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Supersymmetric Particle Searches

SUPERSYMMETRY

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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 [1–3], 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 their gauge interactions). 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. Thus, supersymmetry cannot be an exact symmetry of nature, and must be broken. In theories of "low-energy" supersymmetry, the effective scale of supersymmetry breaking is tied to the electroweak scale [4–6], which is characterized by the Standard Model Higgs vacuum expectation value $v = 246$ GeV. It is thus 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.

At present, there are no unambiguous experimental results that require the existence of low-energy supersymmetry. However, 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 [2,7]. 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) [8,9]. 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 [10].

If supersymmetry is associated with the origin of the scale of electroweak interactions, then the mass parameters introduced by the soft-supersymmetry-breaking terms must in general be of order 1 TeV or below [11] (although models have been proposed in which some supersymmetric particle masses can be larger, in the range of 1–10 TeV [12]). Some lower bounds on these parameters exist due to the absence of supersymmetric-particle production at current accelerators [13]. Additional constraints arise from limits on the contributions of virtual supersymmetric particle exchange to a variety of Standard Model processes [14,15]. In particular, the Standard Model fit (without supersymmetry) to precision electroweak data is quite good [16]. If all supersymmetric particle masses are significantly heavier than m_Z (in practice, masses greater than 300 GeV are sufficient [17]), then the effects of the supersymmetric particles decouple in loop-corrections to electroweak observables [18]. 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 can generate significant one-loop corrections, resulting in a poorer overall fit to the data [19]. Thus, the precision electroweak data provide some constraints on the magnitude of the soft-supersymmetry-breaking terms.

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 [20]. Note that this formula 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 quickly 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 [21]. Consequently, the LSP in a R-parity-conserving theory is weakly-interacting in ordinary matter, *i.e.* it behaves like a stable heavy neutrino and will escape 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" [22], a potentially important component of the non-baryonic dark matter that is required in many models of cosmology and galaxy formation [23].

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 [24]. 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 [25]. 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 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 then 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 [26,27]. 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 [1,28]. 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 [29,30]. 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.

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. 31. 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,]; (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 contribute to the diagonal Higgs squared-masses, given by $m^2_1 + |\mu|^2$ and $m^2_2 + |\mu|^2$, and one off-diagonal Higgs squared-mass term, $m^2_{12} \equiv B\mu$ (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, 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. (Another notation often employed in the literature is $v_1 \equiv v_d$ and $v_2 \equiv v_u$.) Note that $v^2_d + v^2_u = (246\ \text{GeV})^2$ is fixed by the W mass, while 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 which 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. 32 shows that the MSSM possesses 124 truly 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 new real mixing angles to define the squark and slepton mass eigenstates and 40 new 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 [33].

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 [34].

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

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

where the states are ordered such that $M_{\widetilde{\chi}_1^+} \le M_{\widetilde{\chi}_2^+}$. 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 [13] 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 [34]. 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 [35]

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

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. 31. 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

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

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 [14,15]. 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 [36].

I.5. The Higgs sector of the MSSM: Next, consider the Higgs sector of the MSSM [8,9,37]. Despite the large number of potential CP-violating phases among the MSSM-124 parameters, one can show that 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. There are five physical Higgs particles in this model: a charged Higgs boson pair ($H^{\pm}$), two CP-even neutral Higgs bosons (denoted by H_1^0 and H_2^0 where $m_{H_1^0} \leq m_{H_2^0}$) 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. The strengths of the interaction terms are directly related to the gauge couplings by supersymmetry (and are not affected at tree-level by supersymmetry breaking). As a result, $\tan\beta$ [defined in Eq. (1)] and one Higgs mass determine the tree-level Higgs-sector parameters. These include the Higgs 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 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 [38]. For example, at tree-level, MSSM-124 predicts

$m_{H_1^0} \leq m_Z|\cos 2\beta| \leq m_Z$ [8,9]. If this prediction were unmodified, it would imply that H_1^0 must be discovered at the LEP collider (running at its maximum energy and luminosity); otherwise MSSM-124 would be ruled out. 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, $M_{\rm S}^2 \equiv \frac{1}{2}(M_{\widetilde{t}_1}^2 + M_{\widetilde{t}_2}^2)$. In this case (assuming $m_{A^0} > m_Z$), the upper bound on the lightest CP-even Higgs mass at one-loop is approximately given by

$$m_{H_1^0}^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left\{\ln\left(M_{\rm S}^2/m_t^2\right) + \frac{X_t^2}{M_{\rm S}^2}\left(1 - \frac{X_t^2}{12M_{\rm S}^2}\right)\right\}, \quad (5)$$

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 [39] shows that Eq. (5) somewhat overestimates the true upper bound of $m_{H_1^0}$. These more refined computations, which incorporate renormalization group improvement and the leading two-loop contributions, yield $m_{H_1^0} \lesssim 130$ GeV (with an accuracy of a few GeV) for $m_t = 175$ GeV and $M_S \lesssim 1$ TeV [39].

In addition, one-loop radiative corrections can also introduce CP-violating effects in the Higgs sector, which depend on some of the CP-violating phases among the MSSM-124 parameters [40]. Although these effects are more model-dependent, they can have a non-trivial impact on the Higgs searches at LEP and future colliders.

I.6. Reducing the MSSM parameter freedom: Even in the absence of a fundamental theory of supersymmetry breaking, one is hard-pressed to regard MSSM-124 as a fundamental theory. For example, no fundamental explanation is provided for the origin of electroweak symmetry breaking. Moreover, MSSM-124 is not a phenomenologically viable theory over most of its parameter space. Among the phenomenologically deficiencies are: (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. As a result, 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.

MSSM-124 is also theoretically deficient 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, the MSSM contains many new sources of CP violation. For example, 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 [41,42].

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 [5,32,43]). 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 [44]). 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 gaugino mass parameters at some high-energy scale $M_{\rm X}$, *i.e.*,

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

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

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

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.

Recently, attention has been given to a class of supergravity models in which Eq. (7) does not hold. In models where no tree-level gaugino masses are generated, 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 [45]. This approach has been called *anomaly-mediated* supersymmetry breaking. Eq. (7) is then replaced (in the one-loop approximation) by:

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

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 $M_1 \simeq 2.8 M_2$ and $M_3 \simeq -8.3 M_2$, which implies that the lightest chargino pair and neutralino make up a nearly-mass degenerate triplet of winos. The corresponding supersymmetric phenomenology differs significantly from the standard phenomenology based on Eq. (7), and is explored in detail in Ref. [46]. Anomaly-mediated supersymmetry breaking also generates (approximate) flavor-diagonal squark and slepton mass matrices. However, in the MSSM this cannot be the sole source of supersymmetry-breaking in the slepton sector (which yields negative squared-mass contributions for the sleptons).

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 [26]:

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

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. 47.

Clearly, in the mSUGRA approach, the MSSM-124 parameter freedom has been sharply 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. 47). 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. 48.) 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, $\widetilde{\chi}_1^0$, 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.

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 [49].

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 [30,50]. 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 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)$\times$SU(2)$\times$U(1) gauge couplings predicted by models of supersymmetric grand unified theories (SGUTs) [5,51] (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 (*i.e.*, the 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 imposing the unification condition on the three gauge couplings at some high-energy scale, $M_{\rm X}$. This procedure (which fixes $M_{\rm X}$) 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. [52] 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 [53], and an intriguing possibility that $\lambda_b = \lambda_\tau = \lambda_t$ may be phenomenologically viable [54,48] 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 in 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 [55,56]; (ii) an enlarged electroweak gauge group beyond SU(2)×U(1) [57]; (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 [58]. A possible theoretical motivation for such new structure arises from the study of phenomenologically viable string theory ground states [59].

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.

Phenomenological constraints on various low-energy B- and L-violating processes yield limits on each of the coefficients $(\lambda_L)_{pmn}$, $(\lambda'_L)_{pmn}$ and $(\lambda_B)_{pmn}$ taken one at a time [60]. 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.

If R-parity is not conserved, 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 [61], neutrinoless double beta decay [62], sneutrino-antisneutrino mixing [56,63,64], and s-channel resonant production of the sneutrino in e^+e^- collisions [65]. Since the distinction between the Higgs and matter 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: $e^+\overline{u}_m \to \widetilde{\overline{d}}_n \to e^+\overline{u}_m,\ \overline{\nu}\overline{d}_m$ 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.*)

The theory and phenomenology of alternative low-energy supersymmetric models and its consequences for collider physics have recently begun to attract significant attention. In particular, experimental and theoretical constraints place some non-trivial restrictions on R-parity-violating alternatives to the MSSM (see, e.g., Refs. [60,66] 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. Most of these have been guided by the MSSM and are based on the canonical missing-energy signature caused by the escape of the LSP's ('lightest supersymmetric particles').

More recently, other scenarios have received considerable attention from experimenters, widening the range of topologies in which new physics might be found.

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

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

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

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

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

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

Finally, in another scenario the gluino $\widetilde{g}$ is assumed to be light ($M_{\widetilde{g}} < 5$ GeV/c^2) [5]. Its decay to the lightest neutralino is kinematically suppressed, so long-lived supersymmetric hadrons ($\widetilde{g} + g$ bound states called R^0's) are formed [6]. While the sensitivity of most searches at LEP and the Tevatron would be lost, specific searches at fixed target experiments seem to have closed this gap definitively. (See the review article by H. Murayama.)

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

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

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

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

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

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

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

- Select "typical" values for the parameters not shown. These may be suggested by theory, or values giving more conservative—or more powerful—results may be selected. Although the values are usually specified, one sometimes has to work to understand the possible 'loopholes.'
- Scan the parameters not shown. The lowest value for $\epsilon \cdot \sigma$ is used in Eq. (1), thereby giving the weakest limit for the parameters shown. As a consequence, the limit applies for all values of the parameters *not* shown.
- Scan parameters to find the lowest acceptance ϵ and use it as a constant in Eq. (1). The limits are then safe from theoretical uncertainties but may be overconservative, hiding powerful constraints existing in more typical cases.

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

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

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

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

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

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

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

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

The major backgrounds come from three sources. First, there are the so-called 'two-photon interactions,' in which the beam electrons emit photons which combine to produce a low mass hadronic or leptonic system leaving little visible energy in the detector. Since the electrons are seldom deflected through large angles, $p_T^{\rm miss}$ 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 undetected electron or photon, and can be large when there are two massive LSP's. The four-fermion processes cannot be entirely eliminated, however, and a non-negligible irreducible background is expected. Fortunately, the uncertainties for these backgrounds are not large.

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

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

Charginos have been excluded up to 94 GeV/c^2 [8,9] except in cases of very low acceptance ($\Delta M = M_{\widetilde{\chi}^\pm} - M_{\widetilde{\chi}_1^0} \lesssim 3$ GeV/c^2) or low cross section ($M_{\widetilde{\nu}_e} \lesssim 120$ GeV/c^2). When $|\mu| \ll M_2$, the Higgsino components are large for charginos and neutralinos. In this case the associated production of neutralino pairs $\widetilde{\chi}_1^0 \widetilde{\chi}_2^0$ is large and the problem of small mass differences ($M_{\widetilde{\chi}_2^0} - M_{\widetilde{\chi}_1^0}$) less severe. Experimental sensitivity now extends down to mass differences of 3 GeV/c^2, corresponding to M_2 above 2 TeV/c^2.

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

The limits from chargino and neutralino production are most often used to constrain M_2 and μ for fixed $\tan\beta$. For large $|\mu|$ (the gaugino case), chargino bounds limit M_2, and vice versa (the Higgsino case). When $\tan\beta$ is not large, the region of parameter space with $\mu < 0$ and $|\mu| \sim M_2$ corresponds to 'mixed' field content, and the limits on M_2 and $|\mu|$ are

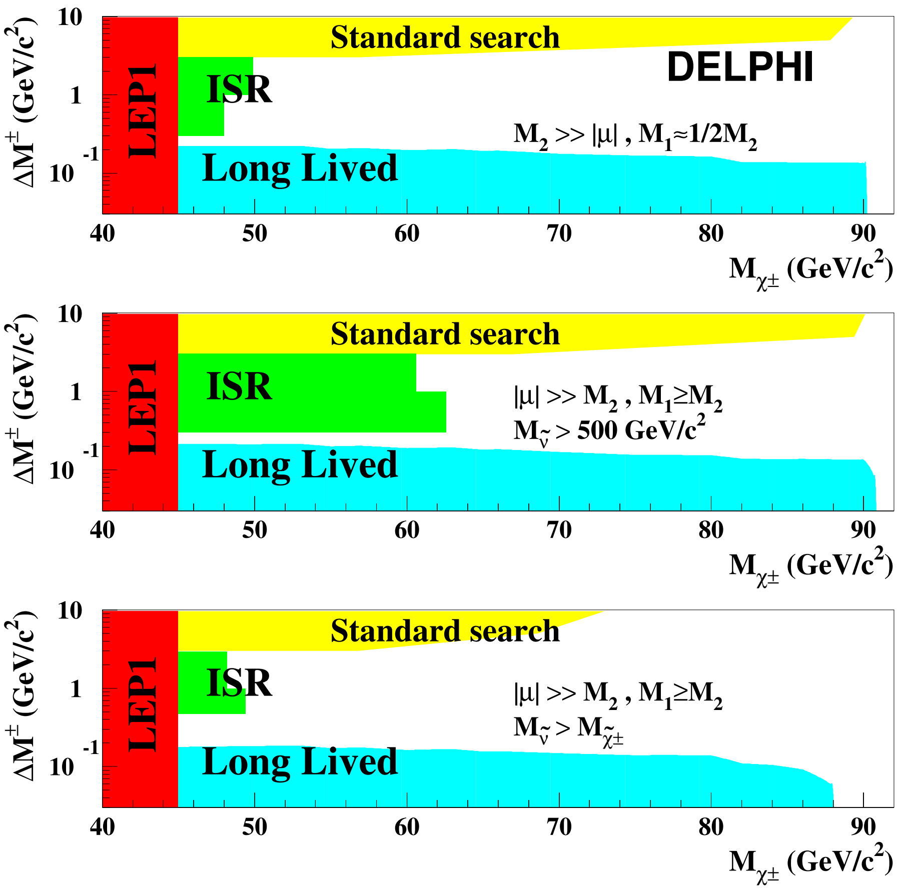

Figure 1: Ranges of excluded chargino and neutralino masses, for very small ΔM , from DELPHI [10].

relatively modest, numerically. This is especially true when electron sneutrinos are light, leading to a degradation of the indirect limits on the LSP mass, as discussed below.

When the sleptons are light, two important effects must be considered for charginos: the cross section is significantly reduced and the branching ratio to leptons is enhanced, especially to τ's via $\widetilde{\tau}$'s which can have non-negligible mixing.

These effects are greatest when the chargino has a large gaugino component. The weakest bounds are found for small negative μ and small $\tan\beta$, as the cross section is reduced with respect to larger $|\mu|$, the impact of $\widetilde{\tau}$ mixing can be large, and the efficiency is not optimal because ΔM is large.

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

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

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

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

Limits on stop and sbottom masses [17,18], vary with the mixing angle because the cross section does: for $\theta_{\widetilde{t}} = 56^\circ$ and $\theta_{\widetilde{b}} = 67^\circ$ the contribution from Z exchange is "turned off." The stop decay $\widetilde{t}_1 \rightarrow c\widetilde{\chi}^0_1$ proceeds through loops, giving a lifetime long enough to allow the top squark to form supersymmetric hadrons which provide a pair of jets and missing energy. If sneutrinos are light, the decay $\widetilde{t}_1 \rightarrow b\ell\widetilde{\nu}$ dominates, giving two leptons in addition to the jets. Access to small ΔM is possible due to the visibility of the decay products of the c and b quarks. Limits vary from 91 GeV/c^2 for an unrealistic pure $\widetilde{t}_L$ state to 89 GeV/c^2 if the coupling of $\widetilde{t}_1$ to the Z vanishes. The electric charge of the sbottoms is smaller than that of stops, leading to weaker limits, but the use of b-jet tagging helps retain sensitivity: the bounds range between 75 and 90 GeV/c^2 depending on $\theta_{\widetilde{b}}$. Limits from the Tevatron reach much higher masses, but only when the neutralino is much lighter than the stop or sbottom. ALEPH has interpreted the results of their search in terms of generic squarks, excluding a rather small region not covered at the Tevatron [17].

In canonical SUSY scenarios the lightest neutralino leaves no signal in the detector. Nonetheless, the tight correspondences among the neutralino and chargino masses allow an indirect

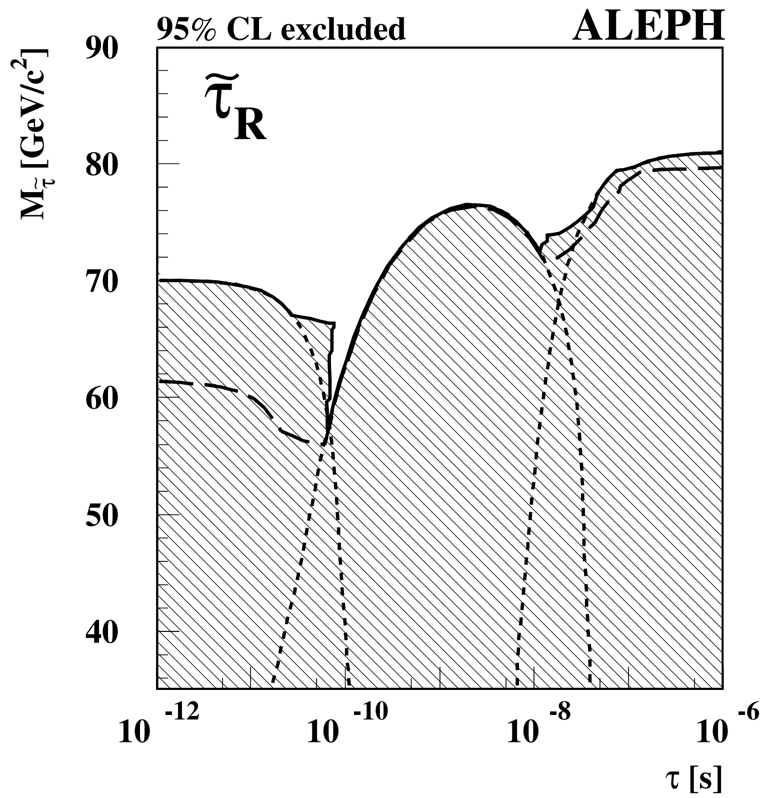

Figure 2: Lower limit on the mass of $\widetilde{\tau}_R$ as a function of its lifetime, from the ALEPH 183 GeV data [12]. The full line shows the actual mass limit obtained, while the long dashed line shows the limit expected from Monte Carlo studies. The short dashed lines indicate the limits from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

limit on $M_{\widetilde{\chi}_1^0}$ to be derived [9,11]. The key assumption is that the gaugino mass parameters M_1 and M_2 unify at the GUT scale, which leads to a definite relation between them at the electroweak scale: $M_1 = \frac{5}{3}\tan^2\theta_W M_2$. Assuming slepton masses to be at least 200 GeV/c^2, the bound on $M_{\widetilde{\chi}_1^0}$ is derived from the results of chargino and neutralino searches and certain bounds from LEP 1.

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

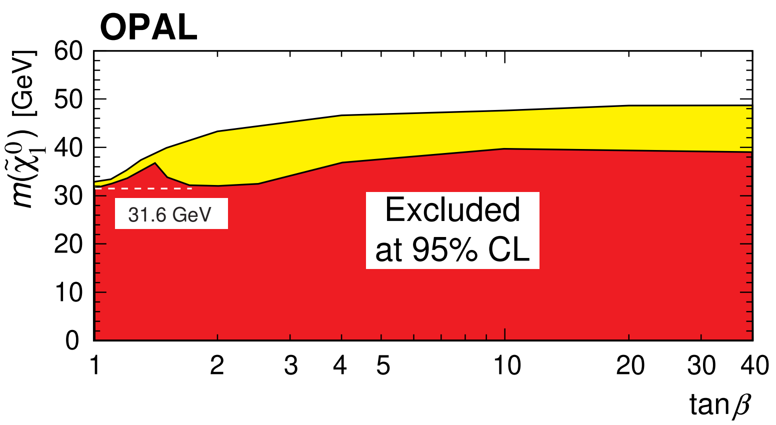

Figure 3: Lower limit on the mass of the lightest neutralino, derived by the OPAL Collaboration using constraints from chargino, neutralino, and slepton searches [8]. The light shaded region is obtained assuming $m_0 \gtrsim 500$ GeV/c^2; the dark region, for any m_0.

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

If R-parity is not conserved, searches based on missing energy are not viable. The three possible RPV interaction terms ($LL\overline{E}$, $LQ\overline{D}$, $\overline{U}\,\overline{D}\,\overline{D}$) violate lepton or baryon number, consequently precisely measured SM processes constrain products of dissimilar terms. Collider searches assume only one of the many possible terms dominates; given this assumption, searches for charginos and neutralinos, sleptons and squarks have been performed. All sets of generational indices (λ_{ijk}, λ'_{ijk}, λ''_{ijk}) have been considered, allowing for both *direct* and *indirect* RPV processes. Rather exotic topologies can occur, such as six-lepton final states in slepton production with $LL\overline{E}$ dominating, or ten-jet final states in chargino production with $\overline{U}\,\overline{D}\,\overline{D}$ dominating; entirely new search criteria keyed to an excess of leptons and/or jets have been devised [20]. Searches with a wide scope have found no evidence for supersymmetry with R-parity violation, and limits are as constraining as in the canonical scenario. In fact, the direct exclusion of pair-produced $\widetilde{\chi}^0_1$'s rules out some parameter space not accessible in the canonical case.

Visible signals from the lightest neutralino are also realized in special cases of GMSB which predict $\widetilde{\chi}^0_1 \to \gamma\,\widetilde{g}_{3/2}$ with a lifetime short enough for the decay to occur inside the detector [21]. The most promising topology consists of two energetic photons and missing energy resulting from $e^+e^- \to$

$\widetilde{\chi}_1^0\widetilde{\chi}_1^0$. For the DELPHI search, a technique was developed to identify photons which do not originate from the primary vertex. No excess was observed over the expected number of background events [21], leading to a bound on the neutralino mass of about 84 GeV/c^2. When the results are combined [22], the limit is $M_{\widetilde{\chi}_1^0} > 89$ GeV/c^2. Single-photon production has been used to constrain the process $e^+e^- \rightarrow \widetilde{g}_{3/2}\widetilde{\chi}_1^0$.

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

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

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

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

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

Charginos and neutralinos may be produced directly by annihilation ($q\overline{q} \to \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^0$) or in the decays of heavier squarks

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

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

The dilepton signal is geared more for the production of charginos in gluino and squark cascades [26]. Jets are required as expected from the rest of the decay chain; the leptons should be well separated from the jets in order to avoid backgrounds from heavy quark decays. Drell-Yan events are rejected with simple cuts on the relative azimuthal angles of the leptons and their transverse momentum. In some analyses the Majorana nature of the gluino is exploited by requiring two leptons with the same charge, thereby greatly reducing the background. In this scenario limits on squarks and gluinos are almost as stringent as in the classic jets+ $\not\!\!E_T$ case.

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

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

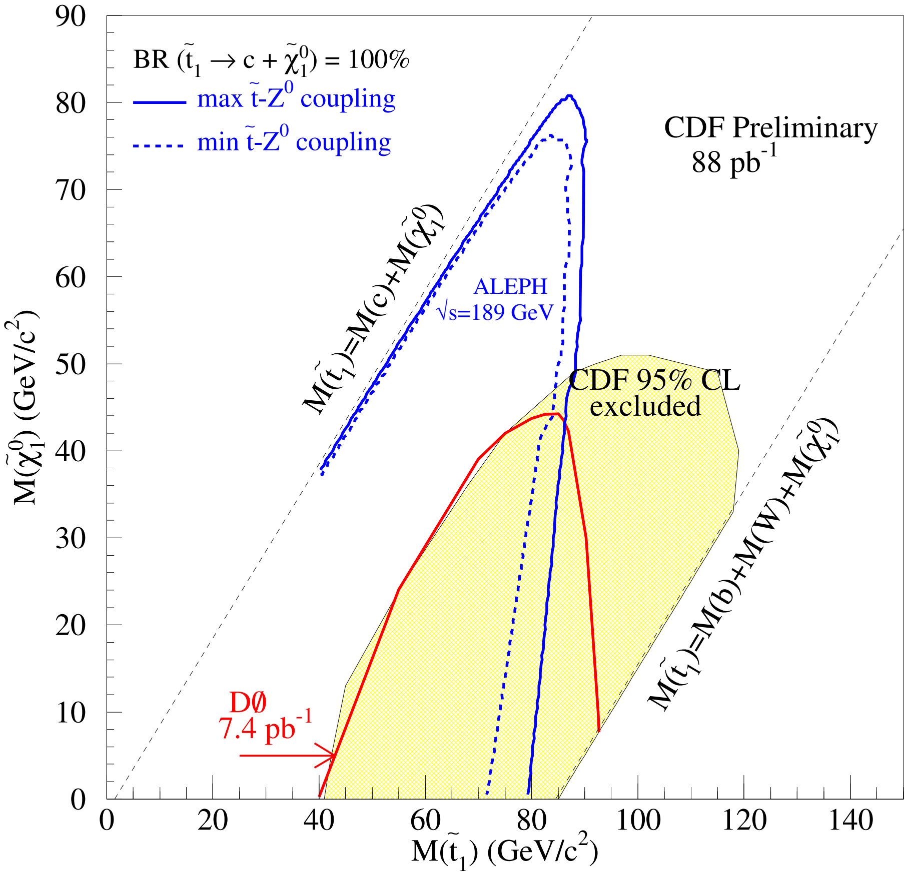

Figure 4: Excluded stop and sneutrino masses, for the $c\widetilde{\chi}^0_1$ decay mode, from the CDF Collaboration [27].

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

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

Interest in GMSB models was generated by an anomalous event observed by the CDF Collaboration [29]. These models predict large inclusive signals for $p\overline{p} \to \gamma\gamma + X$ given kinematic constraints derived from the properties of the CDF event. DØ reported a result from events with two energetic photons and large $\not\!\!E_T$ resulting in the limit $M_{\widetilde{\chi}_1^0} > 75$ GeV/c^2 [30]. DØ also looked specifically for squarks and gluinos in the scenario, which would give two photons and two or more jets, and obtained squark and gluino mass limits of 320 GeV/c^2. An analysis reported by CDF looks for virtually all thinkable topologies involving two energetic photons [30]. The neutralino mass limit is the same.

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

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

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

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

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

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SUPERSYMMETRIC MODEL ASSUMPTIONS

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 $\overline{U}\overline{D}\overline{D}$. 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.

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

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

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

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

Obsolete limits obtained from $e^+ e^-$ collisions up to $\sqrt{s}$=136 GeV have been removed from this compilation and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. $\Delta m_0 = m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>32.5 (CL = 95%)					
>31.6	95	[1] ABBIENDI	00H	OPAL	all $\tan\beta$, all Δm_0 >5 GeV, all m_0
>31.0	95	[2] ABREU	00J	DLPH	$\tan\beta \geq 1$, $m_{\widetilde{\nu}} >$ 300 GeV
>32.5	95	[3] ACCIARRI	00D	L3	$\tan\beta >$ 0.7, $\Delta m_0 >$ 3 GeV, all m_0
>27	95	[4] BARATE	99P	ALEP	all $\tan\beta$, all m_0

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

>30.1	95	[5] ABBIENDI	99G	OPAL	$\tan\beta$=1, all Δm_0, m_0=500 GeV
>24.2	95	[5] ABBIENDI	99G	OPAL	$\tan\beta$=1, all Δm_0, all m_0
>29.1	95	[6] ABREU	99E	DLPH	$\tan\beta \geq 1$, all Δm_0, m_0= 1 TeV
		[2] ABBOTT	98C	D0	$p\overline{p} \rightarrow \widetilde{\chi}_1^{\pm} \widetilde{\chi}_2^0$
>41	95	[7] ABE	98J	CDF	$p\overline{p} \rightarrow \widetilde{\chi}_1^{\pm} \widetilde{\chi}_2^0$
>24.9	95	[8] ABREU	98	DLPH	$\tan\beta > 1$, m_0=1 TeV
>10.9	95	[9] ACCIARRI	98F	L3	$\tan\beta > 1$
>13.3	95	[10] ACKERSTAFF	98L	OPAL	$\tan\beta > 1$
>17	95	[11] ELLIS	97C	RVUE	All $\tan\beta$

[1] 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 $\tan\beta$=1. The results of ABBIENDI 99F are used to constrain regions of parameter space dominated by radiative $\widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 \gamma$ decays. The limit improves to 48.5 GeV for m_0=500 GeV and $\tan\beta$=35. See their Table and Figs 4–5 for the $\tan\beta$ and m_0 dependence of the limits.

[2] ABREU 00J data collected at $\sqrt{s}$=189 GeV. The parameter space is scanned in the domain $0 < M_2 < 3000$ GeV, $|\mu| < 200$ GeV, $1 < \tan\beta < 35$. The analysis includes the effects of gaugino cascade decays. In the case of radiative neutralino decays, the limits from $Z \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_2^0$ decays in ABREU 97J are assumed.

[3] 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 $\tan\beta$=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 $\tan\beta$ and m_0 dependence of the limits.

[4] BARATE 99P data collected at $\sqrt{s}$=183 GeV. The limit is also based on the constraints from the total and invisible Z^0 width from ABBANEO 97, on direct searches for neutralinos at LEP1 from DECAMP 92 and on the slepton limits from BARATE 98K. The limit improves to 29 GeV if the unification of Higgs and sfermion masses is also assumed, and direct constraints on the Higgs mass are used.

[5] ABBIENDI 99G data collected at $\sqrt{s} \leq 184$ GeV. The parameter space is scanned in the domain $0 < M_2 < 2000$ GeV, $|\mu| < 500$ GeV, and for various values of A. No dependence of the limits on A is found. The analysis includes the effects of gaugino cascade decays. In the case of radiative neutralino decays, the limits from ACKERSTAFF 98J are assumed. The limit for all values of m_0 assumes $m_{\widetilde{\nu}_e} > 43$ GeV and direct limits on charged sleptons. See Table 5 for limits under different assumptions on Δm_0 and $\tan\beta$.

[6] ABREU 99E data collected at $\sqrt{s}$=183 GeV. These results include and update the limits from ABREU 98. The parameter space is scanned in the domain $0 < M_2 < 3000$ GeV, $|\mu| < 400$ GeV, $1 < \tan\beta < 35$. The analysis includes the effects of gaugino cascade decays. In the case of radiative neutralino decays, the limits from ABREU 97J are assumed.

[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.

[8] ABREU 98 bound combines the chargino and neutralino searches at $\sqrt{s}$=161, 172 GeV with single-photon-production results at LEP-1 from ABREU 97J.

[9] ACCIARRI 98F limit is obtained for $0 < M_2 < 2000$, $|\mu| < 500$, and $1 < \tan\beta < 40$, but remains valid outside this domain. No dependence on the trilinear-coupling parameter A is found. The limit holds for all values of m_0 consistent with scalar lepton contraints. It improves to 24.6 GeV for $m_{\widetilde{\nu}} > 200$ GeV. Data taken at $\sqrt{s}$ = 130–172 GeV.

[10] ACKERSTAFF 98L limit is obtained for $0 < M_2 < 1500$, $|\mu| < 500$ and $\tan\beta > 1$, but remains valid outside this domain. The limit holds for the smallest value of m_0 consistent with scalar lepton constraints (ACKERSTAFF 97H). It improves to 24.7 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$=130–172 GeV.

[11] ELLIS 97C uses constraints on $\chi^{\pm}$, χ^0, and $\widetilde{\ell}$ production obtained by the LEP experiments from $e^+ e^-$ collisions at $\sqrt{s}$ = 130–172 GeV. It assumes a universal mass m_0 for scalar leptons at the grand unification scale.

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

These papers generally exclude regions in the $M_2 - \mu$ parameter plane assuming that $\widetilde{\chi}_1^0$ 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 neturino detectors. The latter signal is expected if $\widetilde{\chi}_1^0$ accumlates 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. • • •			
	[12] AMBROSIO	99	MCRO
	[13] BOTTINO	97	DAMA
	[14] LOSECCO	95	RVUE
	[15] MORI	93	KAMI
	[16] BOTTINO	92	COSM
	[17] BOTTINO	91	RVUE
	[18] GELMINI	91	COSM
	[19] KAMIONKOW..	91	RVUE
	[20] MORI	91B	KAMI
none 4–15 GeV	[21] OLIVE	88	COSM

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

[13] BOTTINO 97 points out that the current data from the dark-matter detection experiment DAMA are sensitive to neutralinos in domains of parameter space not excluded by terrestrial laboratory searches.

[14] LOSECCO 95 reanalyzed the IMB data and places lower limit on $m_{\widetilde{\chi}_1^0}$ 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-enery neutrinos and the limits on neutrino fluxes from the IMB detector.

[15] MORI 93 excludes some region in M_2–μ parameter space depending on $\tan\beta$ 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.

[16] 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.

[17] 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.

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

[19] 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.

[20] 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.

[21] 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.

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

Most of these papers generally exclude regions in the $M_2-\mu$ parameter plane by requiring that the $\widetilde{\chi}^0_1$ 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	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 42 (CL = 95%)					
> 42	95	[22] ELLIS	98	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<600		[23] ELLIS	98B	COSM	
		EDSJO	97	COSM	Co-annihilation
> 40		[24] ELLIS	97C	RVUE	
> 21.4	95	[25] ELLIS	96B	RVUE	$\tan\beta > 1.2$, $\mu < 0$
		[26] FALK	95	COSM	*CP*-violating phases
		DREES	93	COSM	Minimal supergravity
		FALK	93	COSM	Sfermion mixing
		KELLEY	93	COSM	Minimal supergravity
		MIZUTA	93	COSM	Co-annihilation
		ELLIS	92F	COSM	Minimal supergravity
		KAWASAKI	92	COSM	Minimal supergravity, m_0=A=0
		LOPEZ	92	COSM	Minimal supergravity, m_0=A=0
		MCDONALD	92	COSM	
		NOJIRI	91	COSM	Minimal supergravity
		[27] OLIVE	91	COSM	
		ROSZKOWSKI	91	COSM	
		ELLIS	90	COSM	
		[28] GRIEST	90	COSM	
		[29] GRIFOLS	90	ASTR	$\widetilde{\gamma}$; SN 1987A
		KRAUSS	90	COSM	
		[27] OLIVE	89	COSM	
> 100 eV		[30] ELLIS	88B	ASTR	$\widetilde{\gamma}$; SN 1987A
none 100 eV – (5–7) GeV		SREDNICKI	88	COSM	$\widetilde{\gamma}$; $m_{\widetilde{f}}$=60 GeV
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	$\widetilde{\gamma}$
		[31] KRAUSS	83	COSM	$\widetilde{\gamma}$
		VYSOTSKII	83	COSM	$\widetilde{\gamma}$

[22] ELLIS 98 updates ELLIS 97C (see relative footnote). Use is made of one-loop mass and coupling relations, as well as of chargino limits from e^+e^- data at $\sqrt{s}$=183 GeV. The limits on tanβ from ELLIS 97C improve to: tan$\beta > 2$ ($\mu < 0$) and tan$\beta > 1.65$ ($\mu > 0$).

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

[24] ELLIS 97C uses in addition to cosmological constraints, data from e^+e^- collisions at 170–172 GeV. It assumes a universal scalar mass for both the Higgs and scalar leptons, as well as radiative supersymmetry breaking with universal gaugino masses. ELLIS 97C also uses the absence of Higgs detection (with the assumptions listed above) to set a limit on tan$\beta > 1.7$ for $\mu < 0$ and tan$\beta > 1.4$ for $\mu > 0$. This paper updates ELLIS 96B.

[25] ELLIS 96B uses, in addition to cosmological constraints, data from BUSKULIC 96K and SUGIMOTO 96. It assumes a universal scalar mass m_0 and radiative Supersymmetry breaking, with universal gaugino masses.

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

[27] 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.

[28] 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.

[29] GRIFOLS 90 argues that SN1987A data exclude a light photino ($\lesssim$ 1 MeV) if $m_{\widetilde{q}} < 1.1$ TeV, $m_{\widetilde{e}} < 0.83$ TeV.

[30] ELLIS 88B argues that the observed neutrino flux from SN 1987A is inconsistent with a light photino if 60 GeV $\lesssim m_{\widetilde{q}} \lesssim$ 2.5 TeV. If m(higgsino) is O(100 eV) the same argument leads to limits on the ratio of the two Higgs v.e.v.'s. LAU 93 discusses possible relations of ELLIS 88B bounds.

[31] 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 $\widetilde{\chi}_1^0$ (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. • • •					
>27	95	[32] ABREU	00I	DLPH	$\not\!R$ ($LL\overline{E}$), any Δm_0, $1 \leq$ tan$\beta \leq 30$
>86	95	[33] BARATE	00G	ALEP	$e^+e^- \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ ($\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{G}$)
		[34] ABBIENDI	99F	OPAL	$e^+e^- \rightarrow \widetilde{G}\widetilde{\chi}_1^0$ ($\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{G}$)
none 45–83	95	[35] ABBIENDI	99F	OPAL	$e^+e^- \rightarrow \widetilde{B}\widetilde{B}$ ($\widetilde{B} \rightarrow \gamma\widetilde{G}$)
>29	95	[36] ABBIENDI	99T	OPAL	$e^+e^- \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_1^0$, $\not\!R$, m_0=500 GeV, tan$\beta > 1.2$
>65	95	[37] ABE	99I	CDF	$p\overline{p} \rightarrow \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}$=$\widetilde{\chi}_{1,2}^0$,$\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{G}$
>83	95	[38] ABREU	99D	DLPH	$e^+e^- \rightarrow \widetilde{B}\widetilde{B}$ ($\widetilde{B} \rightarrow \gamma\widetilde{G}$)

		[39] ABREU	99F	DLPH	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$, with $\tilde{\chi}^0_1 \rightarrow \tau\tilde{\tau}$ ($\tilde{\tau} \rightarrow \tau\tilde{G}$)
>26.8	95	[40] ACCIARRI	99I	L3	$\tilde{\chi}^0_1\tilde{\chi}^0_1$, $\not{R}$
		[41] ACCIARRI	99R	L3	$e^+e^- \rightarrow \tilde{G}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$
>88.2	95	[42] ACCIARRI	99R	L3	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$
>29	95	[43] BARATE	99E	ALEP	$\not{R}$, $LQ\overline{D}$, $\tan\beta$=1.41, m_0=500 GeV
>77	95	[44] ABBOTT	98	D0	$p\overline{p} \rightarrow \tilde{\chi}\tilde{\chi}$, $\tilde{\chi}=\tilde{\chi}^0_{1,2}$,$\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$
		[45] ABREU	98	DLPH	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$)
		[46] ACCIARRI	98V	L3	$e^+e^- \rightarrow \tilde{G}\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$)
>79	95	[47] ACCIARRI	98V	L3	$e^+e^- \rightarrow \tilde{B}\tilde{B}$ ($\tilde{B} \rightarrow \gamma\tilde{G}$)
		[48] ACKERSTAFF	98J	OPAL	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$)
		[49] BARATE	98H	ALEP	$e^+e^- \rightarrow \tilde{G}\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$)
>71	95	[50] BARATE	98H	ALEP	$e^+e^- \rightarrow \tilde{B}\tilde{B}$ ($\tilde{B} \rightarrow \gamma\tilde{G}$)
		[51] BARATE	98J	ALEP	$e^+e^- \rightarrow \tilde{G}\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$)
>84	95	[52] BARATE	98J	ALEP	$e^+e^- \rightarrow \tilde{B}\tilde{B}$ ($\tilde{B} \rightarrow \gamma\tilde{G}$)
>23	95	[53] BARATE	98S	ALEP	$\not{R}$, $LL\overline{E}$
		[54] ACCIARRI	97V	L3	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$)
		[55] ELLIS	97	THEO	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$
		[56] CABIBBO	81	COSM	

[32] ABREU 00I searches for the production of charginos and neutralinos in the case of R-parity violation with $LL\overline{E}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling at the time to be non-zero 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 $\tan\beta$.

[33] BARATE 00G search for diphoton + $\not{E}$ topologies using data collected at $\sqrt{s}$=189 GeV. Limits are obtained from a scan of GMSB parameters space, under the assumption of a short-lived $\tilde{\chi}^0_1$ NLSP. The limit is reduced to 45 GeV for long-lived neutralinos.

[34] ABBIENDI 99F obtained an upper bound on the cross section for the process $e^+e^- \rightarrow \tilde{G}\tilde{\chi}^0_1$ followed by the prompt decay $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$ of 0.46–0.075 pb for $m_{\tilde{\chi}^0_1}$=91–183 GeV. See Fig. 8 for the detailed dependence of $m_{\tilde{\chi}^0_1}$. Data taken at $\sqrt{s}$=183 GeV.

[35] ABBIENDI 99F looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$=183 GeV. The limit is for pure bino $\tilde{B}$ and assumes $m_{\tilde{e}_R}$=1.35$m_{\tilde{B}}$ and $m_{\tilde{e}_L}$=2$m_{\tilde{e}_R}$. See Fig. 13 for the cross-section limits as a function of $m_{\tilde{\chi}^0_1}$.

[36] 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 mulitiple 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 $\tan\beta > 20$.

[37] ABE 99I looked for chargino and neutralino production, where the lightest neutralino in their decay products further decays into $\gamma\tilde{G}$. 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.

[38] ABREU 99D looked for $\gamma\gamma\not\!\!E$ final states at $\sqrt{s}$=130–183 GeV. The limit is for prompt decay of pure bino $\widetilde{B}$ and assumes $m_{\widetilde{e}_R}$=1.1$m_{\widetilde{B}}$ GeV. The limit reduces to 76 GeV for $m_{\widetilde{e}_R}$=150 GeV. See Fig. 14 for the limits as a function of $m_{\widetilde{e}_R}$. Model-independent cross-section limits in the range 0.10–0.13 pb are shown in Fig. 9, for neutralino masses in the range 45–81.5 GeV. Cross section limits were also derived, see Fig. 13, as function of the decay length, including non-pointing single photon final states.

[39] ABREU 99F looked for acoplanar ditaus, taus with large impact parameters, kinks, and stable heavy-charged tracks at $\sqrt{s}$=130–183 GeV. See Table 5 for explicit $m_{\widetilde{\chi}^0_1}$ limits under different model assumptions.

[40] ACCIARRI 99I looked for multi-lepton and/or multi-jet final states from $\not\!\!R$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings 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 and both yield the same mass limit.

[41] 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.

[42] 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.

[43] 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.

[44] 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.

[45] 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.

[46] ACCIARRI 98V obtained an upper bound on the cross section for the process $e^+e^- \rightarrow \widetilde{G}\widetilde{\chi}^0_1$ followed by the prompt decay $\widetilde{\chi}^0_1 \rightarrow \widetilde{G}\gamma$ of 0.28–0.07 pb $m_{\widetilde{\chi}^0_1}$=0–183 GeV. See Fig. 4b for the detailed dependence on $m_{\widetilde{\chi}^0_1}$. Data taken at $\sqrt{s}$=183 GeV.

[47] ACCIARRI 98V looked for $\gamma\gamma\not\!\!E$ final states at $\sqrt{s}$=183 GeV. The limit is for pure bino $\widetilde{B}$ and assumes $m_{\widetilde{e}_{R,L}}$=150 GeV. The limit improves to 84 GeV for $m_{\widetilde{e}_{R,L}}$=100 GeV. See Fig. 7 for the cross-section limits as a function of $m_{\widetilde{\chi}^0_1}$, for different cases of neutralino composition.

[48] ACKERSTAFF 98J looked for $\gamma\gamma\not\!\!E$ final states at $\sqrt{s}$=161–172 GeV. They set limits on $\sigma(e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1)$ in the range 0.22–0.50 pb for $m_{\widetilde{\chi}^0_1}$ in the range 45–86 GeV. Mass limits for explicit models from the literature are given in Fig. 19 of their paper. Similar limits on γ+missing energy are also given, relevant for $\widetilde{\chi}^0_1\widetilde{G}$ production.

[49] BARATE 98H obtained an upper bound on the cross section for the process $e^+e^- \rightarrow \widetilde{G}\widetilde{\chi}^0_1$ followed by the prompt decay $\widetilde{\chi}^0_1 \rightarrow \widetilde{G}\gamma$ of 0.4–0.75 pb for $m_{\widetilde{\chi}^0_1}$ = 40–170 GeV. Data taken at $\sqrt{s}$ = 161,172 GeV.

[50] BARATE 98H looked for $\gamma\gamma\not\!\!E$ final states at $\sqrt{s}$ = 161,172 GeV. The limit is for pure bino $\widetilde{B}$ with $\tau(\widetilde{B})$< 3 ns and assumes $m_{\widetilde{e}_R}$ = 1.5$m_{\widetilde{B}}$. See Fig. 5 for the dependence of the limit on $m_{\widetilde{e}_R}$.

[51] BARATE 98J looked for $\gamma\not\!\!E$ final states at $\sqrt{s}$ = 161–183 GeV. They obtained an upper bound on the cross section of about 0.2 pb for the process $e^+e^- \rightarrow XY$ followed by the prompt decay $X \rightarrow Y\gamma$ ($\tau(X)$< 0.1 ns) if m_Y = 0. The bound applies for $\widetilde{G}\widetilde{\chi}^0_1$.

[52] BARATE 98J looked for $\gamma\gamma \not{E}$ final states at $\sqrt{s}$ = 161–183 GeV. The limit is for pure bino $\widetilde{B}$ with $\tau(\widetilde{B})<$ 3 ns and assumes $m_{\widetilde{e}_R} = 1.1 m_{\widetilde{B}}$. See Fig. 5 for the dependence of the limit on $m_{\widetilde{e}_R}$.

[53] BARATE 98S looked for the decay of gauginos via $\not{R}$-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.

[54] ACCIARRI 97V looked for $\gamma\gamma\not{E}$ final states at $\sqrt{s}$=161 and 172 GeV. They set limits on $\sigma(e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1)$ in the range 0.25–0.50 pb for masses in the range 45–85 GeV. The lower limits on $m_{\widetilde{\chi}^0_1}$ vary in the range of 64.8 GeV (pure bino with 90 GeV slepton) to 75.3 GeV (pure higgsino). There is no limit for pure zino case.

[55] ELLIS 97 reanalyzed the LEP2 ($\sqrt{s}$=161 GeV) limits of $\sigma(\gamma\gamma+E_{\rm miss})<$ 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.

[56] 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 (CL = 95%)					
> 55.9	95	[57] ABBIENDI	00H	OPAL	$\widetilde{\chi}^0_2$, tanβ=1.5, Δm >10 GeV, all m_0
>106.6	95	[57] ABBIENDI	00H	OPAL	$\widetilde{\chi}^0_3$, tanβ=1.5, Δm >10 GeV, all m_0
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[58] ABBIENDI	99F	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^0_2\widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_2 \rightarrow \gamma\widetilde{\chi}^0_1$)
		[59] ABBIENDI	99F	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^0_2\widetilde{\chi}^0_2$ ($\widetilde{\chi}^0_2 \rightarrow \gamma\widetilde{\chi}^0_1$)
> 44	95	[60] ABBIENDI	99G	OPAL	$\widetilde{\chi}^0_2$, tanβ > 1, Δm_0 > 10 GeV
>102	95	[60] ABBIENDI	99G	OPAL	$\widetilde{\chi}^0_3$, tanβ=1.5, Δm_0 > 10 GeV
		[61] ABREU	99D	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^0_2\widetilde{\chi}^0_2$ ($\widetilde{\chi}^0_2 \rightarrow \gamma\widetilde{\chi}^0_1$)
> 34.8	95	[62] ACCIARRI	99I	L3	$\widetilde{\chi}^0_2$, $\not{R}$

		[63] ACCIARRI	99R	L3	$e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_{2,1}$, $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma$
		[64] ABBOTT	98C	D0	$p\overline{p} \to \tilde{\chi}^\pm_1\tilde{\chi}^0_2$
>82.2	95	[65] ABE	98J	CDF	$p\overline{p} \to \tilde{\chi}^\pm_1\tilde{\chi}^0_2$
>92	95	[66] ACCIARRI	98F	L3	$\widetilde{H}^0_2$, $\tan\beta$=1.41, $M_2 < 500$ GeV
		[67] ACCIARRI	98V	L3	$e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_{1,2}$ ($\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$)
>45.3	95	[68] ACKERSTAFF	98L	OPAL	$\tilde{\chi}^0_2$, $\tan\beta > 1$
>75.8	95	[68] ACKERSTAFF	98L	OPAL	$\tilde{\chi}^0_3$, $\tan\beta > 1$
>53	95	[69] BARATE	98H	ALEP	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \to \gamma\widetilde{H}^0$)
>74	95	[70] BARATE	98J	ALEP	$e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \to \gamma\widetilde{H}^0$)
		[71] ABACHI	96	D0	$p\overline{p} \to \tilde{\chi}^\pm_1\tilde{\chi}^0_2$
		[72] ABE	96K	CDF	$p\overline{p} \to \tilde{\chi}^\pm_1\tilde{\chi}^0_2$
>86.3	95	[73] ACKERSTAFF	96C	OPAL	$\tilde{\chi}^0_3$

[57] ABBIENDI 00H used the results of direct searches in the $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_{2,3}$ channels, as well as the indirect limits from $\tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1$ 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 ($\tilde{\chi}^0_2$) and 124 GeV ($\tilde{\chi}^0_3$) for $\tan\beta$=35. See their Table 6 for more details on the $\tan\beta$ and m_0 dependence of the limits.

[58] 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 $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_1$ followed by the prompt decay $\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$ of 0.075–0.80 pb in the region $m_{\tilde{\chi}^0_2}+m_{\tilde{\chi}^0_1} > m_Z$, $m_{\tilde{\chi}^0_2}$=91–183 GeV, and $\Delta m_0 > 5$ GeV. See Fig. 7 for explicit limits in the ($m_{\tilde{\chi}^0_2}$,$m_{\tilde{\chi}^0_1}$) plane.

[59] 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 $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$ followed by the prompt decay $\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$ of 0.08–0.37 pb for $m_{\tilde{\chi}^0_2}$=45–81.5 GeV, and $\Delta m_0 > 5$ GeV. See Fig. 11 for explicit limits in the ($m_{\tilde{\chi}^0_2}$,$m_{\tilde{\chi}^0_1}$) plane.

[60] ABBIENDI 99G uses the results of direct searches in the $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_{2,3}$ channels, as well as the indirect limits from $\tilde{\chi}^0_1$,$\tilde{\chi}^\pm_1$ searches within the MSSM. See the footnote to ABBIENDI 99G in the Chargino Section for further details on the assumptions. Data collected at $\sqrt{s}$=181–184 GeV.

[61] ABREU 99D looked for $\gamma\,\gamma\,\not\!\!E$ final states at $\sqrt{s}$=183 GeV. They obtained upper bounds in the range 0.10–0.25 pb on the cross section for the production $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$ followed by the prompt decay $\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$ with $\Delta m_0 > 6$ GeV. See Fig. 12 for explicit limits in the ($m_{\tilde{\chi}^0_2}$,$m_{\tilde{\chi}^0_1}$) plane.

[62] ACCIARRI 99I looked for multi-lepton and/or multi-jet final states from $\not\!R$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings at $\sqrt{s}$=130–183 GeV. The situations where the $\tilde{\chi}^0_1$ is the LSP (indirect decays) and where a $\tilde{\ell}$ is the LSP (direct decays) were both considered. The weakest limit, quoted above, comes from direct decays with $\overline{UDD}$ couplings; indirect decays lead to a limit of 44.3 GeV.

[63] 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 $e^+ e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_{2,1}$ with the decay $\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 \gamma$ are derived, as shown in their Figs. 4 and 7. Supersedes the results of ACCIARRI 98V.

[64] 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 $m_{\widetilde{\chi}^0_2} \gtrsim$ 103 GeV.

[65] 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 $m_{\widetilde{\chi}^0_2}$ 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.

[66] ACCIARRI 98F is obtained from direct searches in the $e^+ e^- \rightarrow \widetilde{\chi}^0_{1,2} \widetilde{\chi}^0_2$ production channels, and indirectly from $\widetilde{\chi}^\pm_1$ and $\widetilde{\chi}^0_1$ searches within the MSSM. See footone to ACCIARRI 98F in the chargino Section for futher details on the assumptions. Data taken at $\sqrt{s}$ = 130–172 GeV.

[67] 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 $e^+ e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_{1,2}$ followed by the prompt decay $\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$. See Figs. 4a and 6a for explicit limits in the ($m_{\widetilde{\chi}^0_2}$,$m_{\widetilde{\chi}^0_1}$) plane.

[68] ACKERSTAFF 98L is obtained from direct searches in the $e^+ e^- \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_{2,3}$ production channels, and indirectly from $\widetilde{\chi}^\pm_1$ and $\widetilde{\chi}^0_1$ searches within the MSSM. See footnote to ACKERSTAFF 98L in the chargino Section for further details on the assumptions. Data taken at $\sqrt{s}$=130–172 GeV.

[69] 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 $e^+ e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_2$ followed by the prompt decay $\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$ of 0.4–0.8 pb for $m_{\widetilde{\chi}^0_2}$ = 10–80 GeV. The bound above is for the specific case of $\widetilde{\chi}^0_1 = \widetilde{H}^0$ and $\widetilde{\chi}^0_2 = \widetilde{\gamma}$ and $m_{\widetilde{e}_R}$ = 100 GeV. See Fig. 6 and 7 for explicit limits in the ($\widetilde{\chi}^0_2$,$\widetilde{\chi}^0_1$) plane and in the ($\widetilde{\chi}^0_2$,$\widetilde{e}_R$) plane.

[70] 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 $e^+ e^- \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_2$ followed by the prompt decay $\widetilde{\chi}^0_2 \rightarrow \gamma \widetilde{\chi}^0_1$ of 0.08–0.24 pb for $m_{\widetilde{\chi}^0_2}$ < 91 GeV. The bound above is for the specific case of $\widetilde{\chi}^0_1 = \widetilde{H}^0$ and $\widetilde{\chi}^0_2 = \widetilde{\gamma}$ and $m_{\widetilde{e}_R}$ = 100 GeV.

[71] 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 $\sigma(\widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2) \times$ B($\widetilde{\chi}^\pm_1 \rightarrow \ell \nu_\ell \widetilde{\chi}^0_1$) × B($\widetilde{\chi}^0_2 \rightarrow \ell^+ \ell^- \widetilde{\chi}^0_1$) as a function of $m_{\widetilde{\chi}^0_1}$. Limits range from 3.1 pb ($m_{\widetilde{\chi}^0_1}$ = 45 GeV) to 0.6 pb ($m_{\widetilde{\chi}^0_1}$ = 100 GeV).

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

[73] ACKERSTAFF 96C is obtained from direct searches in the $e^+ e^- \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_{2,3}$ production channel, and indirectly from $\widetilde{\chi}^\pm_1$ searches within MSSM. Data from $\sqrt{s}$ = 130, 136, and 161 GeV are combined. The same assumptions and constraints of ALEXANDER 96J apply. The limit improves to 94.3 GeV for m_0 = 1 TeV.

$\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_2^\pm$ (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 1999 run of LEP2 at $\sqrt{s}$ up to 202 GeV give therefore a lower mass limit of approximately 101 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
> 67.7 (CL = 95%)					
> 71.7	95	[74] ABBIENDI	00H	OPAL	$\tan\beta$=35, Δm_+ >5 GeV, all m_0
> 88.4	95	[75] ABREU	00J	DLPH	$\Delta m_+ \geq$ 3 GeV, $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^\pm}$, $\tan\beta \geq 1$
> 67.7	95	[76] ACCIARRI	00D	L3	$\tan\beta > 0.7$, $\Delta m_+ > 3$ GeV, all m_0
> 68	95	[77] BARATE	98X	ALEP	$\tan\beta$=1.41, all m_0
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 89	95	[78] ABREU	00I	DLPH	$\not{R}$ ($LL\overline{E}$), any Δm_0, $1 \leq \tan\beta \leq 30$
> 94.1	95	[79] ABREU	00J	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^\pm\widetilde{\chi}^\mp$ ($\widetilde{\chi}^0 \rightarrow \gamma\widetilde{G}$), $\tan\beta \geq 1$
> 91	95	[80] BARATE	00H	ALEP	$\not{R}$ $LL\overline{E}$, $LQ\overline{D}$, $\overline{UDD}$, $m_0 > 500$ GeV
> 90.0	95	[81] ABBIENDI	99G	OPAL	$\tan\beta$=1.5, $\Delta m_+ >$ 5 GeV, m_0=500 GeV
> 69.1	95	[81] ABBIENDI	99G	OPAL	$\tan\beta$=1.5, $\Delta m_+ > 5$ GeV, all m_0
> 76	95	[82] ABBIENDI	99T	OPAL	$\not{R}$, m_0=500 GeV
>120	95	[83] ABE	99I	CDF	$p\overline{p} \rightarrow \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}$=$\widetilde{\chi}_{1,2}^0$,$\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{G}$
> 89.4	95	[84] ABREU	99E	DLPH	$\Delta m_+ > 10$ GeV, $m_{\widetilde{\nu}} > 300$ GeV

>88.8	95	[84] ABREU	99E	DLPH	$\Delta m_+ > 5$ GeV, $m_{\widetilde{\nu}} > 41$ GeV
>90.5	95	[85] ABREU	99E	DLPH	$e^+e^- \rightarrow \widetilde{\chi}_1^+\widetilde{\chi}_1^-$, $\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{G}$
>85.5	95	[86] ABREU	99V	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $\widetilde{\chi} \rightarrow \widetilde{\tau}\nu$, $\widetilde{\tau} \rightarrow \tau\widetilde{G}$
		[87] ABREU	99Z	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $\Delta m_+ < 3$ GeV
>76.9	95	[88] ACCIARRI	99I	L3	$\not{R}$, $LL\overline{E}$ or $\overline{UDD}$
>82	95	[89] BARATE	99E	ALEP	$\not{R}$, $LQ\overline{D}$
>51	95	[90] MALTONI	99B	THEO	EW analysis, $\Delta m_+ \sim 1$ GeV
>150	95	[91] ABBOTT	98	D0	$p\overline{p} \rightarrow \widetilde{\chi}\widetilde{\chi}$, $\widetilde{\chi}=\widetilde{\chi}_{1,2}^0$,$\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_1^0 \rightarrow \gamma\widetilde{G}$
		[92] ABBOTT	98C	D0	$p\overline{p} \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$
>81.5	95	[93] ABE	98J	CDF	$p\overline{p} \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$
>67.6	95	[94] ABREU	98	DLPH	$\Delta m > 10$ GeV
>71.8	95	[95] ABREU	98	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $\widetilde{\chi}_1^0 \rightarrow \widetilde{G}\gamma$
>69.2	95	[96] ACCIARRI	98F	L3	$\tan\beta < 1.41$, all m_0
		[97] ACKERSTAFF	98K	OPAL	$\widetilde{\chi}^+ \rightarrow \ell^+ \not{E}$
>65.7	95	[98] ACKERSTAFF	98L	OPAL	$\Delta m_+ > 3$ GeV, $\Delta m_{\nu} > 2$ GeV
		[99] ACKERSTAFF	98V	OPAL	light gluino
>73	95	[100] BARATE	98S	ALEP	$\not{R}$, $LL\overline{E}$
		[101] CARENA	97	THEO	$g_{\mu} - 2$
		[102] KALINOWSKI	97	THEO	$W \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^0$
		[103] ABE	96K	CDF	$p\overline{p} \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$
>62	95	[104] ACKERSTAFF	96C	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$

[74] 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 $\tan\beta$=1.5. See their Table 5 and Fig. 4 for the $\tan\beta$ and M_2 dependence of the limits.

[75] ABREU 00J data collected at $\sqrt{s}$=189 GeV. They investigate topologies with multiple leptons, jets plus leptons, multi-jets, or isolated photons. The parameter space is scanned in the domain $0<M_2 < 3000$ GeV, $|\mu| < 200$ GeV, $1<\tan\beta < 35$. The analysis includes the effects of gaugino cascade decays.

[76] 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 $\tan\beta$ 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.

[77] BARATE 98X limit holds for all values of m_0 consistent with the slepton mass limits of BARATE 97N. The limit improves to 79 GeV for a mostly higgsino $\widetilde{\chi}_1^{\pm}$ (with $\Delta m > 5$ GeV) and to 85.5 GeV for a mostly gaugino $\widetilde{\chi}_1^{\pm}$ ($\mu=-500$ GeV and $m_{\widetilde{\nu}} > 200$ GeV). The cases of $m_{\widetilde{\chi}_1^{\pm}} > m_{\widetilde{\nu}}$ or nonuniversal scalar mass or nonuniversal gaugino mass are also studied in the paper. Data collected at $\sqrt{s}$=161–172 GeV.

[78] ABREU 00I searches for the production of charginos and neutralinos in the case of R-parity violation with $LL\overline{E}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling at the time to be non-zero 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 $\tan\beta$.

[79] This ABREU 00J limit holds for $\Delta m_+ > 10$ GeV and $m_{\widetilde{\nu}} > 300$ GeV. For the other assumptions, see previous footnote to ABREU 00J in this Section. A limit of 94.2 GeV is obtained for Δm_+=1 GeV and $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^\pm}$.

[80] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limit holds for any possible R-parity violating coupling.

[81] ABBIENDI 99G data collected at $\sqrt{s} \leq 184$ GeV. The parameter space is scanned in the domain $0 < M_2 < 2000$ GeV, $|\mu| < 500$ GeV, and for various values of A. No dependence of the limits on A is found. The analysis includes the effects of gaugino cascade decays. In the case of radiative neutralino decays, the limits from ACKERSTAFF 98J are assumed. The limit for all values of m_0 assumes $m_{\widetilde{\nu}_e} > 43$ GeV and direct limits on charged sleptons. See Table 5 for limits under different assumptions on Δm_+ and $\tan\beta$.

[82] 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 mulitiple 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^*.

[83] 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.

[84] ABREU 99E data collected at $\sqrt{s} \leq 183$ GeV. These results include and update the limits from ABREU 98. The parameter space is scanned in the domain $0 < M_2 < 3000$ GeV, $|\mu| < 400$ GeV, $1 < \tan\beta < 35$. The analysis includes the effects of gaugino cascade decays. In the case of radiative neutralino decays, the limits from ABREU 97J are assumed.

[85] This ABREU 99E limit holds for $\Delta m_0 > 10$ GeV and $m_{\widetilde{\nu}} > 300$ GeV. For the other assumptions, see previous footnote to ABREU 99E in this Section. A limit of 90.6 GeV is obtained for Δm_+=1 GeV and $m_{\widetilde{\nu}} >$41 GeV.

[86] ABREU 99V reinterprets search results at 183 GeV on $\widetilde{\tau}$ decays at the interaction vertex (ABREU 99E), visible decay vertices in the tracking devices or large impact parameters (ABREU 99F) and stable charged heavy particles (ABREU 98P). Limits are computed by scanning the GMSB parameter space where $\widetilde{\tau}_1$ is the NLSP, with the constraints that electroweak symmetry is broken radiatively and that trilinear couplings are zero at the messenger scale. All branching ratios in the above decay chain are taken equal to 1. The limit holds for $m_{\widetilde{\chi}_1} - m_{\widetilde{\tau}_1} > 0.3$ GeV, and any gravitino mass, in the domain $m_{\widetilde{\tau}_1} > 68$ GeV, not excluded by the direct $\widetilde{\tau}$ production searches of ABREU 99F. The limit is reached for $m_{\widetilde{G}} \leq 1$ eV and improves to 89 GeV for $m_{\widetilde{G}} > 100$ eV. See Fig. 4 for the dependence of the limit on $m_{\widetilde{\tau}_1}$.

[87] ABREU 99Z searches for the production of charginos degenerate with $\widetilde{\chi}^0_1$, using data from $\sqrt{s}$= 130 to 183 GeV. The range $\Delta m_+ < 200$ MeV is covered by a search for decays visible in the detector or for heavy stable particles identified by their ionization or Cherenkov radiation. The region 300 MeV$< \Delta m_+ <$ 3 GeV is explored by searching events with initial state radiation and few low energy particles. For 200 MeV$< \Delta m_+ <$ 300 MeV, no limits are obtained. For limits in various scenarios, see Fig. 12 and Table 3.

[88] ACCIARRI 99I looked for multi-lepton and/or multi-jet final states from $\not{R}$ prompt decays with $LL\overline{E}$ or $\overline{UDD}$ couplings 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; indirect decays lead to a limit of 91.1 GeV for $LL\overline{E}$ and 90.9 GeV for $\overline{UDD}$ couplings.

[89] BARATE 99E looked for the decay of charginos via R-violating couplings $LQ\overline{D}$. The bound is reduced to 56 GeV for m_0=80 GeV (in the case of decays via a neutralino), and to 51 GeV for m_0=70 GeV (in the case of direct R-violating decays). Data collected at $\sqrt{s}$=130–172 GeV.

[90] 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.

[91] 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.

[92] 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 $m_{\widetilde{\chi}_1^\pm}$=$m_{\widetilde{\chi}_2^0}$ and $m_{\widetilde{\chi}_1^\pm}$=$2m_{\widetilde{\chi}_1^0}$. Results are presented in Fig. 1 as upper bounds on $\sigma(p\overline{p} \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0)\times$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.

[93] 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 $\sigma(p\overline{p} \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0)\times$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.

[94] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. The limit is for 41 $< m_{\widetilde{\nu}} <$ 100 GeV, and tanβ=1–35. The limit improves to 84.3 GeV for $m_{\widetilde{\nu}} >$ 300 GeV. For Δm_+ below 10 GeV, the limit is independent of $m_{\widetilde{\nu}}$, and is given by 80.3 GeV for $\Delta m_+ = 5$ GeV, and by 52.4 GeV for $\Delta m_+ = 3$ GeV.

[95] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. The radiative decay of the lightest neutralino into gravitino is assumed. The limit is for $\Delta m >$ 10 GeV, 41 $< m_{\widetilde{\nu}} <$ 100 GeV, and tanβ=1–35. The limit improves to 84.5 GeV if either $m_{\widetilde{\nu}} >$ 300 GeV, or Δm_+=1 GeV independently of $m_{\widetilde{\nu}}$.

[96] ACCIARRI 98F limit is obtained for 0 $< M_2 <$ 2000, tan$\beta <$ 1.41, and $\mu = -200$ GeV, and holds for all values of m_0. No dependence on the trilinear-coupling parameter A is found. It improves to 84 GeV for large sneutrino mass, at μ=-200 GeV. See the paper for limits obtained with specific assumptions on the gaugino/higgsino composition of the state. Data taken at $\sqrt{s}$ = 130–172 GeV.

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

[98] 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 neglibible. 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 $\widetilde{\chi}^{\pm} \rightarrow \ell \widetilde{\nu}_{\ell}$. The limit improves to 84.5 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$=130–172 GeV.

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

[100] BARATE 98S looked for the decay of charginos via R-violating coupling $LL\overline{E}$. The bound improves to 78 GeV if the chargino decays into neutralino which further decays into lepton pairs. Data collected at $\sqrt{s}$=130–172 GeV.

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

[102] KALINOWSKI 97 studies the constraints on the chargino-neutralino parameter space from limits on $\Gamma(W \rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^0)$ 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.

[103] ABE 96K looked for tripleton 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.

[104] ACKERSTAFF 96C assumes the dominance of off-shell W-exchange in the chargino decay and applies for Δm >10 GeV in the region of parameter space defined by: M_2 <1500 GeV, $|\mu|$ <500 GeV and tanβ > 1.5. The bound is for the smallest $\widetilde{\ell}$,$\widetilde{\nu}$ mass allowed by LEP, with the efficiency for $\widetilde{\chi}^{\pm} \rightarrow \widetilde{\nu}\nu$ decays set to zero. The limit improves to 78.5 GeV for m_0 = 1 TeV. Data taken at $\sqrt{s}$ = 130,136, and 161 GeV.

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

Limits on charginos which leave the detector before decaying.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
none 2–87.5	95	[105] ABREU	98P	DLPH	$m_{\widetilde{\nu}} > 41$ GeV
>89.5	95	[106] ACKERSTAFF	98P	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>80	95	[107] ABREU	97D	DLPH	
>83	95	[108] BARATE	97K	ALEP	
>45	95	ABREU	90G	DLPH	
>28.2	95	ADACHI	90C	TOPZ	

[105] ABREU 98P searches for production of pairs of heavy, charged particles in e^+e^- annihilation at $\sqrt{s}$=130–183 GeV. The upper bound improves to 89.5 GeV for $m_{\widetilde{\nu}}$ >200 GeV. These limits include and update the results of ABREU 97D.

[106] ACKERSTAFF 98P bound assumes a heavy sneutrino $m_{\widetilde{\nu}} > 500$ GeV. Data collected at $\sqrt{s}$ = 130–183 GeV.

[107] ABREU 97D bound applies only to masses above 45 GeV. Data collected in e^+e^- collisions at $\sqrt{s}$=130–172 GeV. The limit improves to 84 GeV for $m_{\widetilde{\nu}} > 200$ GeV.

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

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

The limit depends 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 preliminary, unpublished constraints by the LEP Collaborations on the invisible width of the Z boson ($\Delta\Gamma_{\text{inv.}} < 2.0$ MeV, LEP 00): $m_{\widetilde{\nu}} > 43.7$ GeV ($N(\widetilde{\nu})$=1) and $m_{\widetilde{\nu}} > 44.7$ GeV ($N(\widetilde{\nu})$=3) .

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 37.1	95	[109] ADRIANI	93M	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
$>$ 41	95	[110] 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	[111] ALEXANDER	91F	OPAL	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[112] ABBIENDI	00	OPAL	$\widetilde{\nu}_{e,\mu}$, $\not{R}$, $LL\overline{E}$ or $LQ\overline{D}$ decays
$>$ 62	95	[113] ABREU	00I	DLPH	$\widetilde{\nu}_\ell$, $\not{R}$ $LL\overline{E}$ decays
$>$ 62	95	[114] BARATE	00H	ALEP	$\widetilde{\nu}_\ell$, $\not{R}$ $LL\overline{E}$ decays
none 100–215	95	[115] ABBIENDI	99	OPAL	$\widetilde{\nu}_{\mu,\tau}$, $\not{R}$, $(s+t)$-channel
none 100–195	95	[116] ABBIENDI	99	OPAL	$\widetilde{\nu}_\tau$, $\not{R}$, s-channel
none 100–160	95	[117] ABBIENDI	99	OPAL	$\widetilde{\nu}_e$, $\not{R}$, t-channel
		[118] ABREU	99A	DLPH	$\widetilde{\nu}_{e,\mu,\tau}$, $\not{R}$, $(s+t)$-channel
$>$ 51	95	[119] BARATE	99E	ALEP	$\not{R}$, $\widetilde{\nu}_\mu \to jj$
$>$ 49	95	[120] BARATE	98S	ALEP	$\widetilde{\nu}_{\mu,\tau}$, $\not{R}$, $LL\overline{E}$ decays
$>$ 58	95	[120] BARATE	98S	ALEP	$\widetilde{\nu}_e$, $\not{R}$, $LL\overline{E}$ decays
$\neq m_Z$	95	[121] ACCIARRI	97U	L3	$\widetilde{\nu}_\tau$, $\not{R}$, s-channel
none 125–180	95	[121] ACCIARRI	97U	L3	$\widetilde{\nu}_\tau$, $\not{R}$, s-channel
		[122] CARENA	97	THEO	$g_\mu - 2$
$>$ 46.0	95	[123] BUSKULIC	95E	ALEP	$N(\widetilde{\nu})$=1, $\widetilde{\nu} \to \nu\nu\ell\overline{\ell}'$
none 20–25000		[124] BECK	94	COSM	Stable $\widetilde{\nu}$, dark matter
$<$600		[125] FALK	94	COSM	$\widetilde{\nu}$ LSP, cosmic abundance
none 3–90	90	[126] SATO	91	KAMI	Stable $\widetilde{\nu}_e$ or $\widetilde{\nu}_\mu$, dark matter
none 4–90	90	[126] SATO	91	KAMI	Stable $\widetilde{\nu}_\tau$, dark matter

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

[110] DECAMP 92 limit is from Γ(invisible)/$\Gamma(\ell\ell) = 5.91 \pm 0.15$ ($N_\nu = 2.97 \pm 0.07$).

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

[112] 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^0_1. For non-zero $LQ\overline{D}$ couplings, the limits are 86 GeV for indirect decays of $\widetilde{\nu}_e$ with a low mass χ^0_1 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.

[113] ABREU 00I studies decays induced by R-parity-violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling at the time to be non-zero 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 27 GeV, also derived in ABREU 00I. Better limits for specific flavors and for specific $\not{R}$ couplings can be obtained and are discussed in the paper.

[114] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limit holds for indirect $\widetilde{\nu}$ decays mediated by $\not{R}$ $LL\overline{E}$ couplings, and improves to 66 GeV for direct decays. Better limits are obtained for specific flavors, or couplings. Limits are also given for direct decays via $LQ\overline{D}$ couplings ($m_{\nu_{\mu,\tau}}$ > 59GeV) and for indirect decays via $\overline{UDD}$ couplings (m_{ν_e} > 70GeV with μ=−200 GeV and tanβ=2). For $LL\overline{E}$ indirect decays, use is made of neutralino mass limits from BARATE 98S.

[115] ABBIENDI 99 studied the effect of s- and t-channel τ or μ sneutrino exchange in $e^+e^- \rightarrow e^+e^-$ at $\sqrt{s}$=130–183 GeV, via the R-parity violatin coupling $\lambda_{1i1}L_1L_ie_1^c$ (i=2 or 3). The limits quoted here hold for $\lambda_{1i1} > 0.13$. The effect of t-channel electron-sneutrino exchange on rate and asymmetries of $e^+e^- \rightarrow \tau^+\tau^-$ leads to weaker limits on the electron sneutrino mass.

[116] ABBIENDI 99 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 couplings $\lambda_{i3i}L_iL_3e_1^c$ (i=1 and 2), with λ_{131}=λ_{232}. The limits quoted here hold for $\lambda_{131} > 0.09$.

[117] ABBIENDI 99 studied the effect of t-channel electron sneutrino exchange in $e^+e^- \rightarrow \tau^+\tau^-$ at $\sqrt{s}$=130–183 GeV, in presence of the R-parity violating couplings $\lambda_{131}L_1L_3e_1^c$. The limits quoted here hold for $\lambda_{131} > 0.6$.

[118] ABREU 99A 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 $\sqrt{s}$=130–172 GeV. Limits are set on the s- and t-channel exchange of sneutrinos in the presence of $\not{R}$ with λLLe^c 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. 13.

[119] BARATE 99E looked for $\widetilde{\nu}_\mu$ pairs with decay $\widetilde{\nu}_\mu \rightarrow jj$ via R-violating coupling $LQ\overline{D}$. Data collected at $\sqrt{s}$=130–172 GeV.

[120] BARATE 98S looked for $\widetilde{\nu}_\ell$ pairs with decay $\widetilde{\nu}_\ell \rightarrow \ell\widetilde{\chi}_1^0$, where $\widetilde{\chi}_1^0$ further decays to $\ell^+\ell^-\nu$ via R-violating coupling $LL\overline{E}$. The limit assumes tanβ=2, The bound on $\widetilde{\nu}_e$ is for the higgsino region. It improves to 72 GeV for the gaugino region. Data collected at $\sqrt{s}$=130–172 GeV.

[121] ACCIARRI 97U studied the effect of the s-channel tau-sneutrino exchange in $e^+e^- \rightarrow e^+e^-$ at $\sqrt{s}$=m_Z and $\sqrt{s}$=130–172 GeV, via the R-parity violating coupling $\lambda_{131}L_1L_je_1^c$. The limits quoted here hold for $\lambda_{131} > 0.05$. Similar limits were studied in $e^+e^- \rightarrow \mu^+\mu^-$ together with $\lambda_{232}L_2L_3e_2^c$ coupling.

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

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

[124] 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.

[125] 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.

[126] 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 $\Delta\Gamma_{\rm inv}$ < 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 Δm= $m_{\widetilde{\ell}}$ − $m_{\widetilde{\chi}^0_1}$. 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 energies above 161 GeV have been removed from this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) 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*
>87.1 (CL = 95%)					
>87.1	95	[127] ABBIENDI	00G	OPAL	$\Delta m > 5$ GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
none 45–73.7	95	[128] ABREU	99C	DLPH	$m_{\widetilde{\chi}^0_1} < 40$ GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
>85.0	95	[129] ACCIARRI	99W	L3	$\Delta m > 7$ GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
>88	95	[130] BARATE	99Q	ALEP	$\Delta m > 8$ GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>72	95	[131] ABBIENDI	00	OPAL	$\widetilde{e}^+_R\widetilde{e}^-_R$, $\not{R}$, light $\widetilde{\chi}^0_1$
>61	95	[132] ABREU	00I	DLPH	$\widetilde{e}_R$, $\not{R}$ ($LL\overline{E}$)
>85	95	[133] BARATE	00G	ALEP	$\widetilde{\ell}_R \rightarrow \ell\widetilde{G}$, any $\tau(\widetilde{\ell}_R)$
>76	95	[134] BARATE	00H	ALEP	$\widetilde{e}_R$, $\not{R}$ ($LL\overline{E}$)
>80	95	[135] ACCIARRI	99H	L3	$\widetilde{e}^+_R\widetilde{e}^-_R$, $\Delta m > 20$ GeV
>29.5	95	[136] ACCIARRI	99I	L3	$\widetilde{e}_R$, $\not{R}$, tan$\beta \geq 2$
>57	95	[137] BARATE	99E	ALEP	$\widetilde{e}_R$, $\not{R}$ ($LQ\overline{D}$), $\Delta m > 10$ GeV
>56	95	[138] ACCIARRI	98F	L3	$\Delta m > 5$ GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$, tan$\beta \geq 1.41$
>58.0	95	[139] ACKERSTAFF	98K	OPAL	$\Delta m > 5$ GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$

>78	95	[140] BARATE	98K	ALEP	$\Delta m > 5$ GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$
>77	95	[141] BARATE	98K	ALEP	Any Δm, $\widetilde{e}^+_R \widetilde{e}^-_R$, $\widetilde{e}_R \rightarrow e\gamma\widetilde{G}$
>71	95	[142] BARATE	98K	ALEP	$\widetilde{e}^+_R \widetilde{e}^-_R$, $\widetilde{e}_R \rightarrow e\widetilde{G}$, any $\tau(\widetilde{e}_R)$
>65	95	[143] BARATE	98K	ALEP	$\widetilde{e}^+_R \widetilde{e}^-_{L,R}$, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$, universal scalar mass
>64	95	[144] BARATE	98S	ALEP	$\widetilde{e}_R$, $\not{R}$ $(LL\overline{E})$
>77	95	[145] BREITWEG	98	ZEUS	$m_{\widetilde{q}}=m_{\widetilde{e}}$, $m(\widetilde{\chi}^0_1)$= 40 GeV
>58	95	[146] BARATE	97N	ALEP	$\Delta m > 3$ GeV, $\widetilde{e}^+_R \widetilde{e}^-_R$
>63	95	[147] AID	96C	H1	$m_{\widetilde{q}}=m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$=35 GeV
>45.6	95	[148] BUSKULIC	95E	ALEP	$\widetilde{e} \rightarrow e\nu\ell\overline{\ell}'$

[127] ABBIENDI 00G looked for acoplanar dielectron + $\not{E}_T$ final states at $\sqrt{s}$=183–189 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 $\widetilde{e} \rightarrow e\widetilde{\chi}^0_1$. See their Fig. 14 for the dependence of the limit on Δm and tanβ.

[128] ABREU 99C looked for acoplanar dielectron $+\not{E}$ final states at $\sqrt{s}$= 130–172 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$)=100%. See Fig. 8a for limits on the $(m_{\widetilde{e}_R},m_{\widetilde{\chi}^0_1})$ plane and for different tanβ values. These results include and update limits from ABREU 96O.

[129] ACCIARRI 99W looked for acoplanar dielectron $\not{E}_T$ final states at $\sqrt{s}$=130–189 GeV. The limit assumes μ=$-$200 GeV and tanβ=$\sqrt{2}$ for the production cross section and decay branching ratios, evaluated within the MSSM, and zero efficiency for decays other than $\widetilde{e} \rightarrow e\widetilde{\chi}^0_1$. The scan of parameter space, covering the region 1<tanβ < 60, M_2 < 2 TeV, $|\mu|$ < 2 TeV, m_0 < 500 GeV, leads to an absolute lower limit of 65.5 GeV. See their Figs. 5–6 for the dependence of the limit on Δm and tanβ.

[130] BARATE 99Q looked for acoplanar dielectron + $\not{E}_T$ final states at $\sqrt{s}$=189 GeV. The limit assumes μ=$-$200 GeV and tanβ=2 for the production cross section and decay branching ratios, and zero efficiency for decays other than $\widetilde{e} \rightarrow e\widetilde{\chi}^0_1$. Assuming a common scalar mass at the GUT scale, and extending the search to $\widetilde{e}^{\pm}_R \widetilde{e}^{\mp}_L$ final states, a Δm independent limit of 68 GeV is obtained. See their Fig. 3 for the dependence of the limit on Δm. The limits presented here make use of, and supersede, the results of BARATE 98K.

[131] 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 $\widetilde{\chi}^0_1$. For non-zero $LQ\overline{D}$ couplings, the limits are 72 GeV for indirect decays of $\widetilde{e}_R$ with a low mass $\widetilde{\chi}^0_1$ and 76 GeV for direct decays of $\widetilde{e}_L$. It is assumed that tanβ=1.5 and μ=$-$200 GeV.

[132] ABREU 00I studies decays induced by R-parity-violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling at the time to be non-zero 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 27 GeV, also derived in ABREU 00I. Better limits for specific flavors and for specific $\not{R}$ couplings can be obtained and are discussed in the paper.

[133] 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 colleced at $\sqrt{s}$=189 GeV.

[134] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limit holds for indirect decays mediated by $\not{R}$ $LL\overline{E}$ couplings, and improves to 82 GeV for direct decays with μ=−200 GeV and $\tan\beta$=2. Limits are also given for indirect decays via $\overline{UDD}$ couplings ($m_{\widetilde{e}_R} > 81$ and $m_{\widetilde{e}_L} >70$ GeV, with $\Delta m > 10$ GeV). For $LL\overline{E}$ indirect decays, use is made of neutralino mass limits from BARATE 98S.

[135] ACCIARRI 99H looked for acoplanar dilelectron + $\not{E}_T$ final states at $\sqrt{s}$=130–183 GeV. The limit assumes μ=−200 GeV and $\tan\beta=\sqrt{2}$ for for the production cross section and zero efficiency for decays other than $\widetilde{e} \rightarrow e\widetilde{\chi}^0_1$. See Fig. 6 for the dependence of the limit on Δm.

[136] 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.

[137] BARATE 99E looked for $\widetilde{e}_R$ pairs with decay $\widetilde{e}_R \rightarrow e\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays via R-violating coupling $LQ\overline{D}$. The limit assumes gaugino-like $\widetilde{\chi}^0_1$. The limit is 52 GeV for the case of $\widetilde{e}_L$ pair production with $\widetilde{e}_L \rightarrow jj$ decay. Data collected at $\sqrt{s}$=130–172 GeV.

[138] 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 efficiecny 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.

[139] ACKERSTAFF 98K looked for dielectron+$\not{E}$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes $\mu < -100$ GeV, $\tan\beta$=35, and zero efficiency for decays other than $\widetilde{e}_R \rightarrow e\widetilde{\chi}^0_1$. The limit improves to 66.5 GeV for $\tan\beta$=1.5.

[140] BARATE 98K looked for acoplanar dielectron + $\not{E}$ final states at $\sqrt{s}$= 161–184 GeV. The limit assumes μ=−200 GeV and $\tan\beta$=2 in the calculation of the production cross section, and B($\widetilde{e} \rightarrow e\widetilde{\chi}^0_1$)=100%. See Fig. 3 for limits on the ($m_{\widetilde{e}_R}$,$m_{\widetilde{\chi}^0_1}$) plane and for the effect of cascade decays.

[141] 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 $\tan\beta$=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.

[142] BARATE 98K combines the search for acoplanar dielectrons, electrons with large impact parameters, kinks, and stable heavy charged tracks at $\sqrt{s}$= 161–184 GeV. The limit assumes no t-channel neutralino exchange diagram which can make the bound weaker. See Fig. 5 for limits as a function of the lifetime $\tau(\widetilde{e}_R)$.

[143] BARATE 98K combines the search for acoplanar dileptons and single electrons with universal scalar mass assumption at the GUT scale. The limit holds for all Δm, and assumes μ=−200 GeV and $\tan\beta$=2 for the evaluation of the $\widetilde{e}$ production cross section.

[144] BARATE 98S looked for $\widetilde{e}_R$ pairs with decay $\widetilde{e}_R \rightarrow e\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays to $\ell^+\ell^-\nu$ via R-violating coupling $LL\overline{E}$. The limit assumes $\tan\beta$=2 and gaugino-like $\widetilde{\chi}^0_1$. Data collected at $\sqrt{s}$=130–172 GeV.

[145] 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 $m(\widetilde{q})$, $m(\widetilde{\chi}^0_1)$.

[146] BARATE 97N uses e^+e^- data collected at $\sqrt{s}$=161 and 172 GeV. The limit is for $\tan\beta$=2. It improves to 75 GeV if $\Delta m >$35 GeV.

[147] 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 $m_{\widetilde{q}}$, $m_{\widetilde{\chi}^0_1}$.

[148] BUSKULIC 95E looked for $Z \rightarrow \widetilde{e}^+_R\widetilde{e}^-_R$ where $\widetilde{e}_R \rightarrow e\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>82.3 (CL = 95%)				
>82.3	95	[149] ABBIENDI	00G OPAL	$\Delta m > 3$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
none 45–58.6	95	[150] ABREU	99C DLPH	$\Delta m > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>76.6	95	[151] ACCIARRI	99W L3	$\Delta m > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>80	95	[152] BARATE	99Q ALEP	$\Delta m > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>50	95	[153] ABBIENDI	00 OPAL	$\widetilde{\mu}^+_R \widetilde{\mu}^-_R$, $\not{R}$, $\Delta m > 5$ GeV
>61	95	[154] ABREU	00I DLPH	$\widetilde{\mu}_R$, $\not{R}$ $(LL\overline{E})$
>85	95	[155] BARATE	00G ALEP	$\widetilde{\ell}_R \rightarrow \ell \widetilde{G}$, any $\tau(\widetilde{\ell}_R)$
>61	95	[156] BARATE	00H ALEP	$\widetilde{\mu}_R$, $\not{R}$ $(LL\overline{E})$
>66	95	[157] ACCIARRI	99H L3	$\Delta m > 6$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>45	95	[158] BARATE	99E ALEP	$\widetilde{\mu}_R$, $\not{R}$ $(LQ\overline{D})$, $\Delta m > 10$ GeV
>55	95	[159] ACCIARRI	98F L3	$\Delta m > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>55.6	95	[160] ACKERSTAFF	98K OPAL	$\Delta m > 4$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>71	95	[161] BARATE	98K ALEP	$\Delta m > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>77	95	[162] BARATE	98K ALEP	Any Δm, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$, $\widetilde{\mu}_R \rightarrow \mu \gamma \widetilde{G}$
>71	95	[163] BARATE	98K ALEP	$\widetilde{\mu}^+_R \widetilde{\mu}^-_R$, $\widetilde{\mu}_R \rightarrow \mu \gamma \widetilde{G}$, any $\tau(\widetilde{\mu}_R)$
>62	95	[164] BARATE	98S ALEP	$\widetilde{\mu}_R$, $\not{R}$ $(LL\overline{E})$
>51	95	[165] ACKERSTAFF	97H OPAL	$\Delta m > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>59	95	[166] BARATE	97N ALEP	$\Delta m > 10$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>45.6	95	[167] BUSKULIC	95E ALEP	$\widetilde{\mu} \rightarrow \mu \nu \ell \overline{\ell}'$
>45	95	ADRIANI	93M L3	$m_{\widetilde{\chi}^0_1}$ <40 GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>45	95	DECAMP	92 ALEP	$m_{\widetilde{\chi}^0_1}$ <41 GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$

[149] ABBIENDI 00G looked for acoplanar dimuon + $\not{E}_T$ final states at $\sqrt{s}$=183–189 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 81.7 GeV is obtained for $\mu < -100$ GeV and tanβ=1.5. See their Figs. 12 and 15 for the dependence of the limits on the branching ratio and on Δm.

[150] ABREU 99C looked for acoplanar dimuon +$\not{E}$ final states at $\sqrt{s}$= 130–172 GeV. The limit assumes B($\widetilde{\mu} \rightarrow \mu \widetilde{\chi}^0_1$)=100%. See Fig. 8b for limits on the ($m_{\widetilde{\mu}_R}$,$m_{\widetilde{\chi}^0_1}$) plane. These results include and update limits from ABREU 96O.

[151] ACCIARRI 99W looked for acoplanar dimuon + $\not{E}_T$ final states at $\sqrt{s}$=189 GeV. The limit assumes μ=$-$200 GeV and tanβ=$\sqrt{2}$ and zero efficiency for decays other than $\widetilde{\mu} \rightarrow \mu \widetilde{\chi}^0_1$. See their Fig. 5 for the dependence of the limit on Δm and tanβ.

[152] BARATE 99Q looked for acoplanar dimuon + $\not{E}_T$ final states at $\sqrt{s}$=189 GeV. The limit assumes μ=$-$200 GeV and tanβ=2 for the decay branching ratios, evaluated within the MSSM, and zero efficiency for decays other than $\widetilde{\mu} \rightarrow \mu \widetilde{\chi}^0_1$. See their Fig. 3 for the dependence of the limit on Δm. The limits presented here make use of, and supersede, the results of BARATE 98K.

[153] 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 $\widetilde{\chi}^0_1$. 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 $\tan\beta$=1.5 and μ=−200 GeV.

[154] ABREU 00I studies decays induced by R-parity-violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling at the time to be non-zero 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 27 GeV, also derived in ABREU 00I. Better limits for specific flavors and for specific $\not{R}$ couplings can be obtained and are discussed in the paper.

[155] 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 colleced at $\sqrt{s}$=189 GeV.

[156] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limit holds for direct decays mediated by $\not{R}$ $LL\overline{E}^c$ couplings, and improves to 74 GeV for indirect decays. Limits are also given for direct decays via $LQ\overline{D}$ couplings ($m_{\widetilde{\mu}_L} > 61$ GeV) for indirect decays via $\overline{UDD}$ couplings ($m_{\widetilde{\mu}_R} > 67$ GeV and $m_{\widetilde{\mu}_L} > 70$ GeV, with $\Delta m > 10$ GeV). For $LL\overline{E}$ indirect decays, use is made of neutralino mass limits from BARATE 98S.

[157] ACCIARRI 99H looked for acoplanar dimuon + $\not{E}_T$ final states at $\sqrt{s}$=130–183 GeV. The limit assumes μ=−200 GeV and $\tan\beta$=$\sqrt{2}$ and zero efficiency for decays other than $\widetilde{\mu} \to \mu\widetilde{\chi}^0_1$. See Fig. 6 for the dependence of the limit on Δm.

[158] BARATE 99E looked for $\widetilde{\mu}_R$ pairs with decay $\widetilde{\mu}_R \to \mu\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays via R-violating coupling $LQ\overline{D}$. The limit is 52 GeV for the case of $\widetilde{\mu}_L$ pair production with $\widetilde{\mu}_L \to jj$ decay. Data collected at $\sqrt{s}$=130–172 GeV.

[159] ACCIARRI 98F looked for dimuon+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes μ=−200 GeV, and zero efficiecny for decays other than $\widetilde{\mu}_R \to \mu\widetilde{\chi}^0_1$. See their Fig. 6 for the dependence of the limit on Δm.

[160] ACKERSTAFF 98K looked for dimuon+$\not{E}_T$ final states at $\sqrt{s}$=130–172 GeV. The limit assumes $\mu < -100$ GeV, $\tan\beta$=1.5, and zero efficiency for decays other than $\widetilde{\mu}_R \to \mu\widetilde{\chi}^0_1$. The limit improves to 62.7 GeV for B($\widetilde{\mu}_R \to \mu\widetilde{\chi}^0_1$)=1.

[161] BARATE 98K looked for acoplanar dimuon + $\not{E}$ final states at $\sqrt{s}$= 161–184 GeV. The limit assumes B($\widetilde{\mu}_R \to \mu\widetilde{\chi}^0_1$)=1. See Fig. 3 for limits on the ($m_{\widetilde{\mu}_R}$,$m_{\widetilde{\chi}^0_1}$) plane and for the effect of cascade decays.

[162] 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.

[163] BARATE 98K combines the search for acoplanar dimuons, muons with large impact parameters, kinks, and stable heavy charged tracks at $\sqrt{s}$= 161–184 GeV. See Fig. 5 for limits as a function of the lifetime $\tau(\widetilde{\mu}_R)$.

[164] BARATE 98S looked for $\widetilde{\mu}_R$ pairs with decay $\widetilde{\mu}_R \to \mu\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays to $\ell^+\ell^-\nu$ via R-violating coupling $LL\overline{E}$. The limit assumes $\tan\beta$=2, Data collected at $\sqrt{s}$=130–172 GeV.

[165] ACKERSTAFF 97H limit is for $m_{\widetilde{\chi}^0_1}$ >12 GeV allowed by their chargino, neutralino search, and for $\tan\beta \geq 1.5$ and $|\mu| > 200$ GeV. The study includes data from e^+e^- collisions at $\sqrt{s}$=161 GeV, as well as at 130–136 GeV (ALEXANDER 97B).

[166] BARATE 97N uses e^+e^- data collected at $\sqrt{s}$=161 and 172 GeV. The limit assumes B($\widetilde{\mu} \to \mu\widetilde{\chi}^0_1$) = 1.

[167] BUSKULIC 95E looked for $Z \to \widetilde{\mu}^+_R\widetilde{\mu}^-_R$, where $\widetilde{\mu}_R \to \mu\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>81.0 (CL = 95%)					
>81.0	95	[168] ABBIENDI	00G	OPAL	$\Delta m > 8$ GeV, $\theta_\tau=\pi/2$
none 45–55	95	[169] ABREU	99C	DLPH	$m_{\widetilde{\chi}^0_1} < 34$ GeV, $\theta_\tau=\pi/2$
none 45–52	95	[169] ABREU	99C	DLPH	$m_{\widetilde{\chi}^0_1} < 35$ GeV, $\theta_\tau=0.82$
>71.5	95	[170] ACCIARRI	99W	L3	$\Delta m > 12$ GeV, $\theta_\tau=\pi/2$
>60	95	[170] ACCIARRI	99W	L3	$8 < \Delta m < 42$ GeV, $\theta_\tau=0.91$
>71	95	[171] BARATE	99Q	ALEP	$\Delta m > 13$ GeV, $\theta_\tau= \pi/2$
>66	95	[171] BARATE	99Q	ALEP	$\theta_\tau=0.91$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>66	95	[172] ABBIENDI	00	OPAL	$\widetilde{\tau}^+_R\widetilde{\tau}^-_R$, $R\!\!\!/$, light $\widetilde{\chi}^0_1$
>61	95	[173] ABREU	00I	DLPH	$\widetilde{\tau}_R$, $R\!\!\!/$ $(LL\overline{E})$
>85	95	[174] BARATE	00G	ALEP	$\widetilde{\ell}_R \rightarrow \ell\widetilde{G}$, any $\tau(\widetilde{\ell}_R)$
>67	95	[175] BARATE	00G	ALEP	$\widetilde{\tau}_R \rightarrow \tau\widetilde{G}$, any $\tau(\widetilde{\tau}_R)$
>61	95	[176] BARATE	00H	ALEP	$\widetilde{\tau}_R$, $R\!\!\!/$ $(LL\overline{E})$
>55	95	[177] ABREU	99C	DLPH	$\widetilde{\tau}^+_R\widetilde{\tau}^-_R$, $\widetilde{\tau}_R \rightarrow \tau\widetilde{G}$, any $\tau(\widetilde{\tau}_R)$
>68.5	95	[178] ABREU	99F	DLPH	$\widetilde{\tau}^+_R\widetilde{\tau}^-_R$, $\widetilde{\tau}_R \rightarrow \tau\widetilde{G}$, any $\tau(\widetilde{\tau}_R)$
>53	95	[179] ACCIARRI	99H	L3	$\Delta m > 10$ GeV, $\theta_\tau=0.91$
>45	95	[180] BARATE	99E	ALEP	$\widetilde{\tau}_R$, $R\!\!\!/$ $(LQ\overline{D})$, $\Delta m > 10$ GeV
>65	95	[181] BARATE	98K	ALEP	$\Delta m > 10$ GeV, $\theta_\tau=\pi/2$
>62	95	[181] BARATE	98K	ALEP	$\Delta m > 10$ GeV, $\theta_\tau=0.82$
>52	95	[182] BARATE	98K	ALEP	Any Δm, $\theta_\tau=\pi/2$, $\widetilde{\tau}_R \rightarrow \tau\gamma\widetilde{G}$
none 2–35	95	[183] BARATE	98K	ALEP	$\Delta m >2$, $\theta_\tau=0.82$
>56	95	[184] BARATE	98S	ALEP	$\widetilde{\tau}_R$, $R\!\!\!/$ $(LL\overline{E})$

[168] ABBIENDI 00G looked for acoplanar ditau + $E\!\!\!/_T$ final states at $\sqrt{s}$=183–189 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 75.9 at $\Delta m > 7$ GeV is obtained for $\mu < -100$ GeV and tanβ=1.5. See their Figs. 13 and 16 for the dependence of the limits on the branching ratio and on Δm.

[169] ABREU 99C looked for acoplanar ditaus $+E\!\!\!/$ final states at $\sqrt{s}$= 130–172 GeV. The limit assumes B($\widetilde{\tau}_R \rightarrow \tau\widetilde{\chi}^0_1$)=1. See Figs. 4c and 4d for limits on the $(m_{\widetilde{\tau}_R}, m_{\widetilde{\chi}^0_1})$ plane and and as a function of the mixing angle.

[170] ACCIARRI 99W looked for acoplanar ditau + $E\!\!\!/_T$ final states at $\sqrt{s}$=189 GeV. See their Fig. 5 for the dependence of the limit on Δm and tanβ.

[171] BARATE 99Q looked for acoplanar ditau + $E\!\!\!/_T$ final states at $\sqrt{s}$=189 GeV. The limit assumes B($\widetilde{\tau} \rightarrow \tau\widetilde{\chi}^0_1$)=1. See their Fig. 3 for the dependence of the limit on Δm. The limits presented here make use of, and supersede, the results of BARATE 98K.

[172] 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.

[173] ABREU 00I studies decays induced by R-parity-violating $LL\overline{E}$ couplings, using data from $\sqrt{s}$=183 GeV. They investigate topologies with multiple leptons or jets plus leptons, assuming one coupling at the time to be non-zero 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 27 GeV, also derived in ABREU 00I. Better limits for specific flavors and for specific $\not{R}$ couplings can be obtained and are discussed in the paper.

[174] 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 colleced at $\sqrt{s}$=189 GeV.

[175] BARATE 00G combines the search for acoplanar ditaus, taus with large impact parameters, kinks, and stable heavy-charged tracks. Staus are also looked for in the decay chain $\widetilde{\chi}^0_1 \rightarrow \widetilde{\tau}\tau \rightarrow \tau\tau\widetilde{G}$; see paper for results. Data colleced at $\sqrt{s}$=189 GeV.

[176] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limit holds for direct decays mediated by $\not{R}$ $LL\overline{E}$ couplings, and improves up to 70 GeV for indirect decays, using the neutralino mass limits from BARATE 98S.

[177] ABREU 99C combines the search for acoplanar ditaus, taus with large impact parameters, kinks, and stable heavy-charged tracks at $\sqrt{s}$= 130–172 GeV. See Fig. 11 for limits under different lifetime hypothesis.

[178] ABREU 99F combines the search for acoplanar ditaus, taus with large impact parameters, kinks, and stable heavy-charged tracks at $\sqrt{s}$=130–183 GeV. See Fig. 13 for limits under various lifetime scenarios.

[179] ACCIARRI 99H looked for acoplanar ditau + $\not{E}_T$ final states at $\sqrt{s}$=130–183 GeV. The limit assumes μ=− 200 GeV and tanβ=$\sqrt{2}$ and zero efficiency for decays other than $\widetilde{\tau} \rightarrow \tau\widetilde{\chi}^0_1$. See Fig. 6 for the dependence on the limit on Δm.

[180] BARATE 99E looked for $\widetilde{\tau}_R$ pairs with decay $\widetilde{\tau}_R \rightarrow \tau\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays via R-violating coupling $LQ\overline{D}$. Data collected at $\sqrt{s}$=130–172 GeV.

[181] BARATE 98K looked for acoplanar ditaus + $\not{E}$ at $\sqrt{s}$= 161–184 GeV. The limit assumes zero efficiency for decays other than $\widetilde{\tau}_R \rightarrow \tau\widetilde{\chi}^0_1$. See Fig. 3 for limits on the ($m_{\widetilde{\tau}}$,$m_{\widetilde{\chi}^0_1}$) plane and for the effect of cascade decays.

[182] 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.

[183] This limit also uses BARATE 97N to extend limit to low $m_{\widetilde{\tau}}$.

[184] BARATE 98S looked for $\widetilde{\tau}_R$ pairs with decay $\widetilde{\tau}_R \rightarrow \tau\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays to $\ell^+\ell^-\nu$ via R-violating coupling $LL\overline{E}$. The limit assumes tanβ=2, Data collected at $\sqrt{s}$=130–172 GeV.

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. However, selectron limits from continuum e^+e^- annihilation depend on flavor because there is an additional contribution from neutralino exchange that in general yields stronger limits.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>82.5 (CL = 95%)					
>81.2	95	[185] ACCIARRI	99H	L3	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
none 2–80	95	[186] ABREU	98P	DLPH	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
>82.5	95	[187] ACKERSTAFF	98P	OPAL	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
>81	95	[188] BARATE	98K	ALEP	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$

[185] 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 $\widetilde{\mu}_L$, $\widetilde{\tau}_L$.

[186] ABREU 98P searches for production of pairs of heavy, charged particles in e^+e^- annihilation at $\sqrt{s}$=130–183 GeV. The upper bound improves to 81 GeV for $\widetilde{\mu}_L$,$\widetilde{\tau}_L$. These limits include and update the results of ABREU 97D.

[187] ACKERSTAFF 98P bound improves to 83.5 GeV for $\widetilde{\mu}_L$, $\widetilde{\tau}_L$. Data collected at $\sqrt{s}$ = 130–183 GeV.
[188] 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 ($\Delta\Gamma_{\text{inv}}$ < 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 which are obsolete relative to the current results are not included in this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this *Review*.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>250 (CL = 95%)					
>250	95	[189] ABBOTT	99L	D0	$\tan\beta$=2, μ <0, A=0
> 91.5	95	[190] ACCIARRI	99V	L3	Δm > 10 GeV, $e^+ e^- \rightarrow \widetilde{q}\overline{\widetilde{q}}$
> 92	95	[191] BARATE	99Q	ALEP	$e^+ e^- \rightarrow \widetilde{q}\overline{\widetilde{q}}$, Δm > 10 GeV
>224	95	[192] ABE	96D	CDF	$m_{\widetilde{g}} \leq m_{\widetilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 69	95	[193] BARATE	00H	ALEP	$\widetilde{u}_R$, $\not{R}$ $\overline{UDD}$
> 49	95	[193] BARATE	00H	ALEP	$\widetilde{d}_R$, $\not{R}$ $\overline{UDD}$
>240	95	[194] ABBOTT	99	D0	$\widetilde{q} \rightarrow \widetilde{\chi}^0_2 X \rightarrow \widetilde{\chi}^0_1 \gamma X$, $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1}$ > 20 GeV
>320	95	[194] ABBOTT	99	D0	$\widetilde{q} \rightarrow \widetilde{\chi}^0_1 X \rightarrow \widetilde{G}\gamma X$
>243	95	[195] ABBOTT	99K	D0	any $m_{\widetilde{g}}$, $\not{R}$, $\tan\beta$=2, μ < 0
>200	95	[196] ABE	99M	CDF	$p\overline{p} \rightarrow \widetilde{q}\widetilde{q}$, $\not{R}$
>140	95	[197] ACCIARRI	98J	L3	$e^+ e^- \rightarrow q\overline{q}$, $\not{R}$, λ=0.3
>140	95	[197] ACKERSTAFF	98V	OPAL	$e^+ e^- \rightarrow q\overline{q}$, $\not{R}$, λ=0.3
> 87	95	[198] BARATE	98N	ALEP	$e^+ e^- \rightarrow \widetilde{q}\overline{\widetilde{q}}$, Δm >5 GeV

>77	95	[199] BREITWEG	98	ZEUS	$m_{\tilde{q}}=m_{\tilde{e}}$, $m(\tilde{\chi}^0_1)=$ 40 GeV
		[200] DATTA	97	THEO	$\tilde{\nu}$'s lighter than $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_2$
>216	95	[201] DERRICK	97	ZEUS	$e p \rightarrow \tilde{q}$, $\tilde{q} \rightarrow \mu j$ or τj, $\not{R}$
none 130–573	95	[202] HEWETT	97	THEO	$q \tilde{g} \rightarrow \tilde{q}$, $\tilde{q} \rightarrow q \tilde{g}$, with a light gluino
none 190–650	95	[203] TEREKHOV	97	THEO	$q g \rightarrow \tilde{q} \tilde{g}$, $\tilde{q} \rightarrow q \tilde{g}$, with a light gluino
>215	95	[204] AID	96	H1	$e^+ p \rightarrow \tilde{q}$, $\not{R}$, λ=0.3
>150	95	[204] AID	96	H1	$e^+ p \rightarrow \tilde{q}$; $\not{R}$, λ=0.1
>63	95	[205] AID	96C	H1	$m_{\tilde{q}}=m_{\tilde{e}}$, $m_{\tilde{\chi}^0_1}$=35 GeV
none 330–400	95	[206] TEREKHOV	96	THEO	$u g \rightarrow \tilde{u} \tilde{g}$, $\tilde{u} \rightarrow u \tilde{g}$ with a light gluino
>176	95	[207] ABACHI	95C	D0	Any $m_{\tilde{g}}$ <300 GeV; with cascade decays
		[208] ABE	95T	CDF	$\tilde{q} \rightarrow \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \gamma$
>45.3	95	[209] BUSKULIC	95E	ALEP	$\not{R}$, $(LL\overline{E})$
>90	90	[210] ABE	92L	CDF	Any $m_{\tilde{g}}$ <410 GeV; with cascade decay
>100		[211] ROY	92	RVUE	$p \overline{p} \rightarrow \tilde{q} \tilde{q}$; $\not{R}$
		[212] NOJIRI	91	COSM	

[189] 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 $m_{\tilde{g}}$.

[190] ACCIARRI 99V assumes four degenerate flavors and B($\tilde{q} \rightarrow q \tilde{\chi}^0_1$)=1, with $\Delta m = m_{\tilde{q}} - m_{\tilde{\chi}^0_1}$. The bound is reduced to 90 GeV if production of only $\tilde{q}_R$ states is considered. See their Fig. 7 for limits in the ($m_{\tilde{q}}$,$m_{\tilde{\chi}^0_1}$) plane. Data collected at $\sqrt{s}$=189 GeV.

[191] BARATE 99Q assumes five degenerate flavors and B($\tilde{q} \rightarrow q \tilde{\chi}^0_1$)=1, with $\Delta m = m_{\tilde{q}} - m_{\tilde{\chi}^0_1}$. Data collected at $\sqrt{s}$=189 GeV. The limits presented here make use of, and update, the results of BARATE 98N.

[192] 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, $\mu = -400$ 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.

[193] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limits hold for direct decays of u-type and d-type squarks, mediated by $\not{R}$ $\overline{UDD}$ couplings.

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

[195] ABBOTT 99K uses events with an electron pair and four jets to search for the decay of the $\tilde{\chi}^0_1$ LSP via $\not{R}$ $LQ\overline{D}$ couplings. The particle specrum 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.

[196] 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.

[197] 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.

[198] BARATE 98N assumes five degenerate flavors $\widetilde{u}_{L,R}$, $\widetilde{d}_{L,R}$, $\widetilde{c}_{L,R}$, $\widetilde{s}_{L,R}$, $\widetilde{b}_{L,R}$, and their direct decay $\widetilde{q} \rightarrow q\widetilde{\chi}^0_1$. The bound applies for $\Delta m > 5$ GeV. See Fig. 5 for limits in the ($m_{\widetilde{q}}$,$m_{\widetilde{\chi}^0}$) plane. Data collected at $\sqrt{s}$=181–184 GeV.

[199] 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 $m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$.

[200] 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 $\widetilde{\nu}$.

[201] 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.

[202] HEWETT 97 reanalyzed the limits on possilbe 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.

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

[204] AID 96 looked for first-generation squarks as s-channel resonances singly produced in $e^+ p$ collision via the R-parity violating coupling in the superpotential W=$\lambda' L_1 Q_1 d^c_1$. The degeneracy of squarks $\widetilde{Q}_1$ and $\widetilde{d}_1$ is assumed. Eight different channels of possible squark decays are considered.

[205] 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 $m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$.

[206] 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.

[207] 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 $\tan\beta = 2.0$ $\mu = -250$ 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. No limit is given for $m_{\text{gluino}} >$547 GeV.

[208] ABE 95T looked for a cascade decay of five degenerate squarks into $\widetilde{\chi}_2^0$ which further decays into $\widetilde{\chi}_1^0$ 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.

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

[210] 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, $m_{\widetilde{\chi}_1^0} \approx m_{\widetilde{g}}/6$. This last relation implies that as $m_{\widetilde{g}}$ increases, the mass of $\widetilde{\chi}_1^0$ 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.

[211] 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.

[212] 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. • • •					
none 2–85	95	[213] ABREU	98P	DLPH	$\widetilde{u}_L$
none 2–81	95	[213] ABREU	98P	DLPH	$\widetilde{u}_R$
none 2–80	95	[213] ABREU	98P	DLPH	$\widetilde{u}$, θ_u=0.98
none 2–83	95	[213] ABREU	98P	DLPH	$\widetilde{d}_L$
none 5–40	95	[213] ABREU	98P	DLPH	$\widetilde{d}_R$
none 5–38	95	[213] ABREU	98P	DLPH	$\widetilde{d}$, θ_d=1.17

[213] 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
none 80–145		[214] AFFOLDER	00D	CDF	$\widetilde{b} \to b\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1}$ <50 GeV
>89.8	95	[215] ABBIENDI	99M	OPAL	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta m > 10$ GeV
>74.9	95	[215] ABBIENDI	99M	OPAL	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=1.17, $\Delta m > 10$ GeV
>84	95	[216] ACCIARRI	99V	L3	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta m > 15$ GeV
>61	95	[216] ACCIARRI	99V	L3	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=1.17, $\Delta m > 15$ GeV
>86	95	[217] BARATE	99Q	ALEP	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta m > 10$ GeV
>75	95	[217] BARATE	99Q	ALEP	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=1.18, $\Delta m > 10$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 52–115	95	[218] ABBOTT	99F	D0	$\widetilde{b} \to b\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1} < 20$ GeV
>73	95	[219] ABREU	99C	DLPH	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta m > 10$ GeV
>44	95	[219] ABREU	99C	DLPH	$\widetilde{b} \to b\widetilde{\chi}^0_1$, $\theta_b=\pi/2$, $\Delta m > 10$ GeV
>57	95	[220] ACCIARRI	99C	L3	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=1.17, $\Delta m > 35$ GeV
none 40–54.4	95	[221] ACKERSTAFF	99	OPAL	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=1.17, $\Delta m > 7$ GeV
>54	95	[222] BARATE	99E	ALEP	$\not{R}$, θ_b=0
>73	95	[223] BARATE	98N	ALEP	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta m > 6$ GeV
>58	95	[224] BARATE	98S	ALEP	$\not{R}$, θ_b=0

[214] 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.

[215] ABBIENDI 99M looked for events with two acoplanar jets and $\not{p}_T$. See Fig. 4 and Table 5 for the dependence on the limit on Δm and θ_b. Data taken at $\sqrt{s}$=161–189 GeV. These results supersede ACKERSTAFF 99.

[216] ACCIARRI 99V looked for events with two acoplanar b-tagged jets and $\not{p}_T$, at $\sqrt{s}$=189 GeV. See their Figs. 4 and 6 for the more general dependence of the limits on Δm and θ_b.

[217] BARATE 99Q looked for events with two acoplanar b-tagged jets and $\not{p}_T$. The limit assumes B($\widetilde{b} \to b\widetilde{\chi}^0_1$)=1. See their Fig. 2 for the dependence of the limit on Δm and θ_b. Data taken at $\sqrt{s}$=189 GeV.

[218] 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 $m_{\widetilde{\chi}^0_1}$. No limit for $m_{\widetilde{\chi}^0_1} > 47$ GeV.

[219] ABREU 99C looked for $\widetilde{b}$ pair production at $\sqrt{s}$= 130–172 GeV. See Fig. 4 for other choices of Δm. These results include and update limits from ABREU 96O.

[220] ACCIARRI 99C looked for $\widetilde{b}$ pair production at $\sqrt{s}$=161–183 GeV. See Figs. 4–5 for other choices of θ_b and Δm.

[221] ACKERSTAFF 99 looked for $\widetilde{b}$ pair production at $\sqrt{s}$=130–183 GeV. The analysis includes and updates the results of ACKERSTAFF 97Q. See Table 11 and Fig. 12 for other choices of θ_b and Δm.

[222] BARATE 99E looked for $\widetilde{b}_L$ pairs with decay $\widetilde{b}_L \rightarrow b\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays via R-violating coupling $LQ\overline{D}$. $m_{\widetilde{\chi}^0_1} > 30$ GeV. The limit is 73 GeV for the case of $\widetilde{b}_L$ pair production with $\widetilde{b}_L \rightarrow j\nu$ decay. The limits for $\widetilde{b}_R$ pairs with $\widetilde{b}_R \rightarrow b\nu, j\tau$ are much weaker. Data collected at $\sqrt{s}$=130–172 GeV.

[223] BARATE 98N data taken at $\sqrt{s}$=181–184 GeV. The limit is significantly reduced for $\theta_b \approx 1.17$.

[224] BARATE 98S looked for $\widetilde{b}_L$ pairs with decay $\widetilde{b}_L \rightarrow b\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays to $\ell^+\ell^-\nu$ via R-violating coupling $LL\overline{E}$. The limit assumes $\tan\beta$=2, Data collected at $\sqrt{s}$=130–172 GeV.

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

Limits depend on the decay mode. In e^+e^- collisions they also depend on the mixing angle of the mass eigenstate $\widetilde{t}_1 = \widetilde{t}_L \cos\theta_t + \widetilde{t}_R \sin\theta_t$. The coupling to the Z vanishes when $\theta_t = 0.98$. 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." Previous obsolete limits are not included in this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this *Review*.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 86.4 (CL = 95%)					
> 86.4	95	[225] ABBIENDI	99M	OPAL	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m > 5$ GeV
> 88.0	95	[225] ABBIENDI	99M	OPAL	$\widetilde{t} \rightarrow b\ell\widetilde{\nu}$, θ_t=0.98, $\Delta m > 10$ GeV
> 87.5	95	[225] ABBIENDI	99M	OPAL	$\widetilde{t} \rightarrow b\tau\widetilde{\nu}_\tau$, θ_t=0.98, $\Delta m >$ 10 GeV
> 63	95	[226] ABREU	99C	DLPH	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m > 10$ GeV
> 81	95	[227] ACCIARRI	99V	L3	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.96, $\Delta m > 15$ GeV
> 86	95	[227] ACCIARRI	99V	L3	$\widetilde{t} \rightarrow b\ell\widetilde{\nu}$, θ_t=0.96, $\Delta m > 15$ GeV
> 83	95	[227] ACCIARRI	99V	L3	$\widetilde{t} \rightarrow b\tau\widetilde{\nu}_\tau$, θ_t=0.96, $\Delta m >$ 15 GeV
> 84	95	[228] BARATE	99Q	ALEP	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, all θ_t, $10 < \Delta m <$ 40 GeV
> 86	95	[228] BARATE	99Q	ALEP	$\widetilde{t} \rightarrow b\ell\widetilde{\nu}$, all θ_t, $\Delta m > 10$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 76	95	[229] ABBIENDI	00	OPAL	$\not{R}$, $(\overline{UDD})$, all θ_t
> 61	95	[230] ABREU	00I	DLPH	$\not{R}$ $(LL\overline{E})$, θ_t=0.98, $\Delta m > 4$ GeV
none 68–119	95	[231] AFFOLDER	00D	CDF	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1} <$40 GeV
> 58	95	[232] BARATE	00H	ALEP	$\widetilde{t}_L$, $\not{R}$ $(\overline{UDD})$
>120	95	[233] ABE	99M	CDF	$p\overline{p} \rightarrow \widetilde{t}_1\widetilde{t}_1$, $\not{R}$
> 72.5	95	[234] ACCIARRI	99C	L3	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m > 10$ GeV
> 75.8	95	[235] ACKERSTAFF	99	OPAL	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m > 5$ GeV
> 79.2	95	[235] ACKERSTAFF	99	OPAL	$\widetilde{t} \rightarrow b\ell\widetilde{\nu}$, θ_t=0.98, $\Delta m > 10$ GeV

>75.0	95	[235] ACKERSTAFF	99	OPAL	$\widetilde{t} \rightarrow b\tau\widetilde{\nu}_\tau$, θ_t=0.98, $\Delta m >$ 10 GeV
>48	95	[236] BARATE	99E	ALEP	$\not{R}$ ($LQ\overline{D}$), θ_t=0
>65	95	[237] BARATE	98N	ALEP	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m >$ 5 GeV
>82	95	[237] BARATE	98N	ALEP	$\widetilde{t} \rightarrow b\ell\widetilde{\nu}$, any θ_t, $\Delta m >$ 10 GeV
>44	95	[238] BARATE	98S	ALEP	$\not{R}$ ($LL\overline{E}$), θ_t=0.98
none 61–91	95	[239] ABACHI	96B	D0	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1}$ <30 GeV
none 9–24.4	95	[240] AID	96	H1	$ep \rightarrow \widetilde{t}\widetilde{t}$, $\not{R}$ decays
$>$138	95	[241] AID	96	H1	$ep \rightarrow \widetilde{t}$, $\not{R}$, $\lambda\cos\theta_t >$ 0.03
>45		[242] CHO	96	RVUE	B^0-$\overline{B}^0$ and ϵ, θ_t= 0.98, $\tan\beta$ <2
none 11–41	95	[243] BUSKULIC	95E	ALEP	$\not{R}$ ($LL\overline{E}$), θ_t=0.98
none 6.0–41.2	95	AKERS	94K	OPAL	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0, $\Delta m >$2 GeV
none 5.0–46.0	95	AKERS	94K	OPAL	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0, $\Delta m >$5 GeV
none 11.2–25.5	95	AKERS	94K	OPAL	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m >$2 GeV
none 7.9–41.2	95	AKERS	94K	OPAL	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta m >$5 GeV
none 7.6–28.0	95	[244] SHIRAI	94	VNS	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, any θ_t, $\Delta m >$10 GeV
none 10–20	95	[244] SHIRAI	94	VNS	$\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, any θ_t, $\Delta m >$ 2.5 GeV

[225] ABBIENDI 99M looked for events with two acoplanar jets, $\not{p}_T$, and, in the case of $b\ell\widetilde{\nu}$ ($b\tau\widetilde{\nu}$) final states, two leptons (taus). Limits for θ_t are $\sim$ 2.5 GeV stronger. In the case of $c\widetilde{\chi}^0_1$ decays, the limits with $\Delta m >$ 10 GeV improve to 90.3 for θ_t=0 and 87.2 for θ_t=0.98. See Figs. 2–3 and Table 4 for the more general dependence of the limits on Δm. Data taken at $\sqrt{s}$=161–189 GeV. All limits assume 100% branching ratio for the respective decay modes. These results supersede ACKERSTAFF 99.

[226] ABREU 99C looked for $\widetilde{t}$ pair production at $\sqrt{s}$= 130–172 GeV. The limit for θ_t is 72 GeV. See Fig. 4 for other choices of Δm. These results include and update limits from ABREU 96O.

[227] ACCIARRI 99V looked for events with two acoplanar jets, $\not{p}_T$ and, in the case of $b\ell\widetilde{\nu}$ ($b\tau\widetilde{\nu}$) final states, two leptons (taus). The limits for θ_t=0 improve to 88, 89, and 88 GeV, respectively. See their Figs. 4–6 for the more general dependence of the limits on Δm and θ_t. Data taken at $\sqrt{s}$=189 GeV. All limits assume 100% branching ratio for the respective decay modes.

[228] BARATE 99Q looked for events with two acoplanar jets, $\not{p}_T$ and, in the case of $b\ell\widetilde{\nu}$ final states, two leptons. All limits assume 100% branching ratio for the respective decay modes, with flavor-independent rates in the case of semileptonic decays. See their Fig. 1 for the dependence of the limit on Δm and θ_t. Data taken at $\sqrt{s}$=189 GeV. The limits presented here make use of, and supersede, the results of BARATE 98N.

[229] 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.

[230] ABREU 00I searches for the production of stop in the case of R-parity violation wiht $LL\overline{E}$ 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.

[231] 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.

[232] BARATE 00H data collected at $\sqrt{s}$=183 GeV. The limit holds for indirect decays mediated by $\not\!\!R$ $\overline{UDD}$ couplings, and $m_{\widetilde{\chi}^0_1} > 20$ GeV. It improves to 61 GeV for indirect decays mediated by $\not\!\!R$ $LL\overline{E}$ couplings, with neutralino mass limits from BARATE 98S. For direct decays, the limits from BARATE 00H in the squark section apply.

[233] 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 B($\widetilde{t}_1 \rightarrow c\widetilde{\chi}^0_1$)=1, B($\widetilde{\chi}^0_1 \rightarrow e q \overline{q}'$)=0.25 for both e^+ and e^-, and $m_{\widetilde{\chi}^0_1} \geq m_{\widetilde{t}_1}/2$. The limit improves for heavier $\widetilde{\chi}^0_1$.

[234] ACCIARRI 99C looked for $\widetilde{t}$ pair production at $\sqrt{s}$=161–183 GeV. See Figs. 4–5 for other choices of θ_t and Δm. These results update ACCIARRI 96F.

[235] ACKERSTAFF 99 looked for $\widetilde{t}$ pair production. The analysis considers data taken at $\sqrt{s}$=130–183 GeV, and includes the results of ACKERSTAFF 97Q. Unless the ℓ=τ decay mode is explicitly indicated, the same branching fractions to ℓ=e, μ, and τ are assumed for $b\ell\widetilde{\nu}$ modes. See Table 10 and Figs. 9–11 for other choices of θ_t and Δm.

[236] BARATE 99E looked for $\widetilde{t}_L$ pairs with decay $\widetilde{t}_L \rightarrow c\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays via R-violating coupling $LQ\overline{D}$. $m_{\widetilde{\chi}^0_1} > 30$ GeV. The limit is 62 GeV for the case of $\widetilde{t}_L$ pair production with $\widetilde{t}_L \rightarrow q\tau$ decays. Data collected at $\sqrt{s}$=130–172 GeV.

[237] BARATE 98N assumes the lepton universality for the case of $\widetilde{t} \rightarrow b\ell\widetilde{\nu}$ and the lower bound on $m_{\widetilde{\nu}}$ from Z decay is used. See Figs. 2 and 3 for limits as a function of Δm. Data collected at $\sqrt{s}$=181–184 GeV.

[238] BARATE 98S looked for $\widetilde{t}$ pairs with decay $\widetilde{t} \rightarrow c\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ further decays to $\ell^+\ell^-\nu$ via R-violating coupling $LL\overline{E}$. The limit assumes tanβ=2, Data collected at $\sqrt{s}$=130–172 GeV.

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

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

[241] AID 96 considers production and decay of $\widetilde{t}$ via the R-parity violating coupling $\lambda' L_1 Q_3 d^c_1$.

[242] 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 θ_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.

[243] BUSKULIC 95E looked for $Z \rightarrow \widetilde{t}\overline{\widetilde{t}}$, where $\widetilde{t} \rightarrow c\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[244] 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 $\tilde{g}$ (Gluino) MASS LIMIT

For $m_{\tilde{g}} > 60$–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.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>190 (CL = 95%)					
>190	95	[245] ABBOTT	99L	D0	$\tan\beta$=2, μ <0, A=0
>260	95	[245] ABBOTT	99L	D0	$m_{\tilde{g}}=m_{\tilde{q}}$
>173	95	[246] ABE	97K	CDF	Any $m_{\tilde{q}}$; with cascade decays
>216	95	[246] ABE	97K	CDF	$m_{\tilde{q}}=m_{\tilde{g}}$; with cascade decays
>224	95	[247] ABE	96D	CDF	$m_{\tilde{q}} = m_{\tilde{g}}$; with cascade decays
>154	95	[247] ABE	96D	CDF	$m_{\tilde{g}} < m_{\tilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>240	95	[248] ABBOTT	99	D0	$\tilde{g} \to \tilde{\chi}^0_2 X \to \tilde{\chi}^0_1 \gamma X$, $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} > 20$ GeV
>320	95	[248] ABBOTT	99	D0	$\tilde{g} \to \tilde{\chi}^0_1 X \to \tilde{G} \gamma X$
>227	95	[249] ABBOTT	99K	D0	any $m_{\tilde{q}}$, $\not{R}$, $\tan\beta$=2, $\mu < 0$
>212	95	[250] ABACHI	95C	D0	$m_{\tilde{g}} \geq m_{\tilde{q}}$; with cascade decays
>144	95	[250] ABACHI	95C	D0	Any $m_{\tilde{q}}$; with cascade decays
		[251] ABE	95T	CDF	$\tilde{g} \to \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \gamma$
		[252] HEBBEKER	93	RVUE	$e^+ e^-$ jet analyses
>218	90	[253] ABE	92L	CDF	$m_{\tilde{q}} \leq m_{\tilde{g}}$; with cascade decay
>100		[254] ROY	92	RVUE	$p\overline{p} \to \tilde{g}\tilde{g}$; $\not{R}$
		[255] NOJIRI	91	COSM	
none 4–53	90	[256] ALBAJAR	87D	UA1	Any $m_{\tilde{q}} > m_{\tilde{g}}$
none 4–75	90	[256] ALBAJAR	87D	UA1	$m_{\tilde{q}} = m_{\tilde{g}}$
none 16–58	90	[257] ANSARI	87D	UA2	$m_{\tilde{q}} \lesssim 100$ GeV

[245] 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 $m_{\tilde{g}}$.

[246] ABE 97K searched for production of gluinos and five degenerate squarks in events with three or more jets but no electrons or muons and missing transverse energy $\not{E}_T > 60$ GeV. The limit for any $m_{\tilde{q}}$ is for μ=−200 GeV and $\tan\beta$=2, and that for $m_{\tilde{q}}=m_{\tilde{g}}$ is for μ=−400 GeV and $\tan\beta$=4. Different choices for $\tan\beta$ and μ lead to changes of the order of $\pm$10 GeV in the limits. See Footnote [16] of the paper for more details on the assumptions.

[247] 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 limits are derived for fixed $\tan\beta = 4.0$, $\mu = -400$ 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. The bounds are weakly sensitive to the values of the three fixed parameters for a large fraction of parameter space. See Fig. 2 for the limits corresponding to different parameter choices.

[248] 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 $m_{\widetilde{g}}=m_{\widetilde{q}}$.

[249] 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 specrum 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 $\mu > 0$.

[250] 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 tan$\beta = 2.0$ $\mu = -250$ 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.

[251] 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, tan$\beta = 1.5$, and heavy squarks, the range $50 < m_{\widetilde{g}}$ (GeV)<140 is excluded at 90% CL. See the paper for details.

[252] 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 ± 1.1 is obtained, which is compared to that with a light gluino, N=8.

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

[254] 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.

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

[256] 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.

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

LIGHT GLUINO

Written March 1998 by H. Murayama (UC Berkeley).

It is controversial if a light gluino of mass below 5 GeV is phenomenologically allowed. Below we list some of the most important and least controversial constraints which need to be met for a light gluino to be viable. For reviews on the subject, see, *e.g.*, Ref. 1.

1. Either $m_{\tilde{g}} \lesssim 1.5$ GeV or $m_{\tilde{g}} \gtrsim 3.5$ GeV to avoid the CAKIR 94 limit. See also Ref. 2 for similar quarkonium constraints on lighter masses.
2. The lifetime of the gluino or the ground state gluino-containing hadron (typically, $g\tilde{g}$) must be $\gtrsim 10^{-10}$ s in order to evade beam-dump and missing energy limits [1,2].
3. Charged gluino-containing hadrons (*e.g.* $\tilde{g}u\bar{d}$) must decay into neutral ones (*e.g.* $R^0(\tilde{g}g)\pi^+$ or $(\tilde{g}u\bar{u})e^-\bar{\nu}_e$) with a lifetime shorter than about 10^{-7} s to avoid the AKERS 95R limit. Older limits for lower masses and shorter lifetimes are summarized in Ref. 1.
4. The lifetime of R^0 should be outside the ranges excluded by ALAVI-HARATI 99E ($R^0 \to \pi^+\pi^0\tilde{\gamma}$, $\pi^0\tilde{\gamma}$) and FANTI 99 ($\eta\tilde{\gamma}$). The $R_p^+(\tilde{g}uud)$ state, which is believed to decay weakly into $S^0(\tilde{g}uds)\pi^\pm$ (FARRAR 96), must be heavier than 2 GeV or have lifetime $\tau_{R_p} \gtrsim 1$ ns or $\tau_{R_p} \lesssim 50$ ps (*e.g.* if the strong decay into $S^0K^\pm$ is allowed), or its production cross sections must be at least a factor of 5 smaller than those of hyperons, to avoid ALBUQUERQUE 97 limit.
5. $m_{\tilde{g}} \geq 6.8$ GeV (95% CL) if the "experimental optimization" method of fixing the renormalization scale is valid and if the hadronization and resummation uncertainties are as estimated in BARATE 97L, from the D_2 event shape observable in Z^0 decay. The 4-jet angular distribution is less sensitive to renormalization scale ambiguities and yields a 90%CL exclusion of a light gluino (DEGOUVEA 97). A combined LEP analysis based on all

the Z^0 data and using the recent NLO calculations [3] is warranted.

6. Constraints from the effect of light gluinos on the running of α_s apply independently of the gluino lifetime and are insensitive to renormalization scale. They disfavor a light gluino at 70% CL (CSIKOR 97), which improves to more than 99% with jet analysis.

References

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2. R.M. Barnett, in SUSY 95, Proceedings of the International Workshop on Supersymmetry and Unification of Fundamental Interactions, Palaiseau, France, 15-19 May 1995, edited by I. Antoniadis and H. Videau (Editions Frontieres, Gif-sur-Yvette, France, 1996) p. 69.
3. L. Dixon and A. Signer, Phys. Rev. **D56**, 4031 (1997); J.M. Campbell, E.W.N. Glover, and D.J. Miller, Phys. Lett. **B409**, 503 (1997).

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

Limits on light gluinos ($m_{\tilde{g}}$ < 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. • • •					
		[258] ALAVI-HARATI	99E	KTEV	$pN \to R^0$, with $R^0 \to \rho^0 \tilde{\gamma}$ and $R^0 \to \pi^0 \tilde{\gamma}$
		[259] BAER	99	RVUE	Stable $\tilde{g}$ hadrons
		[260] FANTI	99	NA48	$p\text{Be} \to R^0 \to \eta \tilde{\gamma}$

		[261] ACKERSTAFF	98V	OPAL	$e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$
		[262] ADAMS	97B	KTEV	$pN \to R^0 \to \rho^0\widetilde{\gamma}$
		[263] ALBUQUERQ...	97	E761	$R^+(uud\widetilde{g}) \to S^0(uds\widetilde{g})\pi^+$, $X^-(ssd\widetilde{g}) \to S^0\pi^-$
>6.3	95	[264] BARATE	97L	ALEP	Color factors
>5	99	[265] CSIKOR	97	RVUE	β function, $Z \to$ jets
>1.5	90	[266] DEGOUVEA	97	THEO	$Z \to jjjj$
		[267] FARRAR	96	RVUE	$R^0 \to \pi^0\widetilde{\gamma}$
none 1.9–13.6	95	[268] AKERS	95R	OPAL	Z decay into a long-lived $(\widetilde{g}q\overline{q})^{\pm}$
<0.7		[269] CLAVELLI	95	RVUE	quarkonia
none 1.5–3.5		[270] CAKIR	94	RVUE	$\Upsilon(1S) \to \gamma+$ gluinonium
not 3–5		[271] LOPEZ	93C	RVUE	LEP
≈ 4		[272] CLAVELLI	92	RVUE	α_s running
		[273] ANTONIADIS	91	RVUE	α_s running
>1		[274] ANTONIADIS	91	RVUE	$pN \to$ missing energy
		[275] NAKAMURA	89	SPEC	R-Δ^{++}
>3.8	90	[276] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^1$
>3.2	90	[276] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^{0.72}$
none 0.6–2.2	90	[277] TUTS	87	CUSB	$\Upsilon(1S) \to \gamma+$ gluinonium
none 1 –4.5	90	[278] ALBRECHT	86C	ARG	$1\times10^{-11} \lesssim \tau \lesssim 1\times10^{-9}$s
none 1–4	90	[279] BADIER	86	BDMP	$1\times10^{-10} < \tau < 1\times10^{-7}$s
none 3–5		[280] BARNETT	86	RVUE	$p\overline{p} \to$ gluino gluino gluon
none		[281] VOLOSHIN	86	RVUE	If (quasi) stable; $\widetilde{g}uud$
none 0.5–2		[282] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$=300 GeV
none 0.5–4		[282] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$ <65 GeV
none 0.5–3		[282] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$=150 GeV
none 2–4		[283] DAWSON	85	RVUE	$\tau > 10^{-7}$ s
none 1–2.5		[283] DAWSON	85	RVUE	For $m_{\widetilde{q}}$=100 GeV
none 0.5–4.1	90	[284] FARRAR	85	RVUE	FNAL beam dump
>1		[285] GOLDMAN	85	RVUE	Gluononium
>1–2		[286] HABER	85	RVUE	
		[287] BALL	84	CALO	
		[288] BRICK	84	RVUE	
		[289] FARRAR	84	RVUE	
>2		[290] BERGSMA	83C	RVUE	For $m_{\widetilde{q}}$ <100 GeV
		[291] CHANOWITZ	83	RVUE	$\widetilde{g}u\overline{d}$, $\widetilde{g}uud$
>2–3		[292] KANE	82	RVUE	Beam dump
>1.5–2		FARRAR	78	RVUE	R-hadron

[258] ALAVI-HARATI 99E looked for R^0 bound states, yielding $\pi^+\pi^-$ or π^0 in the final state. The experiment is senstive 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($R^0 \to \pi^+\pi^-$ photino) and B($R^0 \to \pi^0$ 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.

[259] BAER 99 set constraints on the existence of stable $\tilde{g}$ hadrons, in the mass range $m_{\tilde{g}} > 3$ 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 $m_{\tilde{g}} < 10$ TeV. They consider jet+$\not\!\!E_T$ as well as heavy-ionizing charged-particle signatures from production of stable $\tilde{g}$ hadrons at LEP and Tevatron, developing modes for the energy loss of $\tilde{g}$ hadrons inside the detectors. Results are obtained as a function of the fragmentation probability P of the $\tilde{g}$ into a charged hadron. For $P< 1/2$, and for various energy-loss models, OPAL and CDF data exclude gluinos in the $3 < m_{\tilde{g}}(\mathrm{GeV}) < 130$ mass range. For $P> 1/2$, gluinos are excluded in the mass ranges $3 < m_{\tilde{g}}(\mathrm{GeV}) < 23$ and $50 < m_{\tilde{g}}(\mathrm{GeV}) < 200$.

[260] 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 $B(R^0 \rightarrow \eta\tilde{\gamma})$, on the value of $m_{R^0}/m_{\tilde{\gamma}}$, 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.

[261] ACKERSTAFF 98V excludes the light gluino with universal gaugino mass where charginos, neutralinos decay as $\tilde{\chi}^\pm_1, \tilde{\chi}^0_2 \rightarrow q\overline{q}\tilde{g}$ from total hadronic cross sections at $\sqrt{s}$=130–172 GeV. See paper for the case of nonuniversal gaugino mass.

[262] ADAMS 97B looked for $\rho^0 \rightarrow \pi^+\pi^-$ as a signature of $R^0=(\tilde{g}g)$ 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 $m_{R^0}/m_{\tilde{\gamma}}$. See Fig. 7 for the excluded mass and lifetime region.

[263] 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.

[264] 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.

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

[266] DEGOUVEA 97 reaanalyzed 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.

[267] FARRAR 96 studied the possible $R^0=(\tilde{g}g)$ 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.

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

[269] 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.

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

[271] 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.

[272] 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.

[273] 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.

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

[275] 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.

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

[277] 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.

[278] 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 $\sim$ 2 GeV may be sensitive to fragmentation effects. Remark that the $\tilde{g}$-hadron mass is expected to be $\sim$ 1 GeV (glueball mass) in the zero $\tilde{g}$ mass limit.

[279] 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.

[280] 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.

[281] 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.

[282] 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.

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

[284] 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.

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

[286] 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.

[287] 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.

[288] BRICK 84 reanalyzed FNAL 147 GeV HBC data for R-$\Delta(1232)^{++}$ with $\tau > 10^{-9}$ s and $p_{\text{lab}} > 2$ 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 $\widetilde{g}$ and 3 up quarks. If mass = 1.2–1.5 GeV, then limits may be lower than theory predictions.

[289] 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.

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

[291] 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.

[292] 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.

$\widetilde{G}$ (Gravitino) MASS LIMIT

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. • • •					
$>8.9 \times 10^{-6}$	95	[293] ACCIARRI	99R	L3	$e^+e^- \rightarrow \widetilde{G}\widetilde{G}\gamma$
$>7.9 \times 10^{-6}$	95	[294] ACCIARRI	98V	L3	$e^+e^- \rightarrow \widetilde{G}\widetilde{G}\gamma$
$>8.3 \times 10^{-6}$	95	[294] BARATE	98J	ALEP	$e^+e^- \rightarrow \widetilde{G}\widetilde{G}\gamma$

[293] ACCIARRI 99R searches for $\gamma\not{E}$ final states using data from $\sqrt{s}$=189 GeV.

[294] 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. • • •				
	[295] ABACHI	97	D0	$\gamma\gamma X$
	[296] BARBER	84B	RVUE	
	[297] HOFFMAN	83	CNTR	$\pi p \rightarrow n(e^+e^-)$

[295] 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.

[296] 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.

[297] 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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ABBIENDI 00H CERN-EP/99-123 G. Abbiendi *et al.* (OPAL Collab.)
EPJ C (to be publ.)
ABREU 00I EPJ C13 591 P. Abreu *et al.* (DELPHI Collab.)
ABREU 00J CERN-EP/2000-008 P. Abreu *et al.* (DELPHI Collab.)
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ACCIARRI 00D PL B472 420 M. Acciarri *et al.* (L3 Collab.)
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BARATE 00G CERN-EP/99-171 R. Barate *et al.* (ALEPH Collab.)
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MALTONI 00 PL B476 107 M. Maltoni *et al.*
ABBIENDI 99 EPJ C6 1 G. Abbiendi *et al.* (OPAL Collab.)
ABBIENDI 99F EPJ C8 23 G. Abbiendi *et al.* (OPAL Collab.)
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ABBIENDI 99T EPJ C11 619 G. Abbiendi *et al.* (OPAL Collab.)
ABBOTT 99 PRL 82 29 B. Abbott *et al.* (D0 Collab.)
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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.)
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Also 99N PL B451 447 (erratum)
ABREU 99F EPJ C7 595 P. Abreu *et al.* (DELPHI Collab.)
ABREU 99V PL B466 61 P. Abreu *et al.* (DELPHI Collab.)
ABREU 99Z EPJ C11 1 P. Abreu *et al.* (DELPHI Collab.)
ACCIARRI 99C PL B445 428 M. Acciarri *et al.* (L3 Collab.)
ACCIARRI 99H PL B456 283 M. Acciarri *et al.* (L3 Collab.)
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ACCIARRI 99R PL B470 268 M. Acciarri *et al.* (L3 Collab.)
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ACKERSTAFF 99 EPJ C6 225 K. Ackerstaff *et al.* (OPAL Collab.)
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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.)
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FANTI 99 PL B446 117 V. Fanti *et al.* (CERN NA48 Collab.)
MALTONI 99B PL B463 230 M. Maltoni, M.I. Vysotsky
ABBOTT 98 PRL 80 442 B. Abbott *et al.* (D0 Collab.)
ABBOTT 98C PRL 80 1591 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.)
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 98J EPJ C2 607 K. Ackerstaff *et al.* (OPAL Collab.)
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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.)
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BARATE 98K PL B433 176 R. Barate *et al.* (ALEPH Collab.)
BARATE 98N PL B434 189 R. Barate *et al.* (ALEPH Collab.)
BARATE 98S EPJ C4 433 R. Barate *et al.* (ALEPH Collab.)
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ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and the LEP Electroweak Working Group.
ABE 97K PR D56 R1357 F. Abe *et al.* (CDF Collab.)
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ABREU 97J ZPHY C74 577 P. Abreu *et al.* (DELPHI Collab.)
ACCIARRI 97U PL B414 373 M. Acciarri *et al.* (L3 Collab.)
ACCIARRI 97V PL B415 299 M. Acciarri *et al.* (L3 Collab.)
ACKERSTAFF 97H PL B396 301 K. Ackerstaff *et al.* (OPAL Collab.)
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ALBUQUERQ... 97 PRL 78 3252 I.F. Albuquerque *et al.* (FNAL E761 Collab.)
ALEXANDER 97B ZPHY C73 201 G. Alexander *et al.* (OPAL Collab.)
BARATE 97K PL B405 379 R. Barate *et al.* (ALEPH Collab.)
BARATE 97L ZPHY C76 1 R. Barate *et al.* (ALEPH Collab.)
BARATE 97N PL B407 377 R. Barate *et al.* (ALEPH Collab.)
BOTTINO 97 PL B402 113 A. Bottino *et al.* (TORI, LAPP, GENO+)
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
ELLIS 97C PL B413 355 J. Ellis *et al.*
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.)
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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.)
ABREU 96O PL B387 651 P. Abreu *et al.* (DELPHI Collab.)
ACCIARRI 96F PL B377 289 M. Acciarri *et al.* (L3 Collab.)
ACKERSTAFF 96C PL B389 616 K. Ackerstaff *et al.* (OPAL Collab.)
AID 96 ZPHY C71 211 S. Aid *et al.* (H1 Collab.)
AID 96C PL B380 461 S. Aid *et al.* (H1 Collab.)
ALEXANDER 96J PL B377 181 G. Alexander *et al.* (OPAL Collab.)
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CHO 96 PL B372 101 G.C. Cho, Y. Kizukuri, N. Oshimo (TOKAH, OCH)
ELLIS 96B PL B388 97 J. Ellis *et al.* (CERN, MINN)
FARRAR 96 PRL 76 4111 G.R. Farrar (RUTG)
SUGIMOTO 96 PL B369 86 Y. Sugimoto *et al.* (AMY Collab.)
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.)
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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)
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)
LAU	93	PR D47 1087	K. Lau	(HOUS)
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.)
ELLIS	92F	PL B283 252	J. Ellis, L. Roszkowski	(CERN)
KAWASAKI	92	PR D46 1634	M. Kawasaki, S. Mizuta	(OSU, TOHO)
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)
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.)
ABREU	90G	PL B247 157	P. Abreu *et al.*	(DELPHI Collab.)
ADACHI	90C	PL B244 352	I. Adachi *et al.*	(TOPAZ Collab.)
ELLIS	90	PL B245 251	J. Ellis *et al.*	(CERN, HARC, TAMU)
GRIEST	90	PR D41 3565	K. Griest, M. Kamionkowski, M.S. Turner	(UCB+)
GRIFOLS	90	NP B331 244	J.A. Grifols, E. Masso	(BARC)
KRAUSS	90	PRL 64 999	L.M. Krauss	(YALE)
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	88B	PL B215 404	J. Ellis *et al.*	(CERN, MINN, RAL, CAMB)
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)