–209 GeV data. The absolute mass bound is obtained by varying the branching ratio of $\widetilde{t} \to c\widetilde{\chi}^0_1$ and the lepton fraction in $\widetilde{t} \to b\widetilde{\chi}^0_1 f\overline{f}'$ decays. The mass bound for $\widetilde{t} \to c\widetilde{\chi}^0_1$ uses the CDF results from AFFOLDER 00D and for $\widetilde{t} \to b\ell\widetilde{\nu}$ the DØ results from ABAZOV 02C. See Figs. 2–5 for the more general dependence of the limits on Δm. Updates BARATE 01 and BARATE 00P.

[297] ABDALLAH 03C looked for events of the type $q\bar{q}R^\pm R^\pm$, $q\bar{q}R^\pm R^0$ or $q\bar{q}R^0 R^0$ in e^+e^- interactions at $\sqrt{s}$ = 189 − 208 GeV. The $R^\pm$ bound states are identified by anomalous dE/dx in the tracking chambers and the R^0 by missing energy, due to their reduced energy loss in the calorimeters. Excluded mass regions in the $(m(\tilde{t}), m(\tilde{g}))$ plane for $m(\tilde{g}) > 2$ GeV are obtained for several values of the probability for the gluino to fragment into $R^\pm$ or R^0, as shown in their Fig. 18. The limit improves to 90 GeV for $\theta_t = 0$.

[298] Theoretical analysis of e^+e^-+2 jet final states from the RPV decay of $\widetilde{t}\widetilde{t}^*$ pairs produced in $p\overline{p}$ collisions at $\sqrt{S}=1.8$ TeV. 95%CL limits of 220 (165) GeV are derived for B($\widetilde{t}\to eq$)=1 (0.5).

[299] HEISTER 03G searches for the production of $\widetilde{t}$ pairs in the case of $\not{R}$ prompt decays with $LL\overline{E}$, $LQ\overline{D}$ or $\overline{UDD}$ couplings at $\sqrt{s}=$ 189–209 GeV. The limit holds for indirect decays mediated by $\not{R}$ $\overline{UDD}$ couplings. It improves to 91 GeV for indirect decays mediated by $\not{R}$ $LL\overline{E}$ couplings, to 97 GeV for direct (assuming B($\widetilde{t}_L\to q\tau$) = 100%) and to 85 GeV for indirect decays mediated by $\not{R}$ $LQ\overline{D}$ couplings. Supersedes the results from BARATE 01B.

[300] HEISTER 03H use e^+e^- data from 183–208 GeV to look for the production of stop decaying into a c quark and a stable gluino hadronizing into charged or neutral R-hadrons. Combining these results with bounds on stable squarks and on a stable gluino LSP from the same paper yields the quoted limit. See their Fig. 13 for the dependence of the mass limit on the gluino mass and on θ_t.

[301] ACHARD 02 searches for the production of squarks in the case of $\not{R}$ prompt decays with $\overline{UDD}$ couplings at $\sqrt{s}$=189–208 GeV. The search is performed for direct and indirect decays, assuming one coupling at the time to be nonzero. The limit is computed for the minimal cross section and holds for both direct and indirect decays.

[302] ABREU 01D searches for multi-jet events, expected in the case of prompt decays from $\not{R}$ $\overline{UDD}$ couplings and indirect decays, using data from $\sqrt{s}$=189 GeV. Limits are obtained in the plane of the squark mass versus $m_{\widetilde{\chi}^0_1}$. The mass limit is derived using the constraint on the neutralino mass from the same paper (see the section on unstable $\widetilde{\chi}^0_1$). See Fig. 9 for other choices of Δm.

[303] AFFOLDER 01B searches for decays of the top quark into stop and LSP, in $t\overline{t}$ events. Limits on the stop mass as a function of the LSP mass and of the decay branching ratio are shown in Fig. 3. They exclude branching ratios in excess of 45% for SLP masses up to 40 GeV.

[304] ABBIENDI 00 searches for the production of stop in the case of R-parity violation with $\overline{UDD}$ or $LQ\overline{D}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons, jets plus leptons, or multiple jets, assuming one coupling at the time to be non-zero. For mass exclusion limits relative to $LQ\overline{D}$-induced decays, see their Table 5.

[305] ABREU 00I searches for the production of stop in the case of R-parity violation with $LL\overline{E}$ couplings, for which only indirect decays are allowed. They investigate topologies with jets plus leptons in data from $\sqrt{s}$=183 GeV. The lower bound on the stop mass assumes a neutralino mass limit of 27 GeV, also derived in ABREU 00I.

[306] AFFOLDER 00D search for final states with 2 or 3 jets and $\not{E}_T$, one jet with a c tag. See their Fig. 2 for the mass exclusion in the ($m_{\widetilde{t}}$,$m_{\widetilde{\chi}^0_1}$) plane. The maximum excluded $m_{\widetilde{t}}$ value is 119 GeV, for $m_{\widetilde{\chi}^0_1}$= 40 GeV.

[307] AFFOLDER 00G searches for $\widetilde{t}_1\widetilde{t}^*_1$ production, with $\widetilde{t}_1\to b\ell\widetilde{\nu}$, leading to topologies with ≥ 1 isolated lepton (e or μ), $\not{E}_T$, and ≥ 2 jets with ≥ 1 tagged as b quark by a secondary vertex. See Fig. 4 for the excluded mass range as a function of $m_{\widetilde{\nu}}$. Cross-section limits for $\widetilde{t}_1\widetilde{t}^*_1$, with $\widetilde{t}_1\to b\chi^\pm_1$ ($\chi^\pm_1\to\ell^\pm\nu\widetilde{\chi}^0_1$), are given in Fig. 2.

[308] BARATE 00P use data from $\sqrt{s}$= 189–202 GeV to explore the region of small mass difference between the stop and the neutralino by searching heavy stable charged particles or tracks with large impact parameters. For prompt decays, they make use of acoplanar jets from BARATE 99Q, updated up to 202 GeV. The limit is reached for Δm=1.6 GeV and a decay length of 1 cm. If the MSSM relation between the decay width and Δm is used, the limit improves to 63 GeV. It is set for Δm=1.9 GeV. tanβ=2.6, and $\theta_{\widetilde{t}}$=0.98, and large negative μ.

[309] ABE 99M looked in 107 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with like sign dielectrons and two or more jets from the sequential decays $\widetilde{q}\to q\widetilde{\chi}^0_1$ and $\widetilde{\chi}^0_1\to eq\overline{q}'$, assuming $\not{R}$ coupling $L_1Q_jD^c_k$, with j=2,3 and k=1,2,3. They assume B($\widetilde{t}_1\to c\widetilde{\chi}^0_1$)=1,

B($\widetilde{\chi}_1^0 \rightarrow e q \overline{q}'$)=0.25 for both e^+ and e^-, and $m_{\widetilde{\chi}_1^0} \geq m_{\widetilde{t}_1}/2$. The limit improves for heavier $\widetilde{\chi}_1^0$.

[310] ABACHI 96B searches for final states with 2 jets and missing E_T. Limits on $m_{\widetilde{t}}$ are given as a function of $m_{\widetilde{\chi}_1^0}$. See Fig. 4 for details.

[311] AID 96 considers photoproduction of $\widetilde{t}\widetilde{t}$ pairs, with 100% R-parity violating decays of $\widetilde{t}$ to $e q$, with q=d, s, or b quarks.

[312] AID 96 considers production and decay of $\widetilde{t}$ via the R-parity violating coupling $\lambda' L_1 Q_3 d_1^c$.

[313] CHO 96 studied the consistency among the B^0-$\overline{B}^0$ mixing, ϵ in K^0-$\overline{K}^0$ mixing, and the measurements of V_{cb}, V_{ub}/V_{cb}. For the range 25.5 GeV$<m_{\widetilde{t}_1}<m_Z/2$ left by AKERS 94K for $\theta_t = 0.98$, and within the allowed range in M_2-μ parameter space from chargino, neutralino searches by ACCIARRI 95E, they found the scalar top contribution to B^0-$\overline{B}^0$ mixing and ϵ to be too large if tanβ <2. For more on their assumptions, see the paper and their reference 10.

[314] BUSKULIC 95E looked for $Z \rightarrow \widetilde{t}\overline{\widetilde{t}}$, where $\widetilde{t} \rightarrow c\chi_1^0$ and χ_1^0 decays via R-parity violating interactions into two leptons and a neutrino.

[315] SHIRAI 94 bound assumes the cross section without the s-channel Z-exchange and the QCD correction, underestimating the cross section up to 20% and 30%, respectively. They assume m_c=1.5 GeV.

Heavy $\widetilde{g}$ (Gluino) MASS LIMIT

For $m_{\widetilde{g}} > 60$–70 GeV, it is expected that gluinos would undergo a cascade decay via a number of neutralinos and/or charginos rather than undergo a direct decay to photinos as assumed by some papers. Limits obtained when direct decay is assumed are usually higher than limits when cascade decays are included. Limits made obsolete by the most recent analyses of $p\overline{p}$ collisions can be found in previous Editions of this *Review*.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>195	95	[316] AFFOLDER	02	CDF	Jets+$\not{E}_T$, any $m_{\widetilde{q}}$
>300	95	[316] AFFOLDER	02	CDF	Jets+$\not{E}_T$, $m_{\widetilde{q}}$=$m_{\widetilde{g}}$
>129	95	[317] ABBOTT	01D	D0	$\ell\ell$+jets+$\not{E}_T$, tan$\beta < 10$, $m_0 <$ 300 GeV, $\mu < 0$, A_0=0
>175	95	[317] ABBOTT	01D	D0	$\ell\ell$+jets+$\not{E}_T$, tanβ=2, large m_0, $\mu < 0$, A_0=0
>255	95	[317] ABBOTT	01D	D0	$\ell\ell$+jets+$\not{E}_T$, tanβ=2, $m_{\widetilde{g}}$=$m_{\widetilde{q}}$, $\mu < 0$, A_0=0
>168	95	[318] AFFOLDER	01J	CDF	$\ell\ell$+Jets+$\not{E}_T$, tanβ=2, μ=−800 GeV, $m_{\widetilde{q}} \gg m_{\widetilde{g}}$
>221	95	[318] AFFOLDER	01J	CDF	$\ell\ell$+Jets+$\not{E}_T$, tanβ=2, μ=−800 GeV, $m_{\widetilde{q}}$=$m_{\widetilde{g}}$
>190	95	[319] ABBOTT	99L	D0	Jets+$\not{E}_T$, tanβ=2, μ <0, A=0
>260	95	[319] ABBOTT	99L	D0	Jets+$\not{E}_T$, $m_{\widetilde{g}}$=$m_{\widetilde{q}}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>224	95	[320] ABAZOV	02F	D0	$\not{R}$ λ'_{2jk} indirect decays, tanβ=2, any $m_{\widetilde{q}}$
>265	95	[320] ABAZOV	02F	D0	$\not{R}$ λ'_{2jk} indirect decays, tanβ=2, $m_{\widetilde{q}}$=$m_{\widetilde{g}}$

		[321] ABAZOV	02G	D0	$p\overline{p} \rightarrow \widetilde{g}\widetilde{g}, \widetilde{g}\widetilde{q}$
		[322] CHEUNG	02B	THEO	
		[323] BERGER	01	THEO	$p\overline{p} \rightarrow$ X+b-quark
>240	95	[324] ABBOTT	99	D0	$\widetilde{g} \rightarrow \widetilde{\chi}^0_2 X \rightarrow \widetilde{\chi}^0_1 \gamma X$, $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} > 20$ GeV
>320	95	[324] ABBOTT	99	D0	$\widetilde{g} \rightarrow \widetilde{\chi}^0_1 X \rightarrow \widetilde{G}\gamma X$
>227	95	[325] ABBOTT	99K	D0	any $m_{\widetilde{q}}$, $\not{R}$, tanβ=2, $\mu < 0$
>212	95	[326] ABACHI	95C	D0	$m_{\widetilde{g}} \geq m_{\widetilde{q}}$; with cascade decays
>144	95	[326] ABACHI	95C	D0	Any $m_{\widetilde{q}}$; with cascade decays
		[327] ABE	95T	CDF	$\widetilde{g} \rightarrow \widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 \gamma$
		[328] HEBBEKER	93	RVUE	e^+e^- jet analyses
>218	90	[329] ABE	92L	CDF	$m_{\widetilde{q}} \leq m_{\widetilde{g}}$; with cascade decay
>100		[330] ROY	92	RVUE	$p\overline{p} \rightarrow \widetilde{g}\widetilde{g}$; $\not{R}$
		[331] NOJIRI	91	COSM	
none 4–53	90	[332] ALBAJAR	87D	UA1	Any $m_{\widetilde{q}} > m_{\widetilde{g}}$
none 4–75	90	[332] ALBAJAR	87D	UA1	$m_{\widetilde{q}} = m_{\widetilde{g}}$
none 16–58	90	[333] ANSARI	87D	UA2	$m_{\widetilde{q}} \lesssim 100$ GeV

[316] AFFOLDER 02 searched in $\sim$ 84 pb^{-1} of $p\overline{p}$ collisions for events with $\geq$ 3 jets and $\not{E}_T$, arising from the production of gluinos and/or squarks. Limits are derived by scanning the parameter space, for $m_{\widetilde{q}} \geq m_{\widetilde{g}}$ in the framework of minimal Supergravity, assuming five flavors of degenerate squarks, and for $m_{\widetilde{q}} < m_{\widetilde{g}}$ in the framework of constrained MSSM, assuming conservatively four flavors of degenerate squarks. See Fig. 3 for the variation of the limit as function of the squark mass. Supersedes the results of ABE 97K.

[317] ABBOTT 01D looked in $\sim$ 108 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with ee, $\mu\mu$, or $e\mu$ accompanied by at least 2 jets and $\not{E}_T$. Excluded regions are obtained in the MSUGRA framework from a scan over the parameters $0 < m_0 < 300$ GeV, $10 < m_{1/2} < 110$ GeV, and $1.2 < \tan\beta < 10$.

[318] AFFOLDER 01J searched in $\sim$ 106 pb^{-1} of $p\overline{p}$ collisions for events with 2 like-sign leptons (e or μ), $\geq$ 2 jets and $\not{E}_T$, expected to arise from the production of gluinos and/or squarks with cascade decays into $\widetilde{\chi}^{\pm}$ or $\widetilde{\chi}^0_2$. Spectra and decay rates are evaluated in the framework of minimal Supergravity, assuming five flavors of degenerate squarks and a pseudoscalar Higgs mass m_A=500 GeV. The limits are derived for tanβ=2, μ=$-$800 GeV, and scanning over $m_{\widetilde{g}}$ and $m_{\widetilde{q}}$. See Fig. 2 for the variation of the limit as function of the squark mass. These limits supersede the results of ABE 96D.

[319] ABBOTT 99L consider events with three or more jets and large $\not{E}_T$. Spectra and decay rates are evaluated in the framework of minimal Supergravity, assuming five flavors of degenerate squarks, and scanning the space of the universal gaugino ($m_{1/2}$) and scalar (m_0) masses See their Figs. 2–3 for the dependence of the limit on the relative value of $m_{\widetilde{q}}$ and $m_{\widetilde{g}}$.

[320] ABAZOV 02F looked in 77.5 pb^{-1} of $p\overline{p}$ collisions at 1.8 TeV for events with $\geq 2\mu + \geq$ 4jets, originating from associated production of squarks followed by an indirect $\not{R}$ decay (of the $\widetilde{\chi}^0_1$) via $LQ\overline{D}$ couplings of the type λ'_{2jk} where j=1,2 and k=1,2,3. Bounds are obtained in the MSUGRA scenario by a scan in the range $0 \leq M_0 \leq 400$ GeV, $60 \leq m_{1/2} \leq 120$ GeV for fixed values A_0=0, μ <0, and tanβ=2 or 6. The bounds are weaker for tanβ=6. See Figs. 2,3 for the exclusion contours in $m_{1/2}$ versus m_0 for tanβ=2 and 6, respectively.

[321] ABAZOV 02G search for associated production of gluinos and squarks in 92.7 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV, using events with one electron, $\geq$ 4 jets, and large $\not{E}_T$. The results are compared to a MSUGRA scenario with $\mu<0$, A_0=0, and tanβ=3 and allow to exclude a region of the $(m_0,m_{1/2})$ shown in Fig. 11.

[322] CHEUNG 02B studies the constraints on a $\widetilde{b}_1$ with mass in the 2.2–5.5 GeV region and a gluino in the mass range 12–16 GeV, using precision measurements of Z^0 decays and e^+e^- annihilations at LEP2. Few detectable events are predicted in the LEP2 data for the model proposed by BERGER 01.

[323] BERGER 01 reanalyzed interpretation of Tevatron data on bottom-quark production. Argues that pair production of light gluinos ($m\sim$ 12–16 GeV) with subsequent 2-body decay into a light sbottom ($m\sim$ 2–5.5 GeV) and bottom can reconcile Tevatron data with predictions of perturbative QCD for the bottom production rate. The sbottom must either decay hadronically via a R-parity- and B-violating interaction, or be long-lived.

[324] ABBOTT 99 searched for $\gamma\not{E}_T+\ \geq$ 2 jet final states, and set limits on $\sigma(p\overline{p}\rightarrow \widetilde{g}+X)\cdot B(\widetilde{g}\rightarrow\ \gamma\not{E}_T X)$. The quoted limits correspond to $m_{\widetilde{q}}\geq m_{\widetilde{g}}$, with $B(\widetilde{\chi}^0_2\rightarrow\widetilde{\chi}^0_1\gamma)$=1 and $B(\widetilde{\chi}^0_1\rightarrow\ \widetilde{G}\gamma)$=1, respectively. They improve to 310 GeV (360 GeV in the case of $\gamma\widetilde{G}$ decay) for $m_{\widetilde{g}}=m_{\widetilde{q}}$.

[325] ABBOTT 99K uses events with an electron pair and four jets to search for the decay of the $\widetilde{\chi}^0_1$ LSP via $\not{R}$ $LQ\overline{D}$ couplings. The particle spectrum and decay branching ratios are taken in the framework of minimal supergravity. An excluded region at 95% CL is obtained in the $(m_0,m_{1/2})$ plane under the assumption that A_0=0, $\mu<0$, tanβ=2 and any one of the couplings $\lambda'_{1jk}>10^{-3}$ (j=1,2 and k=1,2,3) and from which the above limit is computed. For equal mass squarks and gluinos, the corresponding limit is 277 GeV. The results are essentially independent of A_0, but the limit deteriorates rapidly with increasing tanβ or $\mu>0$.

[326] ABACHI 95C assume five degenerate squark flavors with with $m_{\widetilde{q}_L}=m_{\widetilde{q}_R}$. Sleptons are assumed to be heavier than squarks. The limits are derived for fixed tanβ = 2.0 $\mu=-250$ GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space.

[327] ABE 95T looked for a cascade decay of gluino into $\widetilde{\chi}^0_2$ which further decays into $\widetilde{\chi}^0_1$ and a photon. No signal is observed. Limits vary widely depending on the choice of parameters. For $\mu=-40$ GeV, tanβ = 1.5, and heavy squarks, the range 50$<m_{\widetilde{g}}$ (GeV)$<$140 is excluded at 90% CL. See the paper for details.

[328] HEBBEKER 93 combined jet analyses at various e^+e^- colliders. The 4-jet analyses at TRISTAN/LEP and the measured α_s at PEP/PETRA/TRISTAN/LEP are used. A constraint on effective number of quarks N=6.3 $\pm$ 1.1 is obtained, which is compared to that with a light gluino, N=8.

[329] ABE 92L bounds are based on similar assumptions as ABACHI 95C. Not sensitive to m_{gluino} $<$40 GeV (but other experiments rule out that region).

[330] ROY 92 reanalyzed CDF limits on di-lepton events to obtain limits on gluino production in R-parity violating models. The 100% decay $\widetilde{g}\rightarrow\ q\overline{q}\widetilde{\chi}$ where $\widetilde{\chi}$ is the LSP, and the LSP decays either into $\ell q\overline{d}$ or $\ell\ell\overline{e}$ is assumed.

[331] NOJIRI 91 argues that a heavy gluino should be nearly degenerate with squarks in minimal supergravity not to overclose the universe.

[332] The limits of ALBAJAR 87D are from $p\overline{p}\rightarrow\ \widetilde{g}\widetilde{g}X$ ($\widetilde{g}\rightarrow\ q\overline{q}\widetilde{\gamma}$) and assume $m_{\widetilde{q}}>m_{\widetilde{g}}$. These limits apply for $m_{\widetilde{\gamma}}\lesssim$ 20 GeV and $\tau(\widetilde{g})<\ 10^{-10}$ s.

[333] The limit of ANSARI 87D assumes $m_{\widetilde{q}}>m_{\widetilde{g}}$ and $m_{\widetilde{\gamma}}\approx$ 0.

Long-lived/light $\widetilde{g}$ (Gluino) MASS LIMIT

Limits on light gluinos ($m_{\widetilde{g}} < 5$ GeV), or gluinos which leave the detector before decaying.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 2–18	95	[334] ABDALLAH	03C	DLPH	$e^+e^- \rightarrow q\overline{q}\widetilde{g}\widetilde{g}$, stable $\widetilde{g}$
>5		[335] ABDALLAH	03G	DLPH	QCD beta function
		[336] HEISTER	03	ALEP	Color factors
>26.9	95	[337] HEISTER	03H	ALEP	$e^+e^- \rightarrow q\overline{q}\widetilde{g}\widetilde{g}$
>6.3		[338] JANOT	03	RVUE	$\Delta\Gamma_{had}$ <3.9 MeV
		[339] MAFI	00	THEO	$pp \rightarrow$ jets + $\not{p}_T$
		[340] ALAVI-HARATI	99E	KTEV	$pN \rightarrow R^0$, with $R^0 \rightarrow \rho^0\widetilde{\gamma}$ and $R^0 \rightarrow \pi^0\widetilde{\gamma}$
		[341] BAER	99	RVUE	Stable $\widetilde{g}$ hadrons
		[342] FANTI	99	NA48	pBe $\rightarrow R^0 \rightarrow \eta\widetilde{\gamma}$
		[343] ACKERSTAFF	98V	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^+_1\widetilde{\chi}^-_1$
		[344] ADAMS	97B	KTEV	$pN \rightarrow R^0 \rightarrow \rho^0\widetilde{\gamma}$
		[345] ALBUQUERQ...	97	E761	$R^+(uud\widetilde{g}) \rightarrow S^0(uds\widetilde{g})\pi^+$, $X^-(ssd\widetilde{g}) \rightarrow S^0\pi^-$
>6.3	95	[346] BARATE	97L	ALEP	Color factors
>5	99	[347] CSIKOR	97	RVUE	β function, $Z \rightarrow$ jets
>1.5	90	[348] DEGOUVEA	97	THEO	$Z \rightarrow jjjj$
		[349] FARRAR	96	RVUE	$R^0 \rightarrow \pi^0\widetilde{\gamma}$
none 1.9–13.6	95	[350] AKERS	95R	OPAL	Z decay into a long-lived $(\widetilde{g}q\overline{q})^\pm$
<0.7		[351] CLAVELLI	95	RVUE	quarkonia
none 1.5–3.5		[352] CAKIR	94	RVUE	$\Upsilon(1S) \rightarrow \gamma+$ gluinonium
not 3–5		[353] LOPEZ	93C	RVUE	LEP
≈ 4		[354] CLAVELLI	92	RVUE	α_s running
		[355] ANTONIADIS	91	RVUE	α_s running
>1		[356] ANTONIADIS	91	RVUE	$pN \rightarrow$ missing energy
		[357] NAKAMURA	89	SPEC	R-Δ^{++}
>3.8	90	[358] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^1$
>3.2	90	[358] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^{0.72}$
none 0.6–2.2	90	[359] TUTS	87	CUSB	$\Upsilon(1S) \rightarrow \gamma+$ gluinonium
none 1 –4.5	90	[360] ALBRECHT	86C	ARG	$1\times10^{-11} \lesssim \tau \lesssim 1\times10^{-9}$s
none 1–4	90	[361] BADIER	86	BDMP	$1\times10^{-10} < \tau < 1\times10^{-7}$s
none 3–5		[362] BARNETT	86	RVUE	$p\overline{p} \rightarrow$ gluino gluino gluon
none		[363] VOLOSHIN	86	RVUE	If (quasi) stable; $\widetilde{g}uud$
none 0.5–2		[364] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$=300 GeV
none 0.5–4		[364] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$ <65 GeV
none 0.5–3		[364] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$=150 GeV
none 2–4		[365] DAWSON	85	RVUE	$\tau > 10^{-7}$ s
none 1–2.5		[365] DAWSON	85	RVUE	For $m_{\widetilde{q}}$=100 GeV
none 0.5–4.1	90	[366] FARRAR	85	RVUE	FNAL beam dump
>1		[367] GOLDMAN	85	RVUE	Gluononium
>1–2		[368] HABER	85	RVUE	
		[369] BALL	84	CALO	

	[370] BRICK	84	RVUE	
	[371] FARRAR	84	RVUE	
> 2	[372] BERGSMA	83C	RVUE	For $m_{\widetilde{q}}$ <100 GeV
	[373] CHANOWITZ	83	RVUE	$\widetilde{g}\,u\,\overline{d}$, $\widetilde{g}\,u\,u\,d$
>2–3	[374] KANE	82	RVUE	Beam dump
>1.5–2	FARRAR	78	RVUE	*R*-hadron

[334] ABDALLAH 03C looked for events of the type $q\bar{q}R^{\pm}R^{\pm}$, $q\bar{q}R^{\pm}R^{0}$ or $q\bar{q}R^{0}R^{0}$ in $e^{+}e^{-}$ interactions at 91.2 GeV collected in 1994. The $R^{\pm}$ bound states are identified by anomalous dE/dx in the tracking chambers and the R^{0} by missing energy, due to their reduced energy loss in the calorimeters. The upper value of the excluded range depends on the probability for the gluino to fragment into $R^{\pm}$ or R^{0}, see their Fig. 17. It improves to 23 GeV for 100% fragmentation to $R^{\pm}$.

[335] ABDALLAH 03G used $e^{+}e^{-}$ data at and around the Z^{0} peak, above the Z^{0} up to $\sqrt{s}=$ 202 GeV and events from radiative return to cover the low energy region. They perform a direct measurement of the QCD beta-function from the means of fully inclusive event observables. Compared to the energy range, gluinos below 5 GeV can be considered massless and are firmly excluded by the measurement.

[336] HEISTER 03 use $e^{+}e^{-}$ data from 1994 and 1995 at and around the Z^{0} peak to measure the 4-jet rate and angular correlations. The comparison with QCD NLO calculations allow $\alpha_{S}(M_{Z})$ and the color factor ratios to be extracted and the results are in agreement with the expectations from QCD. The inclusion of a massless gluino in the beta functions yields $T_{R}/C_{F}=0.15\pm0.06\pm0.06$ (expectation is $T_{R}/C_{F}=3/8$), excluding a massless gluino at more than 95% CL. As no NLO calculations are available for massive gluinos, the earlier LO results from BARATE 97L for massive gluinos remain valid.

[337] HEISTER 03H use $e^{+}e^{-}$ data at and around the Z^{0} peak to look for stable gluinos hadronizing into charged or neutral R-hadrons with arbitrary branching ratios. Combining these results with bounds on the Z^{0} hadronic width from electroweak measurements (JANOT 03) to cover the low mass region the quoted lower limit on the mass of a long-lived gluino is obtained.

[338] JANOT 03 excludes a light gluino from the upper limit on an additional contribution to the *Z* hadronic width. At higher confidence levels, $m_{\widetilde{g}} > 5.3(4.2)$ GeV at $3\sigma(5\sigma)$ level.

[339] MAFI 00 reanalyzed CDF data assuming a stable heavy gluino as the LSP, with model for *R*-hadron-nucleon scattering. Gluino masses between 35 GeV and 115 GeV are excluded based on the CDF Run I data. Combined with the analysis of BAER 99, this allows a LSP gluino mass between 25 and 35 GeV if the probability of fragmentation into charged *R*-hadron *P*>1/2. The cosmological exclusion of such a gluino LSP are assumed to be avoided as in BAER 99. Gluino could be NLSP with $\tau_{\widetilde{g}} \sim 100$ yrs, and decay to gluon gravitino.

[340] ALAVI-HARATI 99E looked for R^0 bound states, yielding $\pi^{+}\pi^{-}$ or π^{0} in the final state. The experiment is sensitive to values of $\Delta m = m_{R^0} - m_{\widetilde{\gamma}}$ larger than 280 MeV and 140 MeV for the two decay modes, respectively, and to R^0 mass and lifetime in the ranges 0.8–5 GeV and 10^{-10}–10^{-3} s. The limits obtained depend on B($R^0 \rightarrow \pi^{+}\pi^{-}$ photino) and B($R^0 \rightarrow \pi^{0}$ photino) on the value of $m_{R^0}/m_{\widetilde{\gamma}}$, and on the ratio of production rates $\sigma(R^0)/\sigma(K^0_L)$. See Figures in the paper for the excluded R^0 production rates as a function of Δm, R^0 mass and lifetime. Using the production rates expected from perturbative QCD, and assuming dominance of the above decay channels over the suitable phase space, R^0 masses in the range 0.8–5 GeV are excluded at 90%CL for a large fraction of the sensitive lifetime region. ALAVI-HARATI 99E updates and supersedes the results of ADAMS 97B.

[341] BAER 99 set constraints on the existence of stable $\widetilde{g}$ hadrons, in the mass range $m_{\widetilde{g}} > 3$ GeV. They argue that strong-interaction effects in the low-energy annihilation rates could leave small enough relic densities to evade cosmological constraints up to $m_{\widetilde{g}} < 10$ TeV. They consider jet+$\not{E}_T$ as well as heavy-ionizing charged-particle signatures from

production of stable $\widetilde{g}$ hadrons at LEP and Tevatron, developing modes for the energy loss of $\widetilde{g}$ hadrons inside the detectors. Results are obtained as a function of the fragmentation probability P of the $\widetilde{g}$ into a charged hadron. For $P< 1/2$, and for various energy-loss models, OPAL and CDF data exclude gluinos in the $3 < m_{\widetilde{g}}(\text{GeV}) < 130$ mass range. For $P> 1/2$, gluinos are excluded in the mass ranges $3 < m_{\widetilde{g}}(\text{GeV}) < 23$ and $50 < m_{\widetilde{g}}(\text{GeV}) < 200$.

342 FANTI 99 looked for R^0 bound states yielding high P_T $\eta \rightarrow 3\pi^0$ decays. The experiment is sensitive to a region of R^0 mass and lifetime in the ranges of 1–5 GeV and 10^{-10}–10^{-3} s. The limits obtained depend on B($R^0 \rightarrow \eta\widetilde{\gamma}$), on the value of $m_{R^0}/m_{\widetilde{\gamma}}$, and on the ratio of production rates $\sigma(R^0)/\sigma(K^0_L)$. See Fig. 6–7 for the excluded production rates as a function of R^0 mass and lifetime.

343 ACKERSTAFF 98V excludes the light gluino with universal gaugino mass where charginos, neutralinos decay as $\widetilde{\chi}^{\pm}_1,\widetilde{\chi}^0_2 \rightarrow q\overline{q}\widetilde{g}$ from total hadronic cross sections at $\sqrt{s}$=130–172 GeV. See paper for the case of nonuniversal gaugino mass.

344 ADAMS 97B looked for $\rho^0 \rightarrow \pi^+\pi^-$ as a signature of R^0=($\widetilde{g}g$) bound states. The experiment is sensitive to an R^0 mass range of 1.2–4.5 GeV and to a lifetime range of 10^{-10}–10^{-3} sec. Precise limits depend on the assumed value of $m_{R^0}/m_{\widetilde{\gamma}}$. See Fig. 7 for the excluded mass and lifetime region.

345 ALBUQUERQUE 97 looked for weakly decaying baryon-like states which contain a light gluino, following the suggestions in FARRAR 96. See their Table 1 for limits on the production fraction. These limits exclude gluino masses in the range 100–600 MeV for the predicted lifetimes (FARRAR 96) and production rates, which are assumed to be comparable to those of strange or charmed baryons.

346 BARATE 97L studied the QCD color factors from four-jet angular correlations and the differential two-jet rate in Z decay. Limit obtained from the determination of $n_f = 4.24 \pm 0.29 \pm 1.15$, assuming T_F/C_F=3/8 and C_A/C_F=9/4.

347 CSIKOR 97 combined the α_s from $\sigma(e^+e^- \rightarrow$ hadron), τ decay, and jet analysis in Z decay. They exclude a light gluino below 5 GeV at more than 99.7%CL.

348 DEGOUVEA 97 reanalyzed AKERS 95A data on Z decay into four jets to place constraints on a light stable gluino. The mass limit corresponds to the pole mass of 2.8 GeV. The analysis, however, is limited to the leading-order QCD calculation.

349 FARRAR 96 studied the possible R^0=($\widetilde{g}g$) component in Fermilab E799 experiment and used its bound B($K^0_L \rightarrow \pi^0\nu\overline{\nu}$) $\leq 5.8\times10^{-5}$ to place constraints on the combination of R^0 production cross section and its lifetime.

350 AKERS 95R looked for Z decay into $q\overline{q}\widetilde{g}\widetilde{g}$, by searching for charged particles with dE/dx consistent with $\widetilde{g}$ fragmentation into a state $(\widetilde{g}q\overline{q})^{\pm}$ with lifetime $\tau > 10^{-7}$ sec. The fragmentation probability into a charged state is assumed to be 25%.

351 CLAVELLI 95 updates the analysis of CLAVELLI 93, based on a comparison of the hadronic widths of charmonium and bottomonium S-wave states. The analysis includes a parametrization of relativisitic corrections. Claims that the presence of a light gluino improves agreement with the data by slowing down the running of α_s.

352 CAKIR 94 reanalyzed TUTS 87 and later unpublished data from CUSB to exclude pseudo-scalar gluinonium $\eta_{\widetilde{g}}(\widetilde{g}\widetilde{g})$ of mass below 7 GeV. it was argued, however, that the perturbative QCD calculation of the branching fraction $\Upsilon \rightarrow \eta_{\widetilde{g}}\gamma$ is unreliable for $m_{\eta_{\widetilde{g}}} < 3$ GeV. The gluino mass is defined by $m_{\widetilde{g}}=(m_{\eta_{\widetilde{q}}})/2$. The limit holds for any gluino lifetime.

353 LOPEZ 93C uses combined restraint from the radiative symmetry breaking scenario within the minimal supergravity model, and the LEP bounds on the (M_2,μ) plane. Claims that the light gluino window is strongly disfavored.

354 CLAVELLI 92 claims that a light gluino mass around 4 GeV should exist to explain the discrepancy between α_s at LEP and at quarkonia (Υ), since a light gluino slows the running of the QCD coupling.

[355] ANTONIADIS 91 argue that possible light gluinos (< 5 GeV) contradict the observed running of α_s between 5 GeV and m_Z. The significance is less than 2 s.d.

[356] ANTONIADIS 91 interpret the search for missing energy events in 450 GeV/c pN collisions, AKESSON 91, in terms of light gluinos.

[357] NAKAMURA 89 searched for a long-lived ($\tau \gtrsim 10^{-7}$ s) charge-(± 2) particle with mass $\lesssim$ 1.6 GeV in proton-Pt interactions at 12 GeV and found that the yield is less than 10^{-8} times that of the pion. This excludes R-Δ^{++} (a $\tilde{g}uuu$ state) lighter than 1.6 GeV.

[358] The limits assume $m_{\tilde{q}} = 100$ GeV. See their figure 3 for limits vs. $m_{\tilde{q}}$.

[359] The gluino mass is defined by half the bound $\tilde{g}\tilde{g}$ mass. If zero gluino mass gives a $\tilde{g}\tilde{g}$ of mass about 1 GeV as suggested by various glueball mass estimates, then the low-mass bound can be replaced by zero. The high-mass bound is obtained by comparing the data with nonrelativistic potential-model estimates.

[360] ALBRECHT 86C search for secondary decay vertices from $\chi_{b1}(1P) \rightarrow \tilde{g}\tilde{g}g$ where $\tilde{g}$'s make long-lived hadrons. See their figure 4 for excluded region in the $m_{\tilde{g}} - m_{\tilde{g}}$ and $m_{\tilde{g}} - m_{\tilde{q}}$ plane. The lower $m_{\tilde{g}}$ region below ~ 2 GeV may be sensitive to fragmentation effects. Remark that the $\tilde{g}$-hadron mass is expected to be ~ 1 GeV (glueball mass) in the zero $\tilde{g}$ mass limit.

[361] BADIER 86 looked for secondary decay vertices from long-lived $\tilde{g}$-hadrons produced at 300 GeV π^- beam dump. The quoted bound assumes $\tilde{g}$-hadron nucleon total cross section of 10μb. See their figure 7 for excluded region in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane for several assumed total cross-section values.

[362] BARNETT 86 rule out light gluinos (m = 3–5 GeV) by calculating the monojet rate from gluino gluino gluon events (and from gluino gluino events) and by using UA1 data from $p\overline{p}$ collisions at CERN.

[363] VOLOSHIN 86 rules out stable gluino based on the cosmological argument that predicts too much hydrogen consisting of the charged stable hadron $\tilde{g}uud$. Quasi-stable ($\tau > 1. \times 10^{-7}$s) light gluino of $m_{\tilde{g}}$ <3 GeV is also ruled out by nonobservation of the stable charged particles, $\tilde{g}uud$, in high energy hadron collisions.

[364] COOPER-SARKAR 85B is BEBC beam-dump. Gluinos decaying in dump would yield $\tilde{\gamma}$'s in the detector giving neutral-current-like interactions. For $m_{\tilde{q}}$ >330 GeV, no limit is set.

[365] DAWSON 85 first limit from neutral particle search. Second limit based on FNAL beam dump experiment.

[366] FARRAR 85 points out that BALL 84 analysis applies only if the $\tilde{g}$'s decay before interacting, i.e. $m_{\tilde{q}} < 80 m_{\tilde{g}}^{1.5}$. FARRAR 85 finds $m_{\tilde{g}}$ <0.5 not excluded for $m_{\tilde{q}}$ = 30–1000 GeV and $m_{\tilde{g}}$ <1.0 not excluded for $m_{\tilde{q}}$ = 100–500 GeV by BALL 84 experiment.

[367] GOLDMAN 85 use nonobservation of a pseudoscalar $\tilde{g}$-$\tilde{g}$ bound state in radiative ψ decay.

[368] HABER 85 is based on survey of all previous searches sensitive to low mass $\tilde{g}$'s. Limit makes assumptions regarding the lifetime and electric charge of the lightest supersymmetric particle.

[369] BALL 84 is FNAL beam dump experiment. Observed no interactions of $\tilde{\gamma}$ in the calorimeter, where $\tilde{\gamma}$'s are expected to come from pair-produced $\tilde{g}$'s. Search for long-lived $\tilde{\gamma}$ interacting in calorimeter 56m from target. Limit is for $m_{\tilde{q}}$ = 40 GeV and production cross section proportional to $A^{0.72}$. BALL 84 find no $\tilde{g}$ allowed below 4.1 GeV at CL = 90%. Their figure 1 shows dependence on $m_{\tilde{q}}$ and A. See also KANE 82.

[370] BRICK 84 reanalyzed FNAL 147 GeV HBC data for R-$\Delta(1232)^{++}$ with $\tau > 10^{-9}$ s and p_{lab} >2 GeV. Set CL = 90% upper limits 6.1, 4.4, and 29 microbarns in pp, $\pi^+ p$, $K^+ p$ collisions respectively. R-Δ^{++} is defined as being $\tilde{g}$ and 3 up quarks. If mass = 1.2–1.5 GeV, then limits may be lower than theory predictions.

[371] FARRAR 84 argues that $m_{\widetilde{g}}$ <100 MeV is not ruled out if the lightest R-hadrons are long-lived. A long lifetime would occur if R-hadrons are lighter than $\widetilde{\gamma}$'s or if $m_{\widetilde{q}}$ >100 GeV.

[372] BERGSMA 83C is reanalysis of CERN-SPS beam-dump data. See their figure 1.

[373] CHANOWITZ 83 find in bag-model that charged s-hadron exists which is stable against strong decay if $m_{\widetilde{g}}$ <1 GeV. This is important since tracks from decay of neutral s-hadron cannot be reconstructed to primary vertex because of missed $\widetilde{\gamma}$. Charged s-hadron leaves track from vertex.

[374] KANE 82 inferred above $\widetilde{g}$ mass limit from retroactive analysis of hadronic collision and beam dump experiments. Limits valid if $\widetilde{g}$ decays inside detector.

LIGHT $\widetilde{G}$ (Gravitino) MASS LIMITS FROM COLLIDER EXPERIMENTS

The following are bounds on light ($\ll$ 1 eV) gravitino indirectly inferred from its coupling to matter suppressed by the gravitino decay constant.

Unless otherwise stated, all limits assume that other supersymmetric particles besides the gravitino are too heavy to be produced. The gravitino is assumed to be undetected and to give rise to a missing energy ($\not\!\!E$) signature.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$> 1.3 \times 10^{-5}$	95	[375] HEISTER	03C	ALEP	$e^+e^- \to \widetilde{G}\widetilde{G}\gamma$
$>11.7 \times 10^{-6}$	95	[376] ACOSTA	02H	CDF	
$> 8.7 \times 10^{-6}$	95	[377] ABBIENDI,G	00D	OPAL	$e^+e^- \to \widetilde{G}\widetilde{G}\gamma$
$>10.0 \times 10^{-6}$	95	[378] ABREU	00Z	DLPH	$e^+e^- \to \widetilde{G}\widetilde{G}\gamma$
$>11 \times 10^{-6}$	95	[379] AFFOLDER	00J	CDF	$p\overline{p} \to \widetilde{G}\widetilde{G}$ +jet
$> 8.9 \times 10^{-6}$	95	[378] ACCIARRI	99R	L3	$e^+e^- \to \widetilde{G}\widetilde{G}\gamma$
$> 7.9 \times 10^{-6}$	95	[380] ACCIARRI	98V	L3	$e^+e^- \to \widetilde{G}\widetilde{G}\gamma$
$> 8.3 \times 10^{-6}$	95	[380] BARATE	98J	ALEP	$e^+e^- \to \widetilde{G}\widetilde{G}\gamma$

[375] HEISTER 03C use the data from $\sqrt{s}$= 189-209 GeV to search for $\gamma \not\!\!E_T$ final states.

[376] ACOSTA 02H looked in 87 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with a high-E_t photon and $\not\!\!E_T$. They compared the data with a GMSB model where the final state could arise from $q\overline{q} \to \widetilde{G}\widetilde{G}\gamma$. Since the cross section for this process scales as $1/|F|^4$, a limit at 95% CL is derived on $|F|^{1/2} >$ 221 GeV. A model independent limit for the above topology is also given in the paper.

[377] ABBIENDI,G 00D searches for $\gamma \not\!\!E$ final states from $\sqrt{s}$=189 GeV.

[378] ABREU 00Z, ACCIARRI 99R search for $\gamma \not\!\!E$ final states using data from $\sqrt{s}$=189 GeV.

[379] AFFOLDER 00J searches for final states with an energetic jet (from quark or gluon) and large $\not\!\!E_T$ from undetected gravitinos.

[380] Searches for $\gamma \not\!\!E$ final states at $\sqrt{s}$=183 GeV.

Supersymmetry Miscellaneous Results

Results that do not appear under other headings or that make nonminimal assumptions.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			

[381] AFFOLDER	02D	CDF	$p\overline{p} \rightarrow \gamma b$ ($\not\!\!E_T$)
[382] AFFOLDER	01H	CDF	$p\overline{p} \rightarrow \gamma\gamma X$
[383] ABBOTT	00G	D0	$p\overline{p} \rightarrow 3\ell + \not\!\!E_T$, $\not\!R$, $LL\overline{E}$
[384] ABREU,P	00C	DLPH	$e^+ e^- \rightarrow \gamma + S/P$
[385] ABACHI	97	D0	$\gamma\gamma X$
[386] BARBER	84B	RVUE	
[387] HOFFMAN	83	CNTR	$\pi p \rightarrow n(e^+ e^-)$

[381] AFFOLDER 02D looked in 85 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}$=1.8 TeV for events with a high-E_T photon, and a b-tagged jet with or without $\not\!\!E_T$. They compared the data with models where the final state could arise from cascade decays of gluinos and/or squarks into $\widetilde{\chi}^{\pm}$ and $\widetilde{\chi}^0_2$ or direct associated production of $\widetilde{\chi}^0_2 \widetilde{\chi}^{\pm}_2$, followed by $\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$ or a GMSB model where $\widetilde{\chi}^0_1 \rightarrow \gamma \widetilde{G}$. It is concluded that the experimental sensitivity is insufficient to detect the associated production or the GMSB model, but some sensitivity may exist to the cascade decays. A model independent limit for the above topology is also given in the paper.

[382] AFFOLDER 01H searches for $p\overline{p} \rightarrow \gamma\gamma X$ events, where the di-photon system originates from sgoldstino production, in 100 pb^{-1} of data. Upper limits on the cross section times branching ratio are shown as function of the di-photon mass >70 GeV in Fig. 5. Excluded regions are derived in the plane of the sgoldstino mass versus the supersymmetry breaking scale for two representative sets of parameter values, as shown in Figs. 6 and 7.

[383] ABBOTT 00G searches for trilepton final states (ℓ=e,μ) with $\not\!\!E_T$ from the indirect decay of gauginos via $LL\overline{E}$ couplings. Efficiencies are computed for all possible production and decay modes of SUSY particles in the framework of the Minimal Supergravity scenario. See Figs. 1–4 for excluded regions in the $m_{1/2}$ versus m_0 plane.

[384] ABREU,P 00C look for the CP-even (S) and CP-odd (P) scalar partners of the goldstino, expected to be produced in association with a photon. The S/P decay into two photons or into two gluons and both the tri-photon and the photon + two jets topologies are investigated. Upper limits on the production cross section are shown in Fig. 5 and the excluded regions in Fig. 6. Data collected at $\sqrt{s}$= 189–202 GeV.

[385] ABACHI 97 searched for $p\overline{p} \rightarrow \gamma\gamma \not\!\!E_T + X$ as supersymmetry signature. It can be caused by selectron, sneutrino, or neutralino production with a radiative decay of their decay products. They placed limits on cross sections.

[386] BARBER 84B consider that $\widetilde{\mu}$ and $\widetilde{e}$ may mix leading to $\mu \rightarrow e\widetilde{\gamma}\widetilde{\gamma}$. They discuss mass-mixing limits from decay dist. asym. in LBL-TRIUMF data and e^+ polarization in SIN data.

[387] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B($e^+ e^-$) $< 3.5 \times 10^{-32}$ cm^2/GeV^2 for spin-1 partner of Goldstone fermions with 140 $< m <$160 MeV decaying $\rightarrow e^+ e^-$ pair.

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ABREU 01C PL B502 24 P. Abreu *et al.* (DELPHI Collab.)
ABREU 01D PL B500 22 P. Abreu *et al.* (DELPHI Collab.)
ABREU 01G PL B503 34 P. Abreu *et al.* (DELPHI Collab.)
ACCIARRI 01 EPJ C19 397 M. Acciarri *et al.* (L3 Collab.)
ADAMS 01 PRL 87 041801 T. Adams *et al.* (NuTeV Collab.)
ADLOFF 01B EPJ C20 639 C. Adloff *et al.* (H1 Collab.)
AFFOLDER 01B PR D63 091101 T. Affolder *et al.* (CDF Collab.)
AFFOLDER 01H PR D64 092002 T. Affolder *et al.* (CDF Collab.)
AFFOLDER 01J PRL 87 251803 T. Affolder *et al.* (CDF Collab.)
BALTZ 01 PRL 86 5004 E. Baltz, P. Gondolo

BARATE	01	PL B499 67	R. Barate *et al.*	(ALEPH Collab.)
BARATE	01B	EPJ C19 415	R. Barate *et al.*	(ALEPH Collab.)
BARATE	01C	PL B499 53	R. Barate *et al.*	(ALEPH Collab.)
BARGER	01C	PL B518 117	V. Barger, C. Kao	
BAUDIS	01	PR D63 022001	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
BENOIT	01	PL B513 15	A. Benoit *et al.*	(EDELWEISS Collab.)
BERGER	01	PRL 86 4231	E. Berger *et al.*	
BERNABEI	01	PL B509 197	R. Bernabei *et al.*	(DAMA Collab.)
BOTTINO	01	PR D63 125003	A. Bottino *et al.*	
BREITWEG	01	PR D63 052002	J. Breitweg *et al.*	(ZEUS Collab.)
CORSETTI	01	PR D64 125010	A. Corsetti, P. Nath	
DJOUADI	01	JHEP 0108 55	A. Djouadi, M. Drees, J.L. Kneur	
ELLIS	01B	PL B510 236	J. Ellis *et al.*	
ELLIS	01C	PR D63 065016	J. Ellis, A. Ferstl, K.A. Olive	
GOMEZ	01	PL B512 252	M.E. Gomez, J.D. Vergados	
LAHANAS	01	PL B518 94	A. Lahanas, D.V. Nanopoulos, V. Spanos	
ROSZKOWSKI	01	JHEP 0108 024	L. Roszkowski, R. Ruiz de Austri, T. Nihei	
SAVINOV	01	PR D63 051101	V. Savinov *et al.*	(CLEO Collab.)
ABBIENDI	00	EPJ C12 1	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	00G	EPJ C14 51	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	00H	EPJ C14 187	G. Abbiendi *et al.*	(OPAL Collab.)
Also	00Y	EPJ C16 707 (erratum)	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	00J	EPJ C12 551	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	00R	EPJ C13 553	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	00Y	EPJ C16 707 (erratum)	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI,G	00D	EPJ C18 253	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	00C	PRL 84 2088	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	00G	PR D62 071701R	B. Abbott *et al.*	(D0 Collab.)
ABREU	00I	EPJ C13 591	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00J	PL B479 129	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00Q	PL B478 65	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00S	PL B485 45	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00T	PL B485 95	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00U	PL B487 36	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00V	EPJ C16 211	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00W	PL B489 38	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
ABREU,P	00C	PL B494 203	P. Abreu *et al.*	(DELPHI Collab.)
ABREU,P	00D	PL B496 59	P. Abreu *et al.*	(DELPHI Collab.)
ABUSAIDI	00	PRL 84 5699	R. Abusaidi *et al.*	(CDMS Collab.)
ACCIARRI	00C	EPJ C16 1	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00D	PL B472 420	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00K	PL B482 31	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri *et al.*	(L3 Collab.)
ACCOMANDO	00	NP B585 124	E. Accomando *et al.*	
AFFOLDER	00D	PRL 84 5704	T. Affolder *et al.*	(CDF Collab.)
AFFOLDER	00G	PRL 84 5273	T. Affolder *et al.*	(CDF Collab.)
AFFOLDER	00J	PRL 85 1378	T. Affolder *et al.*	(CDF Collab.)
AFFOLDER	00K	PRL 85 2056	T. Affolder *et al.*	(CDF Collab.)
BARATE	00G	EPJ C16 71	R. Barate *et al.*	(ALEPH Collab.)
BARATE	00H	EPJ C13 29	R. Barate *et al.*	(ALEPH Collab.)
BARATE	00I	EPJ C12 183	R. Barate *et al.*	(ALEPH Collab.)
BARATE	00P	PL B488 234	R. Barate *et al.*	(ALEPH Collab.)
BERNABEI	00	PL B480 23	R. Bernabei *et al.*	(DAMA Collab.)
BERNABEI	00C	EPJ C18 283	R. Bernabei *et al.*	(DAMA Collab.)
BERNABEI	00D	NJP 2 15	R. Bernabei *et al.*	(DAMA Collab.)
BOEHM	00B	PR D62 035012	C. Boehm, A. Djouadi, M. Drees	
BREITWEG	00E	EPJ C16 253	J. Breitweg *et al.*	(ZEUS Collab.)
CHO	00B	NP B574 623	G.-C. Cho, K. Hagiwara	
COLLAR	00	PRL 85 3083	J.I. Collar *et al.*	(SIMPLE Collab.)
ELLIS	00	PR D62 075010	J. Ellis *et al.*	
FENG	00	PL B482 388	J.L. Feng, K.T. Matchev, F. Wilczek	
LAHANAS	00	PR D62 023515	A. Lahanas, D.V. Nanopoulos, V.C. Spanos	
LEP	00	CERN-EP-2000-016	LEP Collabs.	(ALEPH, DELPHI, L3, OPAL, SLD+)
MAFI	00	PR D62 035003	A. Mafi, S. Raby	
MALTONI	00	PL B476 107	M. Maltoni *et al.*	
MORALES	00	PL B489 268	A. Morales *et al.*	(IGEX Collab.)
PDG	00	EPJ C15 1	D.E. Groom *et al.*	
SPOONER	00	PL B473 330	N.J.C. Spooner *et al.*	(UK Dark Matter Col.)
ABBIENDI	99	EPJ C6 1	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	99F	EPJ C8 23	G. Abbiendi *et al.*	(OPAL Collab.)

ABBIENDI	99G	EPJ C8 255	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	99M	PL B456 95	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	99T	EPJ C11 619	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	99	PRL 82 29	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	99F	PR D60 031101	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	99J	PRL 83 2896	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	99K	PRL 83 4476	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	99L	PRL 83 4937	B. Abbott *et al.*	(D0 Collab.)
ABE	99I	PR D59 092002	F. Abe *et al.*	(CDF Collab.)
ABE	99M	PRL 83 2133	F. Abe *et al.*	(CDF Collab.)
ABREU	99A	EPJ C11 383	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99C	EPJ C6 385	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99D	EPJ C6 371	P. Abreu *et al.*	(DLEPHI Collab.)
ABREU	99F	EPJ C7 595	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99G	PL B446 62	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	99H	PL B456 283	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99I	PL B459 354	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99L	PL B462 354	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99R	PL B470 268	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99V	PL B471 308	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99W	PL B471 280	M. Acciarri *et al.*	(L3 Collab.)
ALAVI-HARATI	99E	PRL 83 2128	A. Alavi-Harati *et al.*	(FNAL KTeV Collab.)
AMBROSIO	99	PR D60 082002	M. Ambrosio *et al.*	(Macro Collab.)
BAER	99	PR D59 075002	H. Baer, K. Cheung, J.F. Gunion	
BARATE	99E	EPJ C7 383	R. Barate *et al.*	(ALEPH Collab.)
BARATE	99P	EPJ C11 193	R. Barate *et al.*	(ALEPH Collab.)
BARATE	99Q	PL B469 303	R. Barate *et al.*	(ALEPH Collab.)
BAUDIS	99	PR D59 022001	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
BELLI	99C	NP B563 97	P. Belli *et al.*	(DAMA Collab.)
BERNABEI	99	PL B450 448	R. Bernabei *et al.*	(DAMA Collab.)
FANTI	99	PL B446 117	V. Fanti *et al.*	(CERN NA48 Collab.)
MALTONI	99B	PL B463 230	M. Maltoni, M.I. Vysotsky	
OOTANI	99	PL B461 371	W. Ootani *et al.*	
ABBOTT	98	PRL 80 442	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	98C	PRL 80 1591	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	98E	PRL 80 2051	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	98J	PRL 81 38	B. Abbott *et al.*	(D0 Collab.)
ABE	98J	PRL 80 5275	F. Abe *et al.*	(CDF Collab.)
ABE	98L	PRL 81 1791	F. Abe *et al.*	(CDF Collab.)
ABE	98S	PRL 81 4806	F. Abe *et al.*	(CDF Collab.)
ABREU	98	EPJ C1 1	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	98P	PL B444 491	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	98F	EPJ C4 207	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	98J	PL B433 163	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	98V	PL B444 503	M. Acciarri *et al.*	(L3 Collab.)
ACKERSTAFF	98K	EPJ C4 47	K. Ackerstaff *et al.*	(OPAL Collab.)
ACKERSTAFF	98L	EPJ C2 213	K. Ackerstaff *et al.*	(OPAL Collab.)
ACKERSTAFF	98P	PL B433 195	K. Ackerstaff *et al.*	(OPAL Collab.)
ACKERSTAFF	98V	EPJ C2 441	K. Ackerstaff *et al.*	(OPAL Collab.)
BARATE	98H	PL B420 127	R. Barate *et al.*	(ALEPH Collab.)
BARATE	98J	PL B429 201	R. Barate *et al.*	(ALEPH Collab.)
BARATE	98K	PL B433 176	R. Barate *et al.*	(ALEPH Collab.)
BARATE	98S	EPJ C4 433	R. Barate *et al.*	(ALEPH Collab.)
BARATE	98X	EPJ C2 417	R. Barate *et al.*	(ALEPH Collab.)
BERNABEI	98	PL B424 195	R. Bernabei *et al.*	(DAMA Collab.)
BERNABEI	98C	PL B436 379	R. Bernabei *et al.*	(DAMA Collab.)
BREITWEG	98	PL B434 214	J. Breitweg *et al.*	(ZEUS Collab.)
ELLIS	98	PR D58 095002	J. Ellis *et al.*	
ELLIS	98B	PL B444 367	J. Ellis, T. Falk, K. Olive	
PDG	98	EPJ C3 1	C. Caso *et al.*	
ABACHI	97	PRL 78 2070	S. Abachi *et al.*	(D0 Collab.)
ABBOTT	97B	PRL 79 4321	B. Abbott *et al.*	(D0 Collab.)
ABE	97K	PR D56 R1357	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	97U	PL B414 373	M. Acciarri *et al.*	(L3 Collab.)
ACKERSTAFF	97H	PL B396 301	K. Ackerstaff *et al.*	(OPAL Collab.)
ADAMS	97B	PRL 79 4083	J. Adams *et al.*	(FNAL KTeV Collab.)
ALBUQUERQ...	97	PRL 78 3252	I.F. Albuquerque *et al.*	(FNAL E761 Collab.)
BAER	97	PR D57 567	H. Baer, M. Brhlik	
BARATE	97K	PL B405 379	R. Barate *et al.*	(ALEPH Collab.)
BARATE	97L	ZPHY C76 1	R. Barate *et al.*	(ALEPH Collab.)
BERNABEI	97	ASP 7 73	R. Bernabei *et al.*	(DAMA Collab.)

CARENA	97	PL B390 234	M. Carena, G.F. Giudice, C.E.M. Wagner	
CSIKOR	97	PRL 78 4335	F. Csikor, Z. Fodor	(EOTV, CERN)
DATTA	97	PL B395 54	A. Datta, M. Guchait, N. Parua	(ICTP, TATA)
DEGOUVEA	97	PL B400 117	A. de Gouvea, H. Murayama	
DERRICK	97	ZPHY C73 613	M. Derrick *et al.*	(ZEUS Collab.)
EDSJO	97	PR D56 1879	J. Edsjo, P. Gondolo	
ELLIS	97	PL B394 354	J. Ellis, J.L. Lopez, D.V. Nanopoulos	
HEWETT	97	PR D56 5703	J.L. Hewett, T.G. Rizzo, M.A. Doncheski	
KALINOWSKI	97	PL B400 112	J. Kalinowski, P. Zerwas	
TEREKHOV	97	PL B412 86	I. Terekhov	(ALAT)
ABACHI	96	PRL 76 2228	S. Abachi *et al.*	(D0 Collab.)
ABACHI	96B	PRL 76 2222	S. Abachi *et al.*	(D0 Collab.)
ABE	96	PRL 77 438	F. Abe *et al.*	(CDF Collab.)
ABE	96D	PRL 76 2006	F. Abe *et al.*	(CDF Collab.)
ABE	96K	PRL 76 4307	F. Abe *et al.*	(CDF Collab.)
AID	96	ZPHY C71 211	S. Aid *et al.*	(H1 Collab.)
AID	96C	PL B380 461	S. Aid *et al.*	(H1 Collab.)
ARNOWITT	96	PR D54 2374	R. Arnowitt, P. Nath	
BAER	96	PR D53 597	H. Baer, M. Brhlik	
BERGSTROM	96	ASP 5 263	L. Bergstrom, P. Gondolo	
CHO	96	PL B372 101	G.C. Cho, Y. Kizukuri, N. Oshimo	(TOKAH, OCH)
FARRAR	96	PRL 76 4111	G.R. Farrar	(RUTG)
LEWIN	96	ASP 6 87	J.D. Lewin, P.F. Smith	
TEREKHOV	96	PL B385 139	I. Terkhov, L. Clavelli	(ALAT)
ABACHI	95C	PRL 75 618	S. Abachi *et al.*	(D0 Collab.)
ABE	95N	PRL 74 3538	F. Abe *et al.*	(CDF Collab.)
ABE	95T	PRL 75 613	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	95E	PL B350 109	M. Acciarri *et al.*	(L3 Collab.)
AKERS	95A	ZPHY C65 367	R. Akers *et al.*	(OPAL Collab.)
AKERS	95R	ZPHY C67 203	R. Akers *et al.*	(OPAL Collab.)
BEREZINSKY	95	ASP 5 1	V. Berezinsky *et al.*	
BUSKULIC	95E	PL B349 238	D. Buskulic *et al.*	(ALEPH Collab.)
CLAVELLI	95	PR D51 1117	L. Clavelli, P.W. Coulter	(ALAT)
FALK	95	PL B354 99	T. Falk, K.A. Olive, M. Srednicki	(MINN, UCSB)
LOSECCO	95	PL B342 392	J.M. LoSecco	(NDAM)
AKERS	94K	PL B337 207	R. Akers *et al.*	(OPAL Collab.)
BECK	94	PL B336 141	M. Beck *et al.*	(MPIH, KIAE, SASSO)
CAKIR	94	PR D50 3268	M.B. Cakir, G.R. Farrar	(RUTG)
FALK	94	PL B339 248	T. Falk, K.A. Olive, M. Srednicki	(UCSB, MINN)
SHIRAI	94	PRL 72 3313	J. Shirai *et al.*	(VENUS Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani *et al.*	(L3 Collab.)
ALITTI	93	NP B400 3	J. Alitti *et al.*	(UA2 Collab.)
CLAVELLI	93	PR D47 1973	L. Clavelli, P.W. Coulter, K.J. Yuan	(ALAT)
DREES	93	PR D47 376	M. Drees, M.M. Nojiri	(DESY, SLAC)
DREES	93B	PR D48 3483	M. Drees, M.M. Nojiri	
FALK	93	PL B318 354	T. Falk *et al.*	(UCB, UCSB, MINN)
HEBBEKER	93	ZPHY C60 63	T. Hebbeker	(CERN)
KELLEY	93	PR D47 2461	S. Kelley *et al.*	(TAMU, ALAH)
LOPEZ	93C	PL B313 241	J.L. Lopez, D.V. Nanopoulos, X. Wang	(TAMU, HARC+)
MIZUTA	93	PL B298 120	S. Mizuta, M. Yamaguchi	(TOHO)
MORI	93	PR D48 5505	M. Mori *et al.*	(KEK, NIIG, TOKY, TOKA+)
ABE	92L	PRL 69 3439	F. Abe *et al.*	(CDF Collab.)
BOTTINO	92	MPL A7 733	A. Bottino *et al.*	(TORI, ZARA)
Also	91	PL B265 57	A. Bottino *et al.*	(TORI, INFN)
CLAVELLI	92	PR D46 2112	L. Clavelli	(ALAT)
DECAMP	92	PRPL 216 253	D. Decamp *et al.*	(ALEPH Collab.)
LOPEZ	92	NP B370 445	J.L. Lopez, D.V. Nanopoulos, K.J. Yuan	(TAMU)
MCDONALD	92	PL B283 80	J. McDonald, K.A. Olive, M. Srednicki	(LISB+)
ROY	92	PL B283 270	D.P. Roy	(CERN)
ABREU	91F	NP B367 511	P. Abreu *et al.*	(DELPHI Collab.)
AKESSON	91	ZPHY C52 219	T. Akesson *et al.*	(HELIOS Collab.)
ALEXANDER	91F	ZPHY C52 175	G. Alexander *et al.*	(OPAL Collab.)
ANTONIADIS	91	PL B262 109	I. Antoniadis, J. Ellis, D.V. Nanopoulos	(EPOL+)
BOTTINO	91	PL B265 57	A. Bottino *et al.*	(TORI, INFN)
GELMINI	91	NP B351 623	G.B. Gelmini, P. Gondolo, E. Roulet	(UCLA, TRST)
GRIEST	91	PR D43 3191	K. Griest, D. Seckel	
KAMIONKOW...	91	PR D44 3021	M. Kamionkowski	(CHIC, FNAL)
MORI	91B	PL B270 89	M. Mori *et al.*	(Kamiokande Collab.)
NOJIRI	91	PL B261 76	M.M. Nojiri	(KEK)
OLIVE	91	NP B355 208	K.A. Olive, M. Srednicki	(MINN, UCSB)
ROSZKOWSKI	91	PL B262 59	L. Roszkowski	(CERN)

SATO	91	PR D44 2220	N. Sato *et al.*	(Kamiokande Collab.)
ADACHI	90C	PL B244 352	I. Adachi *et al.*	(TOPAZ Collab.)
GRIEST	90	PR D41 3565	K. Griest, M. Kamionkowski, M.S. Turner	(UCB+)
BARBIERI	89C	NP B313 725	R. Barbieri, M. Frigeni, G. Giudice	
NAKAMURA	89	PR D39 1261	T.T. Nakamura *et al.*	(KYOT, TMTC)
OLIVE	89	PL B230 78	K.A. Olive, M. Srednicki	(MINN, UCSB)
ELLIS	88D	NP B307 883	J. Ellis, R. Flores	
GRIEST	88B	PR D38 2357	K. Griest	
OLIVE	88	PL B205 553	K.A. Olive, M. Srednicki	(MINN, UCSB)
SREDNICKI	88	NP B310 693	M. Srednicki, R. Watkins, K.A. Olive	(MINN, UCSB)
ALBAJAR	87D	PL B198 261	C. Albajar *et al.*	(UA1 Collab.)
ANSARI	87D	PL B195 613	R. Ansari *et al.*	(UA2 Collab.)
ARNOLD	87	PL B186 435	R.G. Arnold *et al.*	(BRUX, DUUC, LOUC+)
NG	87	PL B188 138	K.W. Ng, K.A. Olive, M. Srednicki	(MINN, UCSB)
TUTS	87	PL B186 233	P.M. Tuts *et al.*	(CUSB Collab.)
ALBRECHT	86C	PL 167B 360	H. Albrecht *et al.*	(ARGUS Collab.)
BADIER	86	ZPHY C31 21	J. Badier *et al.*	(NA3 Collab.)
BARNETT	86	NP B267 625	R.M. Barnett, H.E. Haber, G.L. Kane	(LBL, UCSC+)
GAISSER	86	PR D34 2206	T.K. Gaisser, G. Steigman, S. Tilav	(BART, DELA)
VOLOSHIN	86	SJNP 43 495	M.B. Voloshin, L.B. Okun	(ITEP)
		Translated from YAF 43 779.		
COOPER-...	85B	PL 160B 212	A.M. Cooper-Sarkar *et al.*	(WA66 Collab.)
DAWSON	85	PR D31 1581	S. Dawson, E. Eichten, C. Quigg	(LBL, FNAL)
FARRAR	85	PRL 55 895	G.R. Farrar	(RUTG)
GOLDMAN	85	Physica 15D 181	T. Goldman, H.E. Haber	(LANL, UCSC)
HABER	85	PRPL 117 75	H.E. Haber, G.L. Kane	(UCSC, MICH)
BALL	84	PRL 53 1314	R.C. Ball *et al.*	(MICH, FIRZ, OSU, FNAL+)
BARBER	84B	PL 139B 427	J.S. Barber, R.E. Shrock	(STON)
BRICK	84	PR D30 1134	D.H. Brick *et al.*	(BROW, CAVE, IIT+)
ELLIS	84	NP B238 453	J. Ellis *et al.*	(CERN)
FARRAR	84	PRL 53 1029	G.R. Farrar	(RUTG)
BERGSMA	83C	PL 121B 429	F. Bergsma *et al.*	(CHARM Collab.)
CHANOWITZ	83	PL 126B 225	M.S. Chanowitz, S. Sharpe	(UCB, LBL)
GOLDBERG	83	PRL 50 1419	H. Goldberg	(NEAS)
HOFFMAN	83	PR D28 660	C.M. Hoffman *et al.*	(LANL, ARZS)
KRAUSS	83	NP B227 556	L.M. Krauss	(HARV)
VYSOTSKII	83	SJNP 37 948	M.I. Vysotsky	(ITEP)
		Translated from YAF 37 1597.		
KANE	82	PL 112B 227	G.L. Kane, J.P. Leveille	(MICH)
CABIBBO	81	PL 105B 155	N. Cabibbo, G.R. Farrar, L. Maiani	(ROMA, RUTG)
FARRAR	78	PL 76B 575	G.R. Farrar, P. Fayet	(CIT)
Also	78B	PL 79B 442	G.R. Farrar, P. Fayet	(CIT)