Supersymmetry – THIS IS PART 1 OF 4

To reduce the size of this section's PostScript file, we have divided it into three PostS
files. We present the following index:

PART 1

Page #	Section name
1	Note on Supersymmetry – Part I Theory

PART 2

Page #	Section name
32	Note on Supersymmetry – Part II Experiment

PART 2

Page #	Section name
48	Note on Supersymmetry – Part II Experiment (cont.)

PART 4

Page #	Section name
66	Data Listings

Supersymmetric Particle Searches

SUPERSYMMETRY

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This review is divided into two parts:

Supersymmetry, Part I (Theory)

I.1. Introduction
I.2. Structure of the MSSM
I.3. Parameters of the MSSM
I.4. The Higgs sector of the MSSM
I.5. The supersymmetric-particle sector
I.6. Reducing the MSSM parameter freedom
I.7. The constrained MSSMs: mSUGRA, GMSB, and SGUTs
I.8. The MSSM and precision of electroweak data
I.9. Beyond the MSSM

Supersymmetry, Part II (Experiment)

II.1. Introduction
II.2. Common supersymmetry scenarios
II.3. Experimental issues
II.4. Supersymmetry searches in e^+e^- colliders
II.5. Supersymmetry searches at proton machines
II.6. Supersymmetry searches at HERA and fixed-target experiments
II.7. Conclusions

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 [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 relevant for explaining the scale of electroweak interactions, then the mass parameters introduced by the soft-supersymmetry-breaking terms must be of order 1 TeV or below [11]. Some bounds on these parameters exist due to the absence of supersymmetric-particle production at current accelerators [12]. Additional constraints arise from limits on the contributions of virtual supersymmetric particle exchange to a variety of Standard Model processes [13,14]. The impact of precision electroweak measurements at LEP and SLC on the MSSM parameter space is discussed briefly in Section I.8.

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 [15]. 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 [16]. 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", a potentially important component of the non-baryonic dark matter that is required in cosmologies with a critical mass density [17].

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 [18]. 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 [19]. 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.

All particles feel the gravitational force. In particular, particles of the hidden sector and the visible sector can interact via the exchange of gravitons. Thus, 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 [20,21]. In this scenario, the gravitino mass is of order the electroweak-symmetry-breaking scale, while its couplings are roughly gravitational in strength [1,22]. 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. The canonical 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 [23,24]. 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. 25. 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 $m_1^2+|\mu|^2$ 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 $v_d^2+v_u^2=(246\ \text{GeV})^2$ is fixed by the W mass (or equivalently by the Fermi constant G_F), 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. 26 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 [27].

I.4. The Higgs sector of the MSSM: Before describing the supersymmetric-particle sector, let us consider the Higgs sector of the MSSM [8,9,28]. 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 [29,30]. 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 accurate, it would imply that H_1^0 must be discovered at the LEP-2 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. For example, in Ref. 29, the following approximate upper bound was obtained for $m_{H_1^0}$ (assuming $m_{A^0} > m_Z$) in the limit of $m_Z \ll m_t \ll M_{\widetilde{t}}$ [where top-squark ($\widetilde{t}_L$–$\widetilde{t}_R$) mixing is neglected]

$$m_{H_1^0}^2 \lesssim m_Z^2 + \frac{3g^2 m_Z^4}{16\pi^2 m_W^2}\left\{\left[\frac{2m_t^4 - m_t^2 m_Z^2}{m_Z^4}\right]\ln\left(\frac{M_{\widetilde{t}}^2}{m_t^2}\right) + \frac{m_t^2}{3m_Z^2}\right\}. \tag{2}$$

More refined computations (which include the effects of top-squark mixing, renormalization group improvement, and the leading two-loop contributions) yield $m_{H_1^0} \lesssim 125$ GeV for $m_t =$

175 GeV and a top-squark mass of $M_{\tilde{t}} \lesssim 1$ TeV [31]. Clearly, the radiative corrections to the Higgs masses can have a significant impact on the search for the Higgs bosons of the MSSM at LEP [32].

I.5. 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 [33].

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

$$
\begin{aligned}
M^2_{\widetilde{\chi}_1^+, \widetilde{\chi}_2^+} = \tfrac{1}{2}\Big\{ & |\mu|^2 + |M_2|^2 + 2m_W^2 \\
& \mp \Big[\left(|\mu|^2 + |M_2|^2 + 2m_W^2 \right)^2 - 4|\mu|^2 |M_2|^2 \\
& \qquad - 4m_W^4 \sin^2 2\beta + 8m_W^2 \sin 2\beta \, \mathrm{Re}(\mu M_2) \Big]^{1/2} \Big\} , \quad (3)
\end{aligned}
$$

where the states are ordered such that $M_{\widetilde{\chi}_1^+} \leq M_{\widetilde{\chi}_2^+}$. If CP-violating effects are ignored (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. (3) is used by the LEP collaborations [12] 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 [33]. The corresponding neutralino eigenstates are usually denoted by $\widetilde{\chi}_i^0$ ($i = 1, \ldots 4$), according to the convention that $M_{\widetilde{\chi}_1^0} \le M_{\widetilde{\chi}_2^0} \le M_{\widetilde{\chi}_3^0} \le M_{\widetilde{\chi}_4^0}$. If a chargino or neutralino eigenstate approximates a particular gaugino or Higgsino state, it may be convenient to use the corresponding nomenclature. For example, if M_1 and M_2 are small compared to m_Z (and $|\mu|$), then the lightest neutralino $\widetilde{\chi}_1^0$ will be nearly a pure photino, $\widetilde{\gamma}$ (the supersymmetric partner of the photon).

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 [34]

$$M_{LR}^2 = \begin{cases} m_d(A_d - \mu\tan\beta), & \text{for “down”-type } f \\ m_u(A_u - \mu\cot\beta), & \text{for “up”-type } f, \end{cases} \tag{4}$$

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. 25. Due to the appearance of the *fermion* mass in Eq. (4), 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 [2]

$$M^2_{\widetilde{f}_L} = M^2_{\widetilde{F}} + m^2_f + (T_{3f} - e_f \sin^2\theta_W) m^2_Z \cos 2\beta\,,$$

$$M^2_{\widetilde{f}_R} = M^2_{\widetilde{R}} + m^2_f + e_f \sin^2\theta_W m^2_Z \cos 2\beta\,, \tag{5}$$

where $M^2_{\widetilde{F}} = M^2_{\widetilde{Q}}$ $[M^2_{\widetilde{L}}]$ for $\widetilde{u}_L$ and $\widetilde{d}_L$ $[\widetilde{\nu}_L$ and $\widetilde{e}_L]$, and $M^2_{\widetilde{R}} = M^2_{\widetilde{U}}$, $M^2_{\widetilde{D}}$ 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. (5)], 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]. 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.

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 [35].

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 [5,26,36]). 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 [37]). 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 of the most common predictions of the high-energy approach is the unification of gaugino mass parameters at some high-energy scale $M_{\rm X}$, *i.e.*,

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

This is a common prediction of both grand unified supergravity models and gauge-mediated supersymmetry-breaking models. Consequently, the effective low-energy gaugino mass parameters (at the electroweak scale) are related:

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

In this case, the chargino and neutralino masses and mixing angles depend only on three unknown parameters: the gluino mass, μ, and $\tan\beta$. However, the assumption of gaugino-mass unification could prove false and must eventually be tested experimentally. For example, the phenomenology of neutralinos in a model with $M_1 \simeq M_2$ can differ in some interesting ways from the standard phenomenology based on Eq. (7), as shown in Ref. 38.

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 [1,2], 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 [20]:

$$\begin{aligned}
&M^2_{\widetilde{Q}}(M_{\rm P}) = M^2_{\widetilde{U}}(M_{\rm P}) = M^2_{\widetilde{D}}(M_{\rm P}) = m_0^2\mathbf{1}\,,\\
&M^2_{\widetilde{L}}(M_{\rm P}) = M^2_{\widetilde{E}}(M_{\rm P}) = m_0^2\mathbf{1}\,,\\
&m_1^2(M_{\rm P}) = m_2^2(M_{\rm P}) = m_0^2\,,\\
&A_U(M_{\rm P}) = A_D(M_{\rm P}) = A_L(M_{\rm P}) = A_0\mathbf{1}\,, \qquad (8)
\end{aligned}$$

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. (5). Through the renormalization group running with boundary conditions specified in Eq. (7) and Eq. (8), 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. 39.

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. 39). 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. 40.) 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. (4).

Due to the implicit $m_{1/2}$ dependence in the low-energy values of $M^2_{\widetilde{Q}}$, $M^2_{\widetilde{U}}$ and $M^2_{\widetilde{D}}$, there is a tendency for the gluino in mSUGRA models to be lighter than the first and second generation squarks. Moreover, the LSP is typically the lightest neutralino, $\widetilde{\chi}^0_1$, which tends to be dominated by its gaugino components. 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 [41].

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 it is fair to say that 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 [42]. 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)×SU(2)×U(1) gauge couplings predicted by models of supersymmetric grand unified theories (SGUTs) [5,43] (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). Current low-energy data is in fair agreement with the predictions of supersymmetric grand unification as discussed in Section I.8.

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 [44], and an intriguing possibility that $\lambda_b = \lambda_\tau = \lambda_t$ may be phenomenologically viable [45,40] 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. The MSSM and precision of electroweak data: The MSSM provides a framework that can be tested by precision electroweak data. The level of accuracy of the measured Z decay observables at LEP and SLC is sufficient to test the structure of the one-loop radiative corrections of the electroweak model [46]. Thus the precision electroweak data is potentially sensitive to the virtual effects of undiscovered particles. Combining the most recent LEP and SLC electroweak results (including the limits obtained from the direct Higgs search at LEP) with the recent top-quark mass measurement at the Tevatron, a preference is found [47,48] for a light Higgs boson mass of order m_Z, which is consistent with the MSSM Higgs mass upper bound discussed in Section I.4. [More precisely, in Ref. 48, the best fit value for the mass of the Standard Model Higgs boson ranges from about 83 to 140 GeV, while the 95% CL upper limit ranges from 287 to 361 GeV, depending on the value used for $\alpha(m_Z)$. (Similar results have been obtained in Ref. 47). Moreover, for Z decay observables, the effects of virtual supersymmetric-particle exchange are suppressed by a factor of $m_Z^2/M_{\rm SUSY}^2$, and therefore decouple in the limit of large supersymmetric-particle masses. It follows that for $M_{\rm SUSY} \gg m_Z$ (in practice, it is sufficient to have all supersymmetric-particle masses above 200 GeV), the MSSM yields an equally good fit to the precision electroweak data as compared to the Standard Model fit.

At present, a global fit of the electroweak data by Erler and Langacker (EL) [48] is in excellent agreement with the predictions of the Standard Model. If some supersymmetric particles are light (say, below 200 GeV but above present experimental bounds deduced from direct searches), then it is possible that the EL fit could be modified in the MSSM. A few years ago, when the rate for $Z \to b\bar{b}$ was four standard deviations above the Standard Model prediction, the possibility that the MSSM could improve the global electroweak fit was taken quite seriously. However, it is hard to imagine that the MSSM could significantly improve the quality of the current EL fit (given that the Standard Model fit is already quite good, and a global fit in the context of the MSSM would necessarily involve more degrees of freedom). On the other hand, the MSSM could significantly decrease the goodness of the Standard Model fit. This possibility has been explored recently in Ref. 49. Their analysis shows that one can slightly reduce the allowed region of mSUGRA and GMSB model parameter spaces beyond the region already ruled out by the non-observation of direct supersymmetric particle production.

Electroweak observables are also sensitive to the strong coupling constant through the QCD radiative corrections. The EL global fit extracts a value of $\alpha_s(m_Z) = 0.1214 \pm 0.0031$, which is in good agreement with the world average of $\alpha_s(m_Z) = 0.1191 \pm 0.0018$ [48]. This result has important implications for the viability of supersymmetric unification. 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. For example, allowing for low-energy threshold effects but neglecting threshold corrections near the unification scale, Ref. 50 finds that SGUT unification in the mSUGRA model predicts that $\alpha_s(m_Z) > 0.126$, which is only in slight disagreement with the results of the EL fit. (Similar results have been obtained in Ref. 51.) Taking SGUT threshold effects into account could either slightly increase or decrease the predicted value of $\alpha_s(m_Z)$, depending on the details of the model. In contrast, the corresponding result for the Standard Model extrapolation, $\alpha_s(m_Z) \simeq 0.073 \pm 0.002$ [52], is many standard deviations away from the experimentally observed result.

I.9. 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 [53,54]; (ii) an enlarged electroweak gauge group beyond SU(2)×U(1) [55]; (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 [56]. A possible theoretical motivation for such new structure arises from the study of phenomenologically viable string theory ground states [57].

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:

$$(\lambda_L)_{pmn}\widehat{L}_p\widehat{L}_m\widehat{E}^c_n + (\lambda'_L)_{pmn}\widehat{L}_p\widehat{Q}_m\widehat{D}^c_n + (\lambda_B)_{pmn}\widehat{U}^c_p\widehat{D}^c_m\widehat{D}^c_n\,, \quad (9)$$

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. (9) by taking all possible combinations involving two fermions and one scalar superpartner. Note that the term in Eq. (9) 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 [58]. 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 [59], neutrinoless double beta decay [60], sneutrino-antisneutrino mixing [54,61], and s-channel resonant production of the sneutrino in e^+e^- collisions [62]. 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.

Squarks can be regarded as leptoquarks since if $\lambda'_L \neq 0$, the following processes are allowed: $e^+\overline{u}_m \to \overline{\widetilde{d}}_n \to e^+\overline{u}_m$, $\overline{\nu}\overline{d}_m$ and $e^+d_m \to \widetilde{u}_n \to e^+d_m$. (As above, m and n are generation labels, so that $d_2 = s$, $d_3 = b$, *etc.*) These processes have received much attention during the past year as a possible explanation for the HERA high Q^2 anomaly [63].

The theory and phenomenology of alternative low-energy supersymmetric models (such as models with R-parity violation) and its consequences for collider physics have only recently begun to attract significant attention. Experimental and theoretical constraints place some restrictions on these approaches, although no comprehensive treatment has yet appeared in the literature.

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Supersymmetry – THIS IS PART 2 OF 4

To reduce the size of this section's PostScript file, we have divided it into three PostScript files. We present the following index:

PART 1

Page #	Section name
1	Note on Supersymmetry – Part I Theory

PART 2

Page #	Section name
32	Note on Supersymmetry – Part II Experiment

PART 2

Page #	Section name
48	Note on Supersymmetry – Part II Experiment (cont.)

PART 4

Page #	Section name
66	Data Listings

SUPERSYMMETRY, PART II (EXPERIMENT)

(by M. Schmitt)

II.1. Introduction: The theoretical strong points of supersymmetry (SUSY) have motivated many searches for supersymmetric particles. Most of these have been guided by the MSSM and are based on the canonical missing-energy signature caused by the escape of the LSP's ('lightest supersymmetric particles'). More recently, other scenarios have received considerable attention from experimenters, widening the range of topologies in which new physics might be found.

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

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

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

II.2. Common supersymmetry scenarios: In the 'canonical' scenario [1], supersymmetric particles are pair-produced and decay directly or via cascades to the LSP. For most typical choices of model parameters, the lightest neutralino is the LSP. Conservation of R-parity is assumed, so the LSP's do not decay and escape detection, causing an apparent transverse momentum imbalance, $p_T^{\rm miss}$ (also referred to as missing transverse energy, $\not\!\!E_T$), and missing energy, $E^{\rm miss}$. There are always two LSP's per event. The searches demand significant $p_T^{\rm miss}$ as the main discriminant against Standard Model (SM) processes; collimated jets, isolated leptons or photons, and appropriate kinematic cuts provide additional handles to reduce backgrounds.

The conservation of R-parity is not required in supersymmetry, however, and in some searches it is assumed that supersymmetric particles decay via interactions which violate R-parity (RPV), and hence, lepton and/or baryon number. For the most part the production of superpartners is unchanged, but in general the missing-energy signature is lost. Depending on the choice of the R-parity–breaking interaction, SUSY events are characterized by excess leptons or hadronic jets, and in many cases it is relatively easy to suppress SM backgrounds [3]. In this scenario the pair-production of LSP's, which need not be $\widetilde{\chi}_1^0$'s or $\widetilde{\nu}$'s, is a significant SUSY signal.

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

Finally, in another scenario the gluino $\widetilde{g}$ is assumed to be very light ($M_{\widetilde{g}} < 5$ GeV/c^2) [5]. It is a color-octet fermion which can saturate the decays of charginos and neutralinos. In this scenario the decay of the gluino to the lightest neutralino is kinematically suppressed, so long-lived supersymmetric hadrons ($\widetilde{g} + g$ bound states called R^0's) are formed [6]. These will produce hadronic showers in the calorimeters, thus spoiling the canonical missing-energy signature on which most SUSY searches rely. The exclusion of a light gluino is not settled (see the Listings), however, given recent experimental and theoretical developments, this issue may well be settled in the near future.

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

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

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

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

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

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

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

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

II.4. Supersymmetry searches in e^+e^- colliders: The center-of-mass energy of the large electron-positron collider (LEP) at CERN has been raised well above the Z peak in recent years. After collecting approximately 150 pb^{-1} at LEP 1, each experiment (ALEPH, DELPHI, L3, OPAL) has accumulated the first data at LEP 2: about 5.7 pb^{-1} at $\sqrt{s} \sim 133$ GeV (1995) [7], 10 pb^{-1} at 161 GeV and 11 pb^{-1} at 172 GeV (1996). This review emphasizes the most recent LEP 2 results.

At LEP experiments and SLD at SLAC excluded all visible supersymmetric particles up to about half the Z mass (see the Listings for details). These limits come mainly from the comparison of the measured Z widths to the SM expectations, and depend less on the details of the SUSY particle decays than do the results of direct searches [8]. The new data taken at higher energies allow much stronger limits to be set, although the complex interplay of masses, cross sections, and branching ratios makes simple general limits impossible to specify.

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

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

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

The various SUSY particles considered at LEP usually decay directly to SM particles and LSP's, so signatures commonly consist of some combination of jets, leptons, possibly photons, and missing energy. Consequently the search criteria are geared toward a few distinct topologies. Although they may be optimized for one specific signal, they are often efficient for others. For example, acoplanar jets are expected in both $\widetilde{t}_1\overline{\widetilde{t}}_1$ and $\widetilde{\chi}^0_1\widetilde{\chi}^0_2$ 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 a large initial-state radiation induced by the Z pole, which gives events that are well balanced with respect to the beam direction. Finally, there is four-fermion production through states with one or two resonating bosons (W^+W^-, ZZ, $We\nu$, Ze^+e^-, etc.) which can give events with large $E^{\rm miss}$ and $p_T^{\rm miss}$ due to neutrinos and electrons lost down the beam pipe.

In the canonical case, $E^{\rm miss}$ and $p_T^{\rm miss}$ are large enough to eliminate most of these backgrounds. The e^+e^- initial state is well defined so searches utilize both transverse and longitudinal momentum components. It is possible to measure the missing mass ($M_{\rm miss} = \{(\sqrt{s} - E_{\rm vis})^2 - \vec{p}^{\,2}_{\rm vis}\}^{1/2}$) which is small if $p_T^{\rm miss}$ is caused by a single neutrino or undetected electron or photon, and can be large when there are two massive LSP's. The four-fermion processes cannot be entirely eliminated, however, and a non-negligible irreducible background is expected. Fortunately, the uncertainties for these backgrounds are not large.

High efficiencies are easily achieved when the mass of the LSP is lighter than the parent particle by at least 10 GeV/c^2 and greater than about 10 GeV/c^2. Difficulties arise when the mass difference ΔM between the produced particle and the LSP is smaller than 10 GeV/c^2 as the signal resembles background from two-photon interactions. A very light LSP is challenging also since, kinematically speaking, it plays a role similar to a neutrino, so that, for example, a signal for charginos of mass 80 GeV/c^2 is difficult to distinguish from the production of W^+W^- pairs.

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

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

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

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

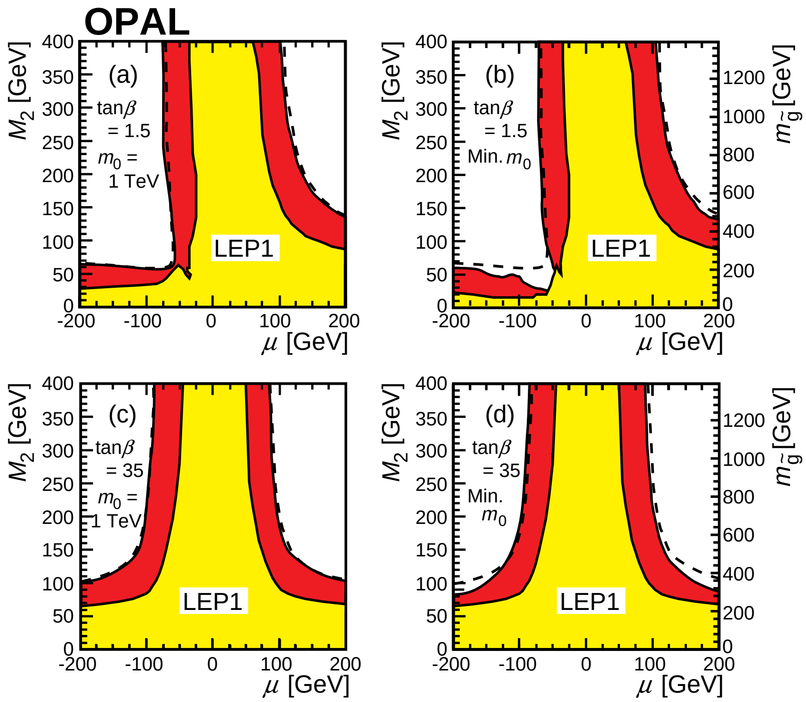

Figure 1: Regions in the (μ, M_2) plane excluded by chargino and neutralino searches performed by the OPAL Collaboration, for two values of $\tan\beta$ [9]. The light shaded region shows the limits derived from the Z width, while the dark region shows the additional exclusion obtained by the direct searches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

effects are greatest when the chargino has a large gaugino component. The weakest bounds are found for $\mu \sim -70\ \mathrm{GeV}/c^2$ and $\tan\beta < 2$, as the cross section is reduced with respect to larger $|\mu|$, the impact of $\widetilde{\tau}$ mixing can be large, and the efficiency is not optimal because ΔM is large. The erosion in the bounds when sneutrinos are light is illustrated clearly by the so-called 'minimal m_0' case (Fig. 1). Here m_0 is a universal mass for sleptons and sneutrinos at the GUT scale; for this analysis the smallest value of m_0 consistent with OPAL slepton limits has been taken.

If the sneutrino is lighter than the chargino, then two-body decays $\widetilde{\chi}^+ \to \ell^+\widetilde{\nu}$ dominate, and in the 'corridor' $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3\ \mathrm{GeV}/c^2$ the acceptance is so low that no exclusion is possible [10]. An example of this is shown in Fig. 2, from the ALEPH Collaboration. Since the chargino cross-section and field content varies with μ, two values were tested: in both cases the corridor $M_{\widetilde{\chi}^\pm} \lesssim M_{\widetilde{\nu}}$ persists, and strictly speaking the lower limit on $M_{\widetilde{\chi}^\pm}$ is the one from LEP 1. Searches for charged sleptons can be used to cover this corridor, as shown in the figure, but this coverage is effective only for low $\tan\beta$. The searches for neutralinos alleviate the problem in some regions of parameter space, but they cannot close the corridor.

The limits on slepton masses [11] are well below the kinematic limit due to a strong p-wave phase space suppression near threshold. A variety of limits have been derived, considering right-sleptons only (which is conservative), or degenerate right/left-sleptons (which is optimistic), or relying on a universal slepton mass m_0 (which is model-dependent). For individual experiments, the limits on selectrons reach $80\ \mathrm{GeV}/c^2$ due to contributions from t-channel neutralino exchange; they depend slightly on μ and $\tan\beta$. For the extreme case $M_{\widetilde{\chi}_1^0} \to 0$,

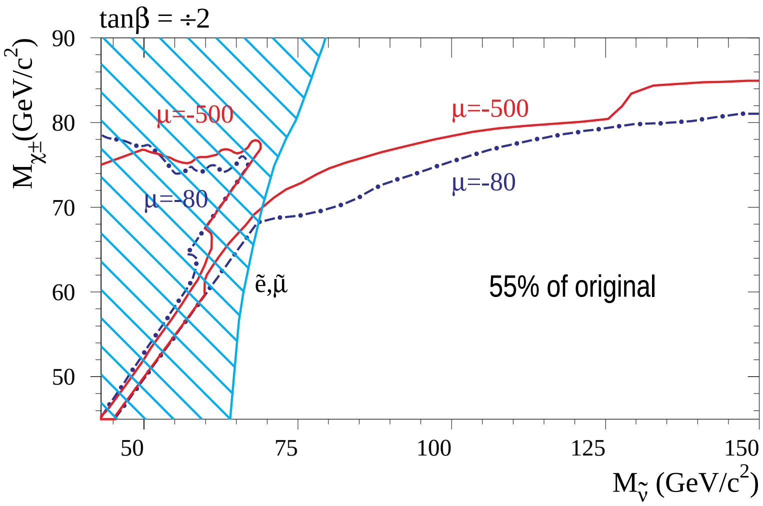

Figure 2: Limit on a gaugino-like chargino as a function of the sneutrino mass, from the ALEPH Collaboration [9]. The open corridor $0 < M_{\widetilde{\chi}^\pm} - M_{\widetilde{\nu}} \lesssim 3$ GeV/c^2 i s evident. $\tan\beta = \sqrt{2}$ is fixed and two values of μ are shown. The hatched region is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

the AMY Collaboration at TRISTAN obtained a result which reaches 79 GeV/c^2 for degenerate selectrons at 90% CL [12]. Limits on smuons reach approximately 60 GeV/c^2, and staus, 55 GeV/c^2. For selectrons and smuons the dependence on $\Delta M = M_{\widetilde{\ell}} - M_{\widetilde{\chi}_1^0}$ is weak for $\Delta M \gtrsim 10$ GeV/c^2 unless parameters are chosen which lead to a large branching ratio for $\widetilde{\ell}_R \to \ell\widetilde{\chi}^0_2$, possible when $M_{\widetilde{\chi}^0_1}$ is very small. Preliminary results from the combination of the four LEP experiments have been derived, leading to significantly stronger bounds [13]: $M_{\widetilde{e}_R} > 80$ GeV/c^2 and $M_{\widetilde{\mu}_R} > 74$ GeV/c^2 for $M_{\widetilde{\chi}^0_1} = 45$ GeV/c^2. Bounds on the parameters M_2 and m_0 also have been derived.

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

Limits on stop and sbottom masses [15], like the slepton mass limits, do not extend to the kinematic limit. The stop decay $\widetilde{t}_1 \to c\widetilde{\chi}^0_1$ proceeds through loops, giving a lifetime long enough to allow the top squark to form supersymmetric hadrons which provide a pair of jets and missing energy. If sneutrinos are light the decay $\widetilde{t}_1 \to b\ell\widetilde{\nu}$ dominates, giving two leptons in addition to the jets. Access to very small ΔM is possible due to the visibility of the decay products of the c and b quarks. Limits vary from 75 GeV/c^2 for an unrealistic pure $\widetilde{t}_L$ state to 60 GeV/c^2 if the coupling of $\widetilde{t}_1$ to the Z vanishes. The DELPHI result is shown in Fig. 3 as an example. The combination of results from all four experiments, shown in Fig. 4, is significantly stronger: for example, $M_{\widetilde{t}} > 75$ GeV/c^2 is obtained for $\Delta M > 10$ GeV/c^2 and *any* mixing [13]. Limits on sbottoms are weaker due to their smaller electric charge.

In canonical SUSY scenarios the lightest neutralino leaves no signal in the detector. Nonetheless, the tight correspondences among the neutralino and chargino masses allow an indirect limit on $M_{\widetilde{\chi}^0_1}$ to be derived [9,10]. The key assumption is that the gaugino mass parameters M_1 and M_2 unify at the

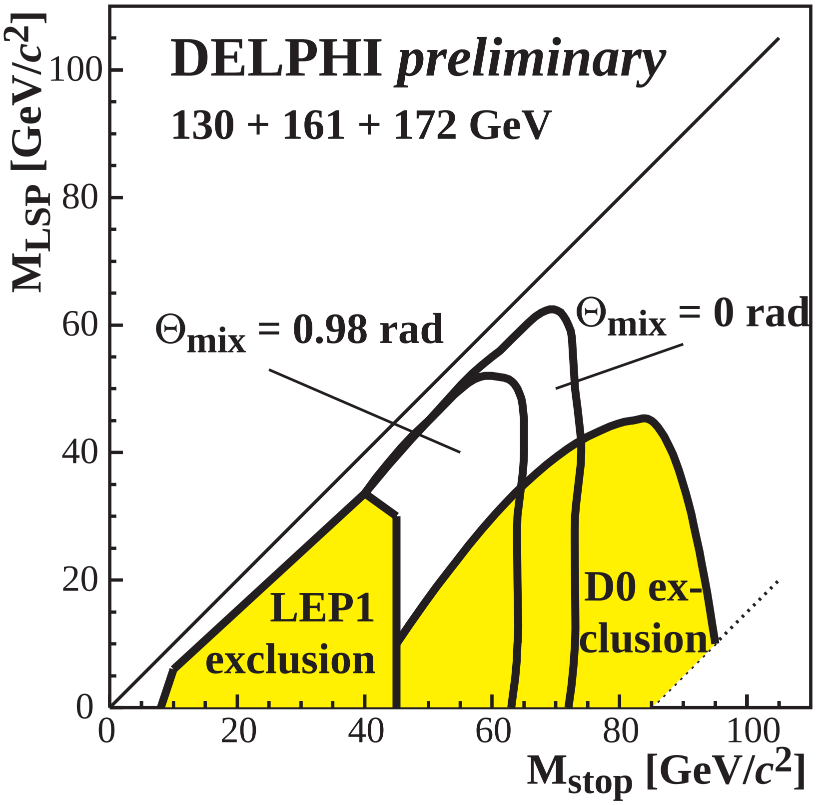

Figure 3: Ranges of excluded stop and neutralino masses reported by the DELPHI Collaboration [15]. Two values of mixing angle are shown: $\theta_{\rm mix} = 0$ gives pure $\widetilde{t}_L$ and $\theta_{\rm mix} = 0.98$ rad gives a stop with no coupling to the Z. The range excluded by DØ is also shown.

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

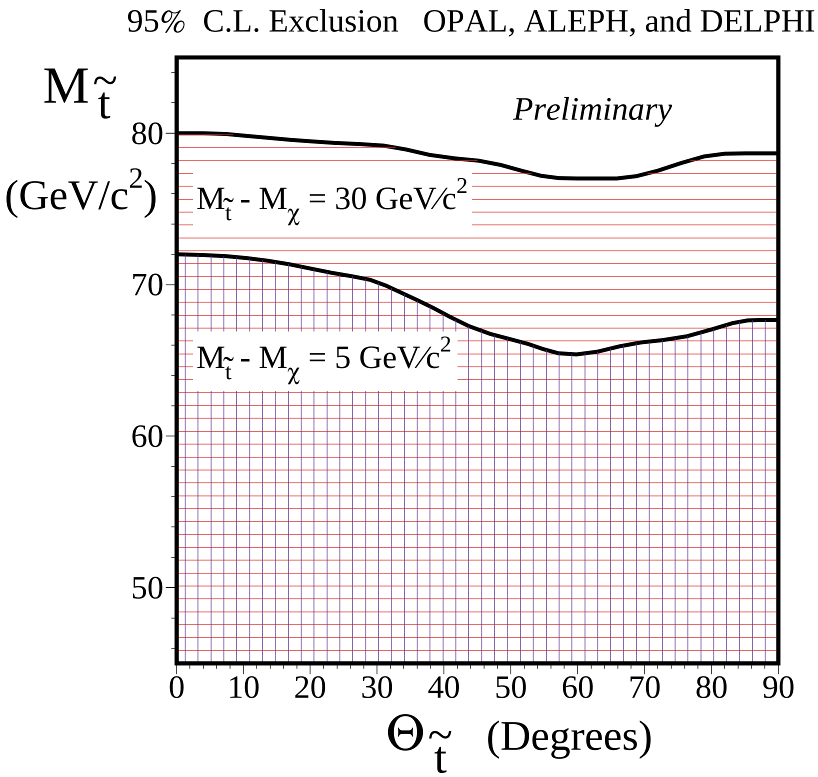

Figure 4: Lower bound on the stop mass as a function of the mixing angle for two values of $\Delta M = M_{\widetilde{t}} - M_{\widetilde{\chi}_1^0}$, derived from the combined results of the LEP experiments. These results are preliminary [13].

from the results of chargino and neutralino searches and certain bounds from LEP 1, as illustrated in Fig. 5, from DELPHI. The various contours change as $\tan\beta$ is increased, with the result that the lower limit on $M_{\widetilde{\chi}_1^0}$ increases also.

When sleptons are lighter than 80 GeV/c^2, all the effects of light sneutrinos on both the production and decay of charginos and heavier neutralinos must be taken into account. Although the bounds from charginos are weakened substantially, useful additional constraints from the slepton searches rule out the possibility of a massless neutralino. The current *preliminary* limit, shown in Fig. 6, is $M_{\widetilde{\chi}_1^0} > 25$ GeV/c^2 for $\tan\beta > 1$ and $M_{\widetilde{\nu}} > 200$ GeV/c^2 (effectively, $m_0 \gtrsim 200$ GeV/c^2). Allowing the universal slepton mass m_0 to have any value, the limit is $M_{\widetilde{\chi}_1^0} > 14$ GeV/c^2 [10]. These bounds can be evaded by dropping gaugino mass unification or R-parity conservation, or by assuming the gluino is very light.

If R-parity is not conserved, the lightest neutralino decays to SM particles and is visible inside the detector. Searches for supersymmetry with R-parity violation [16] usually assume that one of three possible interaction terms ($LL\overline{E}$, $LQ\overline{D}$, $\overline{U}\,\overline{D}\,\overline{D}$) dominates. The relevant term can cause R-parity violation *directly* in the decay of the produced particle, or it can be manifested *indirectly* in the decay of the LSP, which need no longer be neutral or colorless. Rather exotic topologies can occur, such as six-lepton final states in slepton production with $LL\overline{E}$ dominating, or ten-jet final states in chargino production with $\overline{U}\,\overline{D}\,\overline{D}$ dominating; and, for the most part, entirely new search criteria keyed to an excess of leptons and/or jets must be devised. Although not all possibilities have been tested yet, searches with a wide scope have found no evidence for supersymmetry with R-parity violation, and limits are usually as constraining as in the canonical scenario. In fact, the direct exclusion of pair-produced $\widetilde{\chi}_1^0$'s rules out some parameter space not accessible in the canonical case.

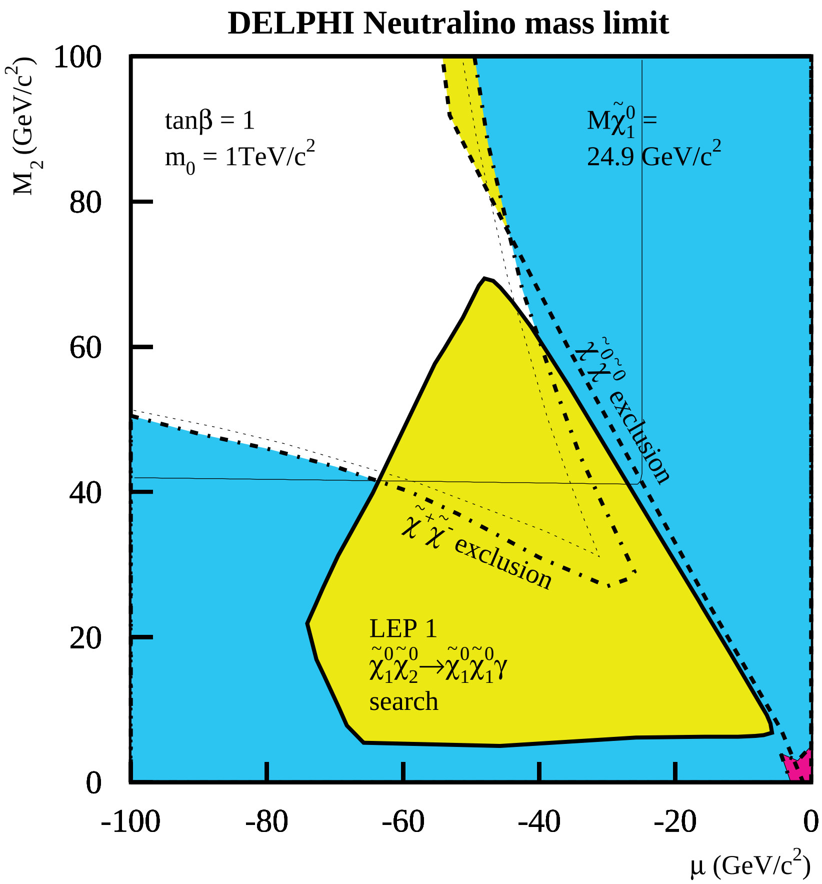

Figure 5: Excluded regions in the (μ, M_2) plane obtained by the DELPHI Collaboration, for $\tan\beta = 1$ and $m_0 = 1$ TeV/c^2 [9]. (This very high value for m_0 is tantamount to setting all slepton masses to 1 TeV/c^2.) The combination of LEP 2 chargino search (dot-dash line) and the neutralino search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

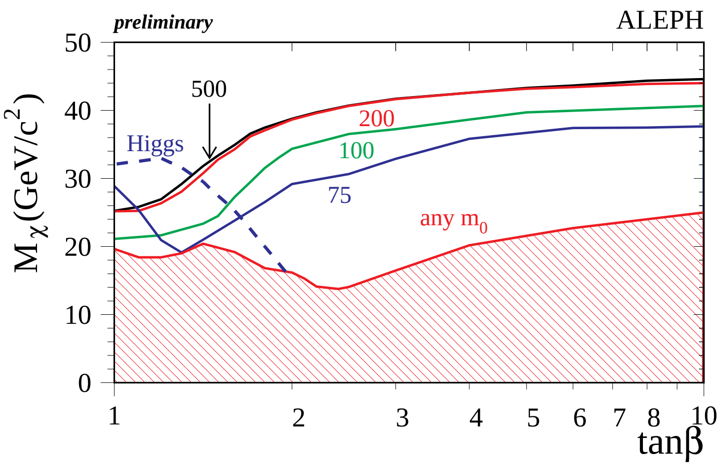

Figure 6: Lower limit on the mass of the lightest neutralino, derived by the ALEPH Collaboration using constraints from chargino, neutralino, and slepton searches [10]. The values $500, \ldots, 75$ show the bound obtained when fixing the universal scalar mass and taking slepton bounds into account; including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

Supersymmetry – THIS IS PART 3 OF 4

To reduce the size of this section's PostScript file, we have divided it into three PostScript files. We present the following index:

PART 1

Page #	Section name
1	Note on Supersymmetry – Part I Theory

PART 2

Page #	Section name
32	Note on Supersymmetry – Part II Experiment

PART 2

Page #	Section name
48	Note on Supersymmetry – Part II Experiment (cont.)

PART 4

Page #	Section name
66	Data Listings

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

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

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

II.5. Supersymmetry searches at proton machines: Although the LEP experiments can investigate a wide range of scenarios and cover obscure corners of parameter space, they cannot match the mass reach of the Tevatron experiments (CDF and DØ). Each experiment has logged approximately 110 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV—ten times the energy of

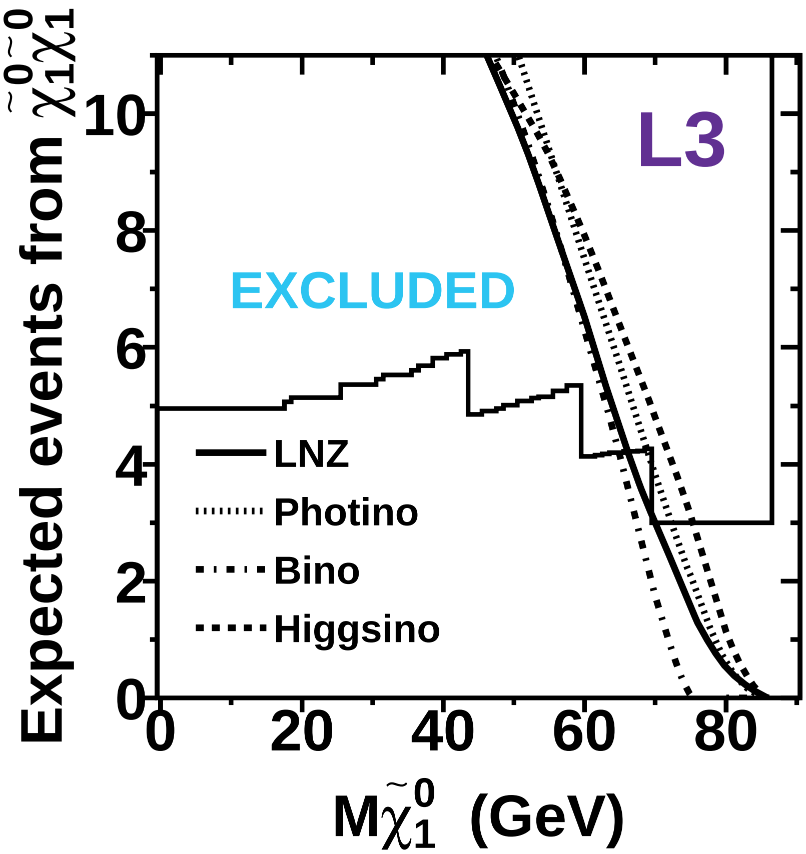

Figure 7: Upper limit on the number of acoplanar photon events as a function of the neutralino mass, from the L3 Collaboration [18]. The theoretical cross section depends on the field content of the neutralino, shown here for pure photinos, binos, and Higgsinos. 'LNZ' refers to a particular model [4].

LEP 2. Although the full energy is never available for annihilation, the cross sections for supersymmetric particle production are large due to color factors and the strong coupling.

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

The classic searches [20] rely on large missing transverse energy $\not\!\!E_T$ caused by the escaping neutralinos. Jets with high transverse energy are also required as evidence of a hard interaction; care is taken to distinguish genuine $\not\!\!E_T$ from fluctuations in the jet energy measurement. Backgrounds from W, Z and top production are reduced by rejecting events with identified leptons. Uncertainties in the rates of these processes are minimized by normalizing related samples, such as events with two jets and one or more leptons. The tails of more ordinary hard-scattering processes accompanied by multiple gluon emission are estimated directly from the data.

The bounds are displayed in the $(M_{\widetilde{g}}, M_{\widetilde{q}})$ plane and have steadily improved with the integrated luminosity. The latest result from the CDF Collaboration is shown in Fig. 8, which also shows a recent result from DØ. If the squarks are heavier than the gluino, then $M_{\widetilde{g}} \gtrsim 180$ GeV/c^2. If they all have the same mass, then that mass is at least 260 GeV/c^2, according to the DØ analysis. If the squarks are much lighter than the gluin (in which case they decay via $\widetilde{q} \to q\widetilde{\chi}_1^0$), the bounds from UA1 and UA2 [21] play a role giving $M_{\widetilde{g}} \gtrsim 300$ GeV/c^2. All of these bounds assume there is no gluino lighter than 5 GeV/c^2.

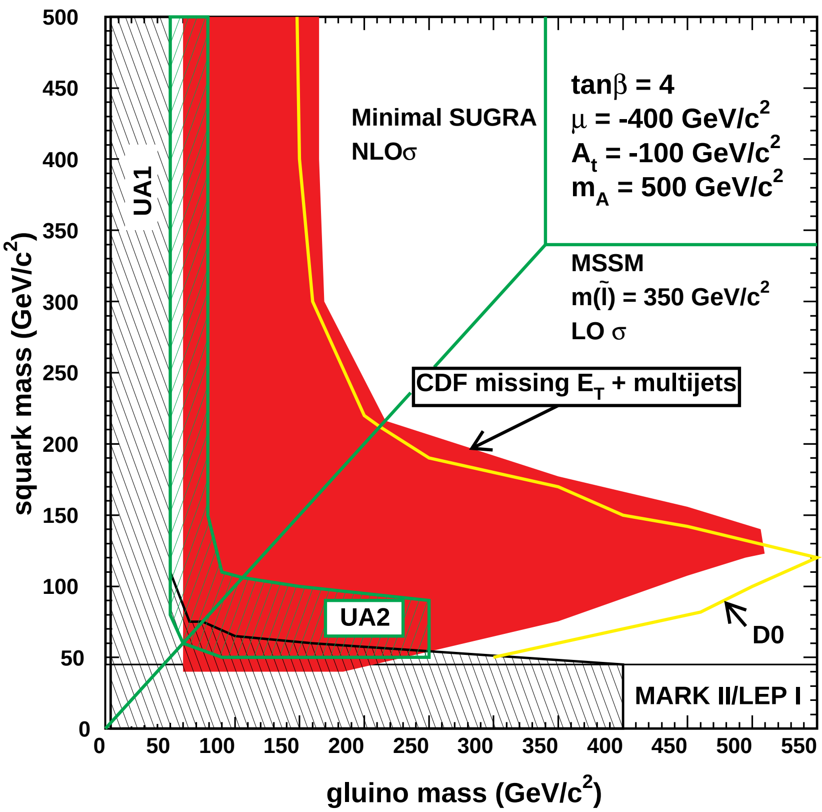

Figure 8: Excluded ranges of squark and gluino masses, derived from the jets+ $\not\!\!E_T$ analysis of the CDF Collaboration [20]. Also shown are recent results from DØ, and much older limits from the CERN proton experiments UA1 and UA2.

Since these results are expressed in terms of the physical masses relevant to the production process and experimental signature, the excluded region depends primarily on the assumption of nearly equal squark masses with only a small dependence on other parameters such as μ and $\tan\beta$. Direct constraints on the theoretical parameters m_0 and $m_{1/2} \approx 0.34\,M_3$, shown in Fig. 9, have been obtained by the DØ Collaboration assuming the mass relations of the mSUGRA model. In particular, m_0 is keyed to the squark mass and $m_{1/2}$ to the gluino mass, while for the LEP results these parameters usually relate to slepton and chargino masses.

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

The search for trileptons is most effective for the associated production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ [22]. The requirement of three energetic leptons reduces backgrounds to a very small level, but is efficient for the signal only in special cases. The results reported to date are not competitive with the LEP bounds.

The dilepton signal is geared more for the production of charginos in gluino and squark cascades [23]. Jets are required as expected from the rest of the decay chain; the leptons should be well separated from the jets in order to avoid backgrounds from heavy quark decays. Drell-Yan events are rejected with simple cuts on the relative azimuthal angles of the leptons and their transverse momentum. In some analyses the Majorana nature of the gluino is exploited by requiring two leptons with

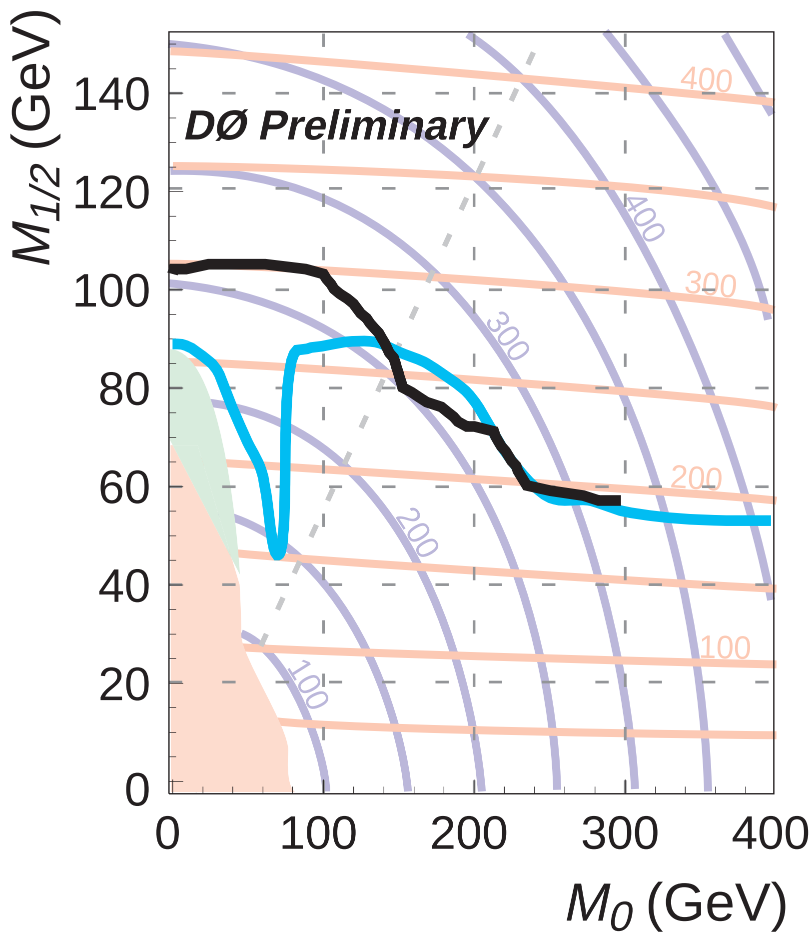

Figure 9: Bounds in the $(m_0, m_{1/2})$ plane obtained by the DØ Collaboration from their searches for squarks and gluinos [20]. The dark solid line shows the result from the jets+ $\not\!\!E_T$ selection, and the grey solid line shows the result from the dielectron selection. The radial contours give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

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.

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

The top squark is different from the other squarks because its SM partner is so massive: large off-diagonal terms in the squared-mass matrix lead to large mixing effects and a possible light mass eigenstate, $M_{\widetilde{t}_1} \ll M_{\widetilde{q}}$. Analyses designed to find light stops have been performed by DØ [25]. The first of these was based on the jets+ $\not\!\!E_T$ signature expected when the the stop is lighter than the chargino. A powerful limit $M_{\widetilde{t}} \gtrsim 90$ GeV/c^2 was obtained, provided the neutralino was at least 30 GeV/c^2 lighter than the stop as depicted in Fig. 3. (These searches are sensitive to the $c\widetilde{\chi}_1^0$ channel which does not apply below the dotted line.) More recently a search for the pair-production of light stops decaying to $b\widetilde{\chi}_1^{\pm}$ was performed. The presence of two energetic electrons was required; backgrounds from W's were greatly reduced. Regrettably this experimental bound does not yet improve existing bounds on stop masses.

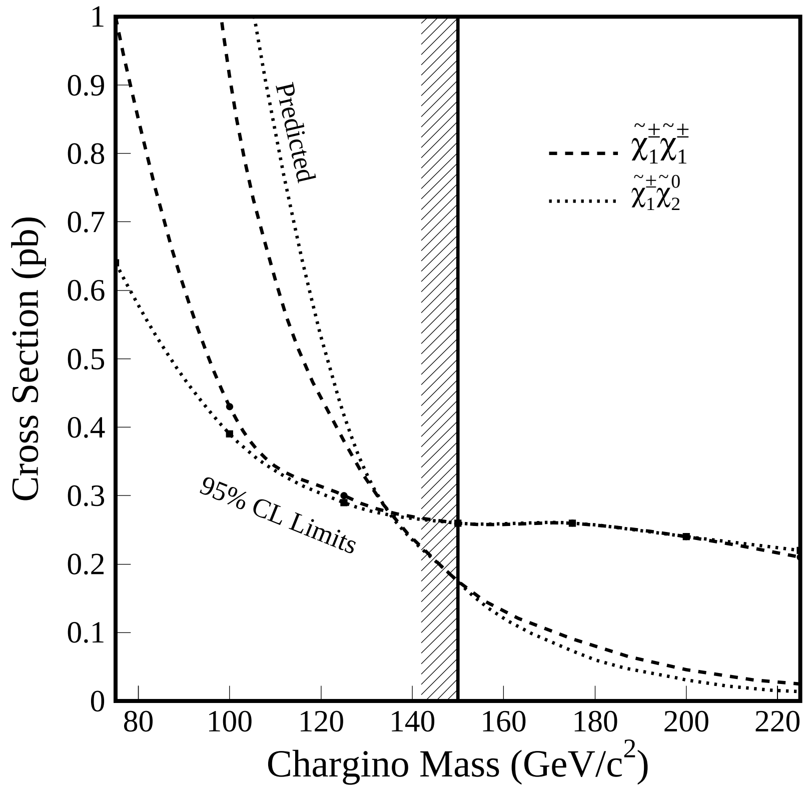

Figure 10: Comparison of the DØ upper limits on chargino and neutralino cross sections with theory in a GMSB scenario, plotted as a function of the chargino mass [28]. The vertical line shows the result obtained from the combined chargino and neutralino exclusions. It corresponds to $M_{\widetilde{\chi}_1^0}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

An anomalous event observed by the CDF Collaboration [26] sparked much theoretical speculation [27]. It contains two energetic electrons, two energetic photons, large $\not\!\!E_T$, and

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

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^{\pm}$	gaugino	$M_{\widetilde{\nu}} > 200$ GeV/c^2	86	LEP 2
		$M_{\widetilde{\nu}} > M_{\widetilde{\chi}^{\pm}}$	67	LEP 2
		any $M_{\widetilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1$ TeV/c^2	79	LEP 2
	GMSB		150	DØ isolated photons
	RPV	$LL\overline{E}$ worst case	73	LEP 2
		$LQ\overline{D}$ $m_0 > 500$ GeV/c^2	83	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 200$ GeV/c^2	25	LEP 2
		any $\tan\beta$, any m_0	14	LEP 2
	GMSB		75	DØ and LEP 2
	RPV	$LL\overline{E}$ worst case	23	LEP 2
$\widetilde{e}_R$	$e\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	75	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	75	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20$ GeV/c^2	53	LEP 2
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	76	LEP 2 combined
$\widetilde{t}_1$	$c\widetilde{\chi}_1^0$	any $\theta_{\rm mix}$, $\Delta M > 10$ GeV/c^2	70	LEP 2 combined
		any $\theta_{\rm mix}$, $M_{\widetilde{\chi}_1^0} < \frac{1}{2}M_{\widetilde{t}}$	86	DØ
	$b\ell\widetilde{\nu}$	any $\theta_{\rm mix}$, $\Delta M > 7$ GeV/c^2	64	LEP 2 combined
$\widetilde{g}$	any $M_{\widetilde{q}}$		190	DØ jets+$\not{E}_T$
			180	CDF dileptons
$\widetilde{q}$	$M_{\widetilde{q}} = M_{\widetilde{g}}$		260	DØ jets+$\not{E}_T$
			230	CDF dileptons

little else. Since it is difficult to explain this event with SM processes, theorists have turned to SUSY. While some models are based on canonical MSSM scenarios (without gaugino mass unification), others are based on GMSB models with selectron production followed by $\widetilde{e} \to e\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^0 \to \gamma\,\widetilde{g}_{3/2}$. These models predict large inclusive signals for $p\overline{p} \to \gamma\gamma + X$ given kinematic constraints derived from the properties of the CDF event. The Tevatron experiments have looked for such events, and have found none [28], aside from the one anomalous event. These results have been translated into the bound $M_{\widetilde{\chi}_1^0} > 75\ \mathrm{GeV}/c^2$, as shown in Fig. 10 from the DØ Collaboration. This bound is as good as that derived from the combination of the four LEP experiments.

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

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

A more interesting opportunity comes in SUSY models with R-parity violation, in particular, with a dominant $LQ\overline{D}$ interaction [30]. Squarks would be produced directly in the s-channel, decaying either directly to a lepton and a quark via R-parity violation or to a pair of fermions and a chargino or neutralino, with the latter possibly decaying via R-parity violation. Less than 3 pb^{-1} were used to look for a squark resonance above SM backgrounds. All possible topologies were considered, so model-independent bounds on the R-parity–violating parameter λ'_{111} could be derived as a function of the squark mass. The special case of a light $\widetilde{t}_1$ was also considered, and limits derived on λ'_{131} as a function of $M_{\widetilde{t}}$. These were improved by considering also the pair-production of stops via photon-gluon fusion (see the Listings for more information).

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

II.7. Conclusions: A huge variety of searches for supersymmetry have been carried out at LEP, the Tevatron, and HERA. Despite all the effort, no signal has been found, forcing the experimenters to derive limits. We have tried to summarize the interesting cases in Table 1. At the present time there is little room for SUSY particles lighter than M_W. The LEP collaborations will analyze more data taken at higher energies, and the Tevatron collaborations will begin a high luminosity run in a couple of years. If still no sign of supersymmetry appears, definitive tests will be made at the LHC.

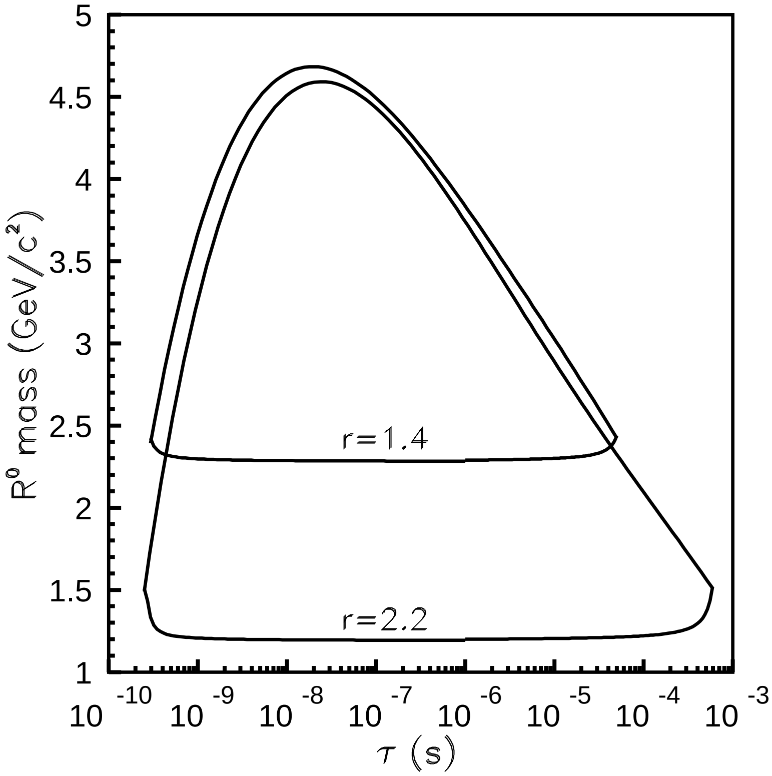

Figure 11: Ranges of R^0 mass and lifetime excluded at 90% CL by the KTeV Collaboration [31]. The ratio of the R^0 to the $\widetilde{\chi}_1^0$ mass is r.

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Supersymmetry – THIS IS PART 4 OF 4

To reduce the size of this section's PostScript file, we have divided it into three PostScript files. We present the following index:

PART 1

Page #	Section name
1	Note on Supersymmetry – Part I Theory

PART 2

Page #	Section name
32	Note on Supersymmetry – Part II Experiment

PART 2

Page #	Section name
48	Note on Supersymmetry – Part II Experiment (cont.)

PART 4

Page #	Section name
66	Data Listings

MINIMAL SUPERSYMMETRIC STANDARD MODEL ASSUMPTIONS

All results shown below (except where stated otherwise) are based on the Minimal Supersymmetric Standard Model (MSSM) as described in the Note on Supersymmetry. This includes the assumption that R-parity is conserved. In addition the following assumptions are made in most cases:

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

Limits involving different assumptions either are identified with comments or are in the miscellaneous section.

When needed, specific assumptions of the eigenstate content of neutralinos and charginos are indicated (use of the notation $\widetilde{\gamma}$ (photino), $\widetilde{H}$ (Higgsino), $\widetilde{W}$ (w-ino), and $\widetilde{Z}$ (z-ino) indicates the approximation of a pure state was made).

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

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

We have divided the $\widetilde{\chi}^0_1$ listings below into three sections: 1) Accelerator limits for $\widetilde{\chi}^0_1$, 2) Bounds on $\widetilde{\chi}^0_1$ from dark matter searches, and 3) Other bounds on $\widetilde{\chi}^0_1$ from astrophysics and cosmology.

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

These papers generally exclude regions in the $M_2-\mu$ parameter plane based on accelerator experiments. Unless otherwise stated, these papers assume minimal supersymmetry and GUT relations (gaugino-mass unification condition). $\Delta m_0 = m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>24.9	95	[1] ABREU	98	DLPH	
>10.9	95	[2] ACCIARRI	98F	L3	$\tan\beta > 1$
>13.3	95	[3] ACKERSTAFF	98L	OPAL	$\tan\beta > 1$
>12.5	95	[4] ALEXANDER	96L	OPAL	$\tan\beta > 1.5$
>12.8	95	[5] BUSKULIC	96A	ALEP	$m_{\widetilde{\nu}} > 200$ GeV
>23	95	[6] ACCIARRI	95E	L3	$\tan\beta > 3$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>17	95	[7] ELLIS	97C	RVUE	All $\tan\beta$
		[8] ABREU	96O	DLPH	
		[9] ACCIARRI	96F	L3	
>12.0	95	[10] ALEXANDER	96J	OPAL	$1.5 < \tan\beta < 35$
≥ 0		[11] FRANKE	94	RVUE	$\widetilde{\chi}^0_1$ mixed with a singlet
>20	95	[12] DECAMP	92	ALEP	$\tan\beta > 3$
>5	90	[13] HEARTY	89	ASP	$\widetilde{\gamma}$; for $m_{\widetilde{e}} < 55$ GeV

[1] 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. The limit is based on the same assumptions as ALEXANDER 96J except m_0=1 TeV.

[2] ACCIARRI 98F evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The 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.

[3] ACKERSTAFF 98L evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The bound is determined indirectly from the $\widetilde{\chi}^+_1$ and $\widetilde{\chi}^0_2$ searches within the MSSM. The 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.

[4] ALEXANDER 96L bound for $\tan\beta$=35 is 26.0 GeV.

[5] BUSKULIC 96A puts a lower limit on $m_{\widetilde{\chi}^0_1}$ from the negative search for neutralinos, charginos. The bound holds for $m_{\widetilde{\nu}} > 200$ GeV. A small region of (μ, M_2) still allows $m_{\widetilde{\chi}^0_1}$=0 if sneutrino is lighter. This analysis combines data from e^+e^- collisions at $\sqrt{s}$=91.2 and at 130–136 GeV.

[6] ACCIARRI 95E limit for $\tan\beta > 2$ is 20 GeV, and the bound disappears if $\tan\beta \sim 1$.

[7] 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.

[8] ABREU 96O searches for possible final states of neutralino pairs produced in e^+e^- collisions at $\sqrt{s}$ = 130–140 GeV. See their Fig. 3 for excluded regions in the (μ, M_2) plane.

[9] ACCIARRI 96F searches for possible final states of neutralino pairs produced in e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 5 for excluded regions in the (μ, M_2) plane.

[10] ALEXANDER 96J bound is determined indirectly from the $\widetilde{\chi}^\pm_1$ and $\widetilde{\chi}^0_2$ searches within MSSM. A universal scalar mass m_0 at the grand unification scale is assumed. The bound is for the smallest possible value of m_0 allowed by the LEP $\widetilde{\ell}$, $\widetilde{\nu}$ mass limits. Branching fractions are calculated using minimal supergravity. The bound is for $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} > 10$ GeV. The limit improves to 21.4 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$ = 130–136 GeV. ACKERSTAFF 96C, using data from $\sqrt{s}$ = 161 GeV, improves the limit for m_0 = 1 TeV to 30.3 GeV.

[11] FRANKE 94 reanalyzed the LEP constraints on the neutralinos in the MSSM with an additional singlet.

[12] DECAMP 92 limit for $\tan\beta > 2$ is $m > 13$ GeV.

[13] HEARTY 89 assumed pure $\widetilde{\gamma}$ eigenstate and $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$. There is no limit for $m_{\widetilde{e}} > 58$ GeV. Uses $e^+e^- \rightarrow \gamma\widetilde{\gamma}\widetilde{\gamma}$. No GUT relation assumptions are made.

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

These papers generally exclude regions in the $M_2-\mu$ parameter plane assuming that $\widetilde{\chi}^0_1$ is the dominant form of dark matter in the galactic halo. These limits are based on the lack of detection in laboratory experiments or by the absence of a signal in underground neturino detectors. The latter signal is expected if $\widetilde{\chi}^0_1$ 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. • • •			
	[14] BOTTINO	97	DAMA
	[15] LOSECCO	95	RVUE
	[16] MORI	93	KAMI
	[17] BOTTINO	92	COSM
	[18] BOTTINO	91	RVUE
	[19] GELMINI	91	COSM
	[20] KAMIONKOW...	91	RVUE
	[21] MORI	91B	KAMI
none 4–15 GeV	[22] OLIVE	88	COSM

[14] 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.

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

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

[17] 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.

[18] 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.

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

[20] 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.

[21] 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.

[22] 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
>40		[23] ELLIS	97C	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>21.4	95	[24] ELLIS	96B	RVUE	$\tan\beta > 1.2$, $\mu < 0$
		[25] 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
		[26] OLIVE	91	COSM	
		ROSZKOWSKI	91	COSM	
		ELLIS	90	COSM	
		[27] GRIEST	90	COSM	
		[28] GRIFOLS	90	ASTR	$\widetilde{\gamma}$; SN 1987A
		KRAUSS	90	COSM	
		[26] OLIVE	89	COSM	
> 100 eV		[29] 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	$\widetilde{\gamma}$
		[30] KRAUSS	83	COSM	$\widetilde{\gamma}$
		VYSOTSKII	83	COSM	$\widetilde{\gamma}$

[23] 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.

[24] 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.

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

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

$\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_4$ (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 $e^+e^- \rightarrow \widetilde{\chi}^0_i\widetilde{\chi}^0_j$. 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.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 45.3	95	[31] ACKERSTAFF	98L	OPAL	$\widetilde{\chi}^0_2$, tan$\beta > 1$
> 75.8	95	[31] ACKERSTAFF	98L	OPAL	$\widetilde{\chi}^0_3$, tan$\beta > 1$
>127	95	[32] ACCIARRI	95E	L3	$\widetilde{\chi}^0_4$, tanβ >3
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 92	95	[33] ACCIARRI	98F	L3	$\widetilde{H}^0_2$, tanβ=1.41, M_2 < 500 GeV
		[34] ABACHI	96	D0	$p\overline{p} \rightarrow \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_2$
		[35] ABE	96K	CDF	$p\overline{p} \rightarrow \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_2$
		[36] ACCIARRI	96F	L3	$\widetilde{\chi}^0_2$
> 86.3	95	[37] ACKERSTAFF	96C	OPAL	$\widetilde{\chi}^0_3$
> 45.3	95	[38] ALEXANDER	96J	OPAL	$\widetilde{\chi}^0_2$1.5 <tanβ <35
> 33.0	95	[39] ALEXANDER	96L	OPAL	$\widetilde{\chi}^0_2$, tan$\beta > 1.5$
> 68	95	[40] BUSKULIC	96K	ALEP	$\widetilde{\chi}^0_2$
> 52	95	[32] ACCIARRI	95E	L3	$\widetilde{\chi}^0_2$, tanβ >3
> 84	95	[32] ACCIARRI	95E	L3	$\widetilde{\chi}^0_3$, tanβ >3
> 45	95	[41] DECAMP	92	ALEP	$\widetilde{\chi}^0_2$, tanβ >3
		[42] ABREU	90G	DLPH	$Z \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$
		[43] AKRAWY	90N	OPAL	$Z \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$
> 57	90	[44] BAER	90	RVUE	$\widetilde{\chi}^0_3$; $\Gamma(Z)$; tan$\beta > 1$

		[45] BARKLOW	90	MRK2	$Z \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$, $\widetilde{\chi}^0_2 \widetilde{\chi}^0_2$
		[46] DECAMP	90K	ALEP	$Z \to \widetilde{\chi}^0 \widetilde{\chi}^0$
$>$ 41	95	[47] SAKAI	90	AMY	$e^+ e^- \to \widetilde{H}^0_1 \widetilde{H}^0_2$ $(\widetilde{H}^0_2 \to f \overline{f} \widetilde{H}^0_1)$
$>$ 31	95	[48] BEHREND	87B	CELL	$e^+ e^- \to \widetilde{\gamma} \widetilde{Z}$ $(\widetilde{Z} \to q \overline{q} \widetilde{\gamma})$, $m_{\widetilde{e}} <$ 70 GeV
$>$ 30	95	[49] BEHREND	87B	CELL	$e^+ e^- \to \widetilde{\gamma} \widetilde{Z}$ $(\widetilde{Z} \to q \overline{q} \widetilde{g})$
$>$ 31.3	95	[50] BEHREND	87B	CELL	$e^+ e^- \to \widetilde{H}^0_1 \widetilde{H}^0_2$ $(\widetilde{H}^0_2 \to f \overline{f} \widetilde{H}^0_1)$
$>$ 22	95	[51] BEHREND	87B	CELL	$e^+ e^- \to \gamma \widetilde{\gamma} \widetilde{Z}$ $(\widetilde{Z} \to \widetilde{\nu} \nu)$
		[52] AKERLOF	85	HRS	$e^+ e^- \to \widetilde{\gamma} \widetilde{\chi}^0$ $(\widetilde{\chi}^0 \to q \overline{q} \widetilde{\gamma})$
none 1–21	95	[53] BARTEL	85L	JADE	$e^+ e^- \to \widetilde{H}^0_1 \widetilde{H}^0_2$, $\widetilde{H}^0_2 \to f \overline{f} \widetilde{H}^0_1$
		[54] BEHREND	85	CELL	$e^+ e^- \to$ monojet X
$>$ 35	95	[55] ADEVA	84B	MRKJ	$e^+ e^- \to \gamma \widetilde{Z}$ $(\widetilde{Z} \to \ell \overline{\ell} \widetilde{\gamma})$
$>$ 28	95	[56] BARTEL	84C	JADE	$e^+ e^- \to \gamma \widetilde{Z}$ $(\widetilde{Z} \to f \overline{f} \widetilde{\gamma})$
		[57] ELLIS	84	COSM	

[31] ACKERSTAFF 98L is obtained from direct searches in the $e^+ e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_{2,3}$ 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.

[32] ACCIARRI 95E limits go down to 0 GeV ($\widetilde{\chi}^0_2$), 60 GeV ($\widetilde{\chi}^0_3$), and 90 GeV ($\widetilde{\chi}^0_4$) for tanβ=1.

[33] ACCIARRI 98F is obtained from direct searches in the $e^+ e^- \to \widetilde{\chi}^0_{1,2} \widetilde{\chi}^0_2$ 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.

[34] 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 $\sigma(\widetilde{\chi}^\pm_1 \widetilde{\chi}^0_2) \times \mathrm{B}(\widetilde{\chi}^\pm_1 \to \ell \nu_\ell \widetilde{\chi}^0_1) \times \mathrm{B}(\widetilde{\chi}^0_2 \to \ell^+ \ell^- \widetilde{\chi}^0_1)$ 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).

[35] 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.

[36] ACCIARRI 96F looked for associated production $e^+ e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$. See the paper for upper bounds on the cross section. Data taken at $\sqrt{s}$ = 130–136 GeV.

[37] ACKERSTAFF 96C is obtained from direct searches in the $e^+ e^- \to \widetilde{\chi}^0_1 \widetilde{\chi}^0_{2,3}$ 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.

[38] ALEXANDER 96J looked for associated $e^+ e^- \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$. A universal scalar mass m_0 at the grand unification scale is assumed. The bound is for the smallest possible value of m_0 allowed by the LEP $\widetilde{\ell}$, $\widetilde{\nu}$ mass limits, 1.5 $<\tan\beta<$35. Branching fractions are calculated using minimal supergravity. The bound is for $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} >$10 GeV. The limit improves to 47.5 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$ = 130–136 GeV. ACKERSTAFF 96C, using data from $\sqrt{s}$ = 161 GeV, improves the limit for m_0 = 1 TeV to 51.9 GeV.

[39] ALEXANDER 96L bound for $\tan\beta$=35 is 51.5 GeV.

[40] BUSKULIC 96K looked for associated $e^+ e^- \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$ and assumed the dominance of off-shell Z-exchange in the $\widetilde{\chi}^0_2$ decay. The bound is for $m_{\widetilde{\chi}^0_2} - m_{\widetilde{\chi}^0_1} >$9 GeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

[41] For $\tan\beta >$2 the limit is $>$40 GeV; and it disappears for $\tan\beta <$ 1.6.

[42] ABREU 90G exclude B($Z \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$) $\geq$ 10^{-3} and B($Z \rightarrow \widetilde{\chi}^0_2 \widetilde{\chi}^0_2$) $\geq$ 2×10^{-3} assuming $\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 f \overline{f}$ via virtual Z. These exclude certain regions in model parameter space, see their Fig. 5.

[43] AKRAWY 90N exclude B($Z \rightarrow \widetilde{\chi}^0_1 \widetilde{\chi}^0_2$) $\gtrsim$ 3–5 $\times 10^{-4}$ assuming $\widetilde{\chi}^0_2 \rightarrow \widetilde{\chi}^0_1 f \overline{f}$ or $\widetilde{\chi}^0_1 \gamma$ for most accessible masses. These exclude certain regions in model parameter space, see their Fig. 7.

[44] BAER 90 is independent of decay modes. Limit from analysis of supersymmetric parameter space restrictions implied by $\Delta\Gamma(Z) <$ 120 MeV. These result from decays of Z to all combinations of $\widetilde{\chi}^{\pm}_i$ and $\widetilde{\chi}^0_i$. Minimal supersymmetry with $\tan\beta >$ 1 is assumed.

[45] See Figs. 4, 5 in BARKLOW 90 for the excluded regions.

[46] DECAMP 90K exclude certain regions in model parameter space, see their figures.

[47] SAKAI 90 assume $m_{\widetilde{H}^0_1}$ = 0. The limit is for $m_{\widetilde{H}^0_2}$.

[48] Pure $\widetilde{\gamma}$ and pure $\widetilde{Z}$ eigenstates. B($\widetilde{Z} \rightarrow q\overline{q}\widetilde{\gamma}$) = 0.60 and B($\widetilde{Z} \rightarrow e^+ e^- \widetilde{\gamma}$) = 0.13. $m_{\widetilde{e}_L} = m_{\widetilde{e}_R} <$ 70 GeV. $m_{\widetilde{\gamma}} <$ 10 GeV.

[49] Pure $\widetilde{\gamma}$ and pure $\widetilde{Z}$ eigenstates. B($\widetilde{Z} \rightarrow q\overline{q}\widetilde{g}$) = 1. $m_{\widetilde{e}_L} = m_{\widetilde{e}_R} <$ 70 GeV. $m_{\widetilde{\gamma}}$ = 0.

[50] Pure higgsino. The LSP is the other higgsino and is taken massless. Limit degraded if $\widetilde{\chi}^0$ not pure higgsino or if LSP not massless.

[51] Pure $\widetilde{\gamma}$ and pure $\widetilde{Z}$ eigenstates. B($\widetilde{Z} \rightarrow \widetilde{\nu}\nu$) = 1. $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$ = 26 GeV. $m_{\widetilde{\gamma}}$ = 10 GeV. No excluded region remains for $m_{\widetilde{e}} >$30 GeV.

[52] AKERLOF 85 is $e^+ e^-$ monojet search motivated by UA1 monojet events. Observed only one event consistent with $e^+ e^- \rightarrow \widetilde{\gamma} + \widetilde{\chi}^0$ where $\widetilde{\chi}^0 \rightarrow$ monojet. Assuming that missing-p_T is due to $\widetilde{\gamma}$, and monojet due to $\widetilde{\chi}^0$, limits dependent on the mixing and $m_{\widetilde{e}}$ are given, see their figure 4.

[53] BARTEL 85L assume $m_{\widetilde{H}^0_1}$ = 0, $\Gamma(Z \rightarrow \widetilde{H}^0_1 \widetilde{H}^0_2) \gtrsim \frac{1}{2} \Gamma(Z \rightarrow \nu_e \overline{\nu}_e)$. The limit is for $m_{\widetilde{H}^0_2}$.

[54] BEHREND 85 find no monojet at E_{cm} = 40–46 GeV. Consider $\widetilde{\chi}^0$ pair production via Z^0. One is assumed as massless and escapes detector. Limit is for the heavier one, decaying into a jet and massless $\widetilde{\chi}^0$. Both $\widetilde{\chi}^0$'s are assumed to be pure higgsino. For these very model-dependent results, BEHREND 85 excludes m = 1.5–19.5 GeV.

[55] ADEVA 84B observed no events with signature of acoplanar lepton pair with missing energy. Above example limit is for $m_{\widetilde{\gamma}} <$2 GeV and $m_{\widetilde{e}} <$40 GeV, and assumes B($\widetilde{Z} \rightarrow \mu^+ \mu^- \widetilde{\gamma}$) = B($\widetilde{Z} \rightarrow e^+ e^- \widetilde{\gamma}$) = 0.10. BR = 0.05 gives 33.5 GeV limit.

[56] BARTEL 84C search for $e^+ e^- \rightarrow \widetilde{Z} + \widetilde{\gamma}$ with $\widetilde{Z} \rightarrow \widetilde{\gamma} + e^+ e^-$, $\mu^+ \mu^-$, $q\overline{q}$, etc. They see no acoplanar events with missing-p_T due to two $\widetilde{\gamma}$'s. Above example limit is for $m_{\widetilde{e}}$ = 40 GeV and for light stable $\widetilde{\gamma}$ with B($\widetilde{Z} \rightarrow e^+ e^- \widetilde{\gamma}$) = 0.1.

[57] ELLIS 84 find if lightest neutralino is stable, then $m_{\widetilde{\chi}^0}$ not 100 eV – 2 GeV (for $m_{\widetilde{q}}$ = 40 GeV). The upper limit depends on $m_{\widetilde{q}}$ (similar to the $\widetilde{\gamma}$ limit) and on nature of $\widetilde{\chi}^0$. For pure higgsino the higher limit is 5 GeV.

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

Unless stated otherwise, the limits below assume that the $\widetilde{\gamma}$ decays either into $\gamma\widetilde{G}$ (goldstino) or into $\gamma\widetilde{H}^0$ (Higgsino).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>77	95	[58] ABBOTT	98	D0	$p\overline{p} \rightarrow \gamma\gamma \not{E}_T + X$
		[59] ABREU	98	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_1 \rightarrow \gamma\widetilde{G}$)
		[60] ACKERSTAFF	98J	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_1 \rightarrow \gamma\widetilde{G}$)
	95	[61] ACCIARRI	97V	L3	$e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_1 \rightarrow \gamma\widetilde{G}$)
		[62] ELLIS	97	THEO	$e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$, $\widetilde{\chi}^0_1 \rightarrow \gamma\widetilde{G}$
		[63] BUSKULIC	96U	ALEP	$e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_1 \rightarrow \nu\ell\overline{\ell}'$)
>40	95	[64] BUSKULIC	95E	ALEP	$e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ ($\widetilde{\chi}^0_1 \rightarrow \nu\ell\overline{\ell}'$)
		[65] BUSKULIC	95E	ALEP	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$ ($\widetilde{\gamma} \rightarrow \nu\ell\overline{\ell}'$)
		[66] ACTON	93G	OPAL	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$ ($\widetilde{\gamma} \rightarrow \tau^\pm\ell^\mp\nu_{\ell'}$)
		[67] ABE	89J	VNS	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$ ($\widetilde{\gamma} \rightarrow \gamma\widetilde{G}$ or $\gamma\widetilde{H}^0$)
>15	95	[68] BEHREND	87B	CELL	$e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$ ($\widetilde{\gamma} \rightarrow \gamma\widetilde{G}$ or $\gamma\widetilde{H}^0$)
		[69] ADEVA	85	MRKJ	
		[70] BALL	84	CALO	Beam dump
		[71] BARTEL	84B	JADE	
		[71] BEHREND	83	CELL	
		[72] CABIBBO	81	COSM	

[58] 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.

[59] 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.

[60] 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.

[61] 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.

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

[63] BUSKULIC 96U extended the search for $e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$ in BUSKULIC 95E under the same assumptions. See their Fig. 5 for excluded region in the neutralino-chargino parameter space. Data taken at $\sqrt{s}$ = 130–136 GeV.

[64] BUSKULIC 95E looked for $e^+e^- \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$, where $\widetilde{\chi}^0_1$ decays via R-parity violating interaction into one neutrino and two opposite-charge leptons. The bound applies provided that B($Z \rightarrow \widetilde{\chi}^0_1\widetilde{\chi}^0_1$)$> 3 \times 10^{-5}\beta^3$, β being the final state $\widetilde{\chi}^0_1$ velocity.

[65] BUSKULIC 95E looked for $e^+e^- \rightarrow \widetilde{\gamma}\widetilde{\gamma}$, where $\widetilde{\gamma}$ decays via R-parity violating interaction into one neutrino and two opposite-charge leptons. They extend the domain in the ($m_{\widetilde{e}}$,$m_{\widetilde{\gamma}}$) plane excluded by ACTON 93G to $m_{\widetilde{e}}$ >220 GeV/c^2 (for $m_{\widetilde{\gamma}}$=15 GeV/c^2) and to $m_{\widetilde{\gamma}}$ >2 GeV/c^2 (for $m_{\widetilde{e}}$ <220 GeV/c^2).

[66] ACTON 93G assume R-parity violation and decays $\widetilde{\gamma} \rightarrow \tau^\pm\ell^\mp\nu_\ell$ (ℓ= e or μ). They exclude $m_{\widetilde{\gamma}}$ = 4–43 GeV for $m_{\widetilde{e}_L}$ <42 GeV, and $m_{\widetilde{\gamma}}$ = 7–30 GeV for $m_{\widetilde{e}_L}$ <100 GeV (95% CL). Assumes $\widetilde{e}_R$ much heavier than $\widetilde{e}_L$, and lepton family number violation but L_e-L_μ conservation.

[67] ABE 89J exclude $m_{\widetilde{\gamma}}$ = 0.15–25 GeV (95%CL) for d = (100 GeV)^2 and $m_{\widetilde{e}}$ = 40 GeV in the case $\widetilde{\gamma} \rightarrow \gamma\widetilde{G}$, and $m_{\widetilde{\gamma}}$ up to 23 GeV for $m_{\widetilde{e}}$ = 40 GeV in the case $\widetilde{\gamma} \rightarrow \gamma\widetilde{H}^0$.

[68] BEHREND 87B limit is for unstable photinos only. Assumes B($\widetilde{\gamma} \rightarrow \gamma(\widetilde{G}$ or $\widetilde{H}^0$)) =1, $m_{\widetilde{G}\text{or}\widetilde{H}^0} \ll m_{\widetilde{\gamma}}$ and pure $\widetilde{\gamma}$ eigenstate. $m_{\widetilde{e}_L} = m_{\widetilde{e}_R} <$ 100 GeV.

[69] ADEVA 85 is sensitive to $\widetilde{\gamma}$ decay path <5 cm. With $m_{\widetilde{e}}$ = 50 GeV, limit (CL = 90%) is $m_{\widetilde{\gamma}}$ >20.5 GeV. Assume $\widetilde{\gamma}$ decays to photon + goldstino and search for acoplanar photons with large missing p_T.

[70] BALL 84 is FNAL beam dump experiment. Observed no $\widetilde{\gamma}$ decay, where $\widetilde{\gamma}$'s are expected to come from $\widetilde{g}$'s produced at the target. Three possible $\widetilde{\gamma}$ lifetimes are considered. Gluino decay to goldstino + gluon is also considered.

[71] BEHREND 83 and BARTEL 84B look for 2γ events from $\widetilde{\gamma}$ pair production. With supersymmetric breaking parameter d = (100 GeV)^2 and $m_{\widetilde{e}}$ = 40 GeV the excluded regions at CL = 95% would be $m_{\widetilde{\gamma}}$ = 100 MeV – 13 GeV for BEHREND 83 $m_{\widetilde{\gamma}}$ = 80 MeV – 18 GeV for BARTEL 84B. Limit is also applicable if the $\widetilde{\gamma}$ decays radiatively within the detector.

[72] 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.

$\widetilde{\chi}^\pm_1$, $\widetilde{\chi}^\pm_2$ (Charginos) MASS LIMITS

Charginos ($\widetilde{\chi}^\pm$'s) are unknown mixtures of w-inos and charged higgsinos (the supersymmetric partners of W and Higgs bosons). Mass limits are relatively model dependent, so assumptions concerning branching ratios need to be specified. When specific assumptions are made, e.g. the chargino is a pure w-ino ($\widetilde{W}$) or pure charged higgsino ($\widetilde{H}^\pm$), the charginos will be labelled as such.

In the Listing below, we use $\Delta m_+ = m_{\widetilde{\chi}^\pm_1} - m_{\widetilde{\chi}^0_1}$ $\Delta m_\nu = m_{\widetilde{\chi}^\pm_1} - m_{\widetilde{\nu}}$, or simply Δm to indicate that the constraint applies to both Δm_+ and Δm_ν.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 67.6	95	[73] ABREU	98	DLPH	$\Delta m>$ 10 GeV
> 69.2	95	[74] ACCIARRI	98F	L3	tan$\beta <$ 1.41

> 65.7	95	[75] ACKERSTAFF	98L	OPAL	$\Delta m_+ > 3$ GeV
> 56.3	95	[76] ABREU	96L	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$
> 64	95	[77] ACCIARRI	96F	L3	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $m_{\widetilde{\chi}^0} < 43$ GeV

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

>150	95	[78] ABBOTT	98	D0	$p\overline{p} \rightarrow \gamma\gamma \not{E}_T$+X
		[79] ABBOTT	98C	D0	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1\widetilde{\chi}^0_2$
> 71.8	95	[80] ABREU	98	DLPH	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $\widetilde{\chi}^0_1 \rightarrow \widetilde{G}\gamma$
		[81] ACKERSTAFF	98K	OPAL	$\widetilde{\chi}^+ \rightarrow \ell^+ \not{E}$
		[82] CARENA	97	THEO	$g_\mu - 2$
		[83] KALINOWSKI	97	THEO	$W \rightarrow \widetilde{\chi}^\pm_1\widetilde{\chi}^0_1$
		[84] ABE	96K	CDF	$p\overline{p} \rightarrow \widetilde{\chi}^\pm_1\widetilde{\chi}^0_2$
> 62	95	[85] ACKERSTAFF	96C	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$
> 58.7	95	[86] ALEXANDER	96J	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$
> 63	95	[87] BUSKULIC	96K	ALEP	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$
		[88] BUSKULIC	96U	ALEP	$e^+e^- \rightarrow \widetilde{\chi}^+_1\widetilde{\chi}^-_1$; R-parity violation
> 44.0	95	[89] ADRIANI	93M	L3	$Z \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $\Gamma(Z)$
> 45.2	95	[90] DECAMP	92	ALEP	$Z \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, all $m_{\widetilde{\chi}^0_1}$
> 47	95	[90] DECAMP	92	ALEP	$Z \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $m_{\widetilde{\chi}^0_1}$ <41 GeV
> 99	95	[91] HIDAKA	91	RVUE	$\widetilde{\chi}^\pm_2$
> 44.5	95	[92] ABREU	90G	DLPH	$Z \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$, $m_{\widetilde{\gamma}}$ < 20 GeV
> 45	95	[93] AKESSON	90B	UA2	$p\overline{p} \rightarrow ZX$ $(Z \rightarrow \widetilde{W}^+\widetilde{W}^-)$
> 45	95	[94] AKRAWY	90D	OPAL	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$; $m_{\widetilde{\gamma}} < 20$ GeV
> 45	95	[95] BARKLOW	90	MRK2	$Z \rightarrow \widetilde{W}^+\widetilde{W}^-$
> 42	95	[96] BARKLOW	90	MRK2	$Z \rightarrow \widetilde{H}^+\widetilde{H}^-$
> 44.5	95	[97] DECAMP	90C	ALEP	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$; $m_{\widetilde{\gamma}}$ < 28 GeV
> 25.5	95	[98] ADACHI	89	TOPZ	$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^-$
> 44	95	[99] ADEVA	89B	L3	$e^+e^- \rightarrow \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W} \rightarrow \ell\widetilde{\nu}$ or $\ell\nu\widetilde{\gamma}$
> 45	90	[100] ANSARI	87D	UA2	$p\overline{p} \rightarrow ZX$ $(Z \rightarrow \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W}^\pm \rightarrow e^\pm\widetilde{\nu})$

[73] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. The universal scalar mass at the GUT scale is assumed to compute branching fractions and mass spectrum. 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.

[74] ACCIARRI 98F evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The 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 $\mu{=}-200$ 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.

[75] ACKERSTAFF 98L evaluates production cross sections and decay branching ratios within the MSSM, and includes in the analysis the effects of gaugino cascade decays. The 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.

[76] ABREU 96L assumes the dominance of off-shell W-exchange in the chargino decay and $\Delta(m)$ >10 GeV. The bound is for the smallest $\widetilde{\ell}$, $\widetilde{\nu}$ mass allowed by LEP, provided either $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^{\pm}}$ or $m_{\widetilde{\chi}^{\pm}} - m_{\widetilde{\nu}}$ >10 GeV. 1<tanβ <35. For a mostly higgsino $\widetilde{\chi}^{+}$ ($m_{\widetilde{\chi}^{\pm}} - m_{\widetilde{\chi}^{0}}$=5 GeV) the limit is 63.8 GeV, independently of the $\widetilde{\ell}$ masses. Data taken at $\sqrt{s}$ = 130–136 GeV.

[77] ACCIARRI 96F assume $m_{\widetilde{\nu}}$ >200 GeV and $m_{\widetilde{\chi}_1^{\pm}} < m_{\widetilde{\chi}_2^{0}}$. See their Fig. 4 for excluded regions in the ($m_{\widetilde{\chi}^{\pm}}$,$m_{\widetilde{\chi}^{0}}$) plane. Data taken at $\sqrt{s}$ = 130–136 GeV.

[78] 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.

[79] ABBOTT 98C searches for trilepton final states (ℓ=e,μ). Efficiencies are calculated using mass relations and branching ratios in the Minimal Supergravity scenario. Results are presented in Fig. 1 of their paper as lower bounds on $\sigma(p\overline{p} \rightarrow \widetilde{\chi}^{\pm}\widetilde{\chi}_2^{0})\times$B(3$\ell$). Limits range from 0.66 pb ($m_{\widetilde{\chi}_1^{\pm}}$=45 GeV) to 0.10 pb ($m_{\widetilde{\chi}_1^{\pm}}$=124 GeV).

[80] ABREU 98 uses data at $\sqrt{s}$=161 and 172 GeV. The universal scalar mass at the GUT scale is assumed to compute branching fractions and mass spectrum, and the radiative decay of the lightest neutralino into gravitino is assumed. The limit is for Δm> 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 $m_{\widetilde{\nu}}$.

[81] 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).

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

[83] 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.

[84] 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.

[85] 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 tan$\beta >$ 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.

86 ALEXANDER 96J assumes a universal scalar mass m_0 at the grand unification scale. The bound is for the smallest possible value of m_0 allowed by the LEP $\widetilde{\ell}$, $\widetilde{\nu}$ mass limits. 1.5 $<\tan\beta<$35. Branching fractions are calculated using minimal supergravity. The bound is for $\Delta(m)$ >10 GeV. The limit improves to 65.4 GeV for m_0=1 TeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

87 BUSKULIC 96K assumes the dominance of off-shell W-exchange in the chargino decay and applies throughout the (M_2,μ) plane for 1.41 $<\tan\beta<$35 provided either $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^{\pm}}$ and $m_{\widetilde{\chi}^{\pm}} - m_{\widetilde{\chi}^0_1}$ >4 GeV, or $m_{\widetilde{\chi}^{\pm}} - m_{\widetilde{\nu}}$ >4 GeV. The limit improves to 67.8 GeV for a pure gaugino $\widetilde{\chi}^{\pm}$ and $m_{\widetilde{\nu}}$ >200 GeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

88 BUSKULIC 96U searched for pair-produced charginos which decay into $\widetilde{\chi}^0_1$ with either leptons or hadrons, where $\widetilde{\chi}^0_1$ further decays leptonically via R-parity violating interactions. See their Fig. 5 for excluded region in the neutralino-chargino parameter space. Data taken at $\sqrt{s}$ = 130–136 GeV.

89 ADRIANI 93M limit from $\Delta\Gamma(Z)<$ 35.1 MeV. For pure wino, the limit is 45.5 GeV.

90 DECAMP 92 limit is for a general $\widetilde{\chi}^{\pm}$ (all contents).

91 HIDAKA 91 limit obtained from LEP and preliminary CDF limits on the gluino mass (as analyzed in BAER 91).

92 ABREU 90G limit is for a general $\widetilde{\chi}^{\pm}$. They assume charginos have a three-body decay such as $\ell^+\nu\widetilde{\gamma}$.

93 AKESSON 90B assume $\widetilde{W} \rightarrow e\widetilde{\nu}$ with B > 20% and $m_{\widetilde{\nu}} = 0$. The limit disappears if $m_{\widetilde{\nu}}$ > 30 GeV.

94 AKRAWY 90D assume charginos have three-body decay such as $\ell^+\nu\widetilde{\gamma}$ (i.e. $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^+}$). A two-body decay, $\widetilde{\chi}^+ \rightarrow \ell\widetilde{\nu}$ would have been seen by their search for acoplanar leptons. The result is independent of the hadronic branching ratio. They search for acoplanar electromagnetic clusters and quark jets.

95 BARKLOW 90 assume 100% $\widetilde{W} \rightarrow W^*\widetilde{\chi}^0_1$. Valid up to $m_{\widetilde{\chi}^0_1} \lesssim [m_{\widetilde{W}} - 5$ GeV].

96 BARKLOW 90 assume 100% $\widetilde{H} \rightarrow H^*\widetilde{\chi}^0_1$. Valid up to $m_{\widetilde{\chi}^0_1} \lesssim [m_{\widetilde{H}} - 8$ GeV].

97 DECAMP 90C assume charginos have three-body decay such as $\ell^+\nu\widetilde{\gamma}$ (i.e. $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^+}$), and branching ratio to each lepton is 11%. They search for acoplanar dimuons, dielectrons, and μe events. Limit valid for $m_{\widetilde{\gamma}}$ < 28 GeV.

98 ADACHI 89 assume only single photon annihilation in the production. The limit applies for arbitrary decay branching ratios with B($\widetilde{\chi} \rightarrow e\nu\widetilde{\gamma}$) + B($\widetilde{\chi} \rightarrow \mu\nu\widetilde{\gamma}$) + B($\widetilde{\chi} \rightarrow \tau\nu\widetilde{\gamma}$) + B($\widetilde{\chi} \rightarrow q\overline{q}\widetilde{\gamma}$) = 1 (lepton universality is *not* assumed). The limit is for $m_{\widetilde{\gamma}}$ = 0 but a very similar limit is obtained for $m_{\widetilde{\gamma}}$ = 10 GeV. For B($\widetilde{\chi} \rightarrow q\overline{q}\widetilde{\gamma}$) = 1, the limit increases to 27.8 GeV.

99 ADEVA 89B assume for $\ell\nu\widetilde{\gamma}$ ($\ell\widetilde{\nu}$) mode that B(e) = B(μ) = B(τ) = 11% (33%) and search for acoplanar dimuons, dielectrons, and μe events. Also assume $m_{\widetilde{\gamma}}$ < 20 GeV and for $\ell\widetilde{\nu}$ mode that $m_{\widetilde{\nu}}$ = 10 GeV.

100 ANSARI 87D looks for high p_T e^+e^- pair with large missing p_T at the CERN $p\overline{p}$ collider at $E_{\rm cm}$ = 546–630 GeV. The limit is valid when $m_{\widetilde{\nu}} \lesssim$ 20 GeV, B($\widetilde{W} \rightarrow e\widetilde{\nu}_e$) = 1/3, and B($Z \rightarrow \widetilde{W}^+\widetilde{W}^-$) is calculated by assuming pure gaugino eigenstate. See their Fig. 3(b) for excluded region in the $m_{\widetilde{W}} - m_{\widetilde{\nu}}$ plane.

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

Limits on charginos which leave the detector before decaying.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>80	95	[101] ABREU	97D	DLPH
>83	95	[102] BARATE	97K	ALEP
>45	95	ABREU	90G	DLPH
>28.2	95	ADACHI	90C	TOPZ

[101] 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.

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

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

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 43.1	95	[103] ELLIS	96B	RVUE	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=3
> 41.8	95	[104] ADRIANI	93M	L3	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=3
> 37.1	95	[104] ADRIANI	93M	L3	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=1
> 41	95	[105] DECAMP	92	ALEP	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=3
> 36	95	ABREU	91F	DLPH	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=1
> 32	95	[106] ABREU	91F	DLPH	$\Gamma(Z)$; $N(\widetilde{\nu})$=1
> 31.2	95	[107] ALEXANDER	91F	OPAL	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$\neq m_Z$	95	[108] ACCIARRI	97U	L3	*R*-parity violation
none 125–180	95	[108] ACCIARRI	97U	L3	*R*-parity violation
		[109] CARENA	97	THEO	$g_\mu - 2$
> 46.0	95	[110] BUSKULIC	95E	ALEP	$N(\widetilde{\nu})$=1, $\widetilde{\nu} \rightarrow \nu\nu\ell\overline{\ell}'$
none 20–25000		[111] BECK	94	COSM	Stable $\widetilde{\nu}$, dark matter
<600		[112] FALK	94	COSM	$\widetilde{\nu}$ LSP, cosmic abundance
none 3–90	90	[113] SATO	91	KAMI	Stable $\widetilde{\nu}_e$ or $\widetilde{\nu}_\mu$, dark matter
none 4–90	90	[113] SATO	91	KAMI	Stable $\widetilde{\nu}_\tau$, dark matter
> 31.4	95	[114] ADEVA	90I	L3	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=1
> 39.4	95	[114] ADEVA	90I	L3	$\Gamma(Z \rightarrow$ invisible); $N(\widetilde{\nu})$=3

[103] ELLIS 96B uses combined LEP data available in the Summer 1995, which constrain the number of neutrino species to N_ν=2.991 ± 0.016.

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

[105] DECAMP 92 limit is from Γ(invisible)/$\Gamma(\ell\ell)$ = 5.91 ± 0.15 (N_ν = 2.97 ± 0.07).

[106] ABREU 91F limit (>32 GeV) is independent of sneutrino decay mode.

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

[108] 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 $\lambda_{131}L_1L_ie_1$. The limits quoted here hold for $\lambda_{131} > 0.05$. Similar limits were studied in $e^+e^- \rightarrow \mu^+\mu^-$ together with $\lambda_{232}L_2L_3e_2$ coupling.

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

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

[111] 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.

[112] 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.

[113] 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.

[114] ADEVA 90I limit is from $\Delta N_\nu < 0.19$.

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

Limits assume $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$ unless otherwise stated. When the assumption of a universal scalar mass parameter m_0 for $\widetilde{e}_L$ and $\widetilde{e}_R$ is mentioned, the relation between $m_{\widetilde{e}_R}$ and $m_{\widetilde{e}_L}$ can be found in the "Note on Supersymmetry."

In the Listings below, we use $\Delta m = m_{\widetilde{e}} - m_{\widetilde{\chi}^0_1}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 56	95	[115] ACCIARRI	98F	L3	$\Delta m >$ 5 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$, $\tan\beta \geq 1.41$
> 58.0	95	[116] ACKERSTAFF	98K	OPAL	$\Delta(m) >$ 5 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
$>$ 55	95	[117] ACKERSTAFF	97H	OPAL	$\Delta(m) >$ 5 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
> 58	95	[118] BARATE	97N	ALEP	$\Delta(m) >$ 3 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>$ 35	95	[119] BARATE	97N	RVUE	$\widetilde{e}_R$, $\Gamma^{\text{inv}}(Z)$
$>$ 57	95	[120] ABREU	96O	DLPH	$\Delta(m)$ >5 GeV, $\widetilde{e}^+\widetilde{e}^-$
$>$ 50	95	[121] ACCIARRI	96F	L3	$\Delta(m)$ >5 GeV, $\widetilde{e}^+\widetilde{e}^-$
$>$ 63	95	[122] AID	96C	H1	$m_{\widetilde{q}}=m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$=35 GeV
$>$ 50	95	[123] BUSKULIC	96K	ALEP	$\Delta(m)$ >10 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$, $\lvert\mu\rvert$= 1 TeV
$>$ 63	90	[124] SUGIMOTO	96	AMY	$m_{\widetilde{\gamma}}$ <5 GeV, $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 77	90	[125] SUGIMOTO	96	RVUE	$m_{\widetilde{\gamma}}$ <5 GeV, $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 46	90	[126] ABE	95A	TOPZ	$m_{\widetilde{\gamma}}$ <5 GeV, $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 45.6	95	[127] BUSKULIC	95E	ALEP	$\widetilde{e} \rightarrow e\nu\ell\overline{\ell}'$
$>$ 51.9	90	HOSODA	94	VNS	$m_{\widetilde{\gamma}}$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 45	95	[128] ADRIANI	93M	L3	$\Delta(m)$ >5 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
$>$ 45	95	[129] DECAMP	92	ALEP	$\Delta(m)$ >4 GeV, $\widetilde{e}^+_R\widetilde{e}^-_R$
$>$ 42	95	ABREU	90G	DLPH	$m_{\widetilde{\gamma}}$ < 40 GeV; $\widetilde{e}^+\widetilde{e}^-$
$>$ 38	95	[130] AKESSON	90B	UA2	$m_{\widetilde{\gamma}} = 0$; $p\overline{p} \rightarrow ZX$ ($Z \rightarrow \widetilde{e}^+\widetilde{e}^-$)
$>$ 43.4	95	[131] AKRAWY	90D	OPAL	$m_{\widetilde{\gamma}}$ < 30 GeV; $\widetilde{e}^+\widetilde{e}^-$

$>$ 38.1	90	[132]	BAER	90	RVUE	$\widetilde{e}_L$; $\Gamma(Z)$; $\tan\beta > 1$
$>$ 43.5	95	[133]	DECAMP	90C	ALEP	$m_{\widetilde{\gamma}} < 36$ GeV; $\widetilde{e}^+\widetilde{e}^-$
$>$830			GRIFOLS	90	ASTR	$m_{\widetilde{\gamma}} < 1$ MeV
$>$ 29.9	95		SAKAI	90	AMY	$m_{\widetilde{\gamma}} < 20$ GeV; $\widetilde{e}^+\widetilde{e}^-$
$>$ 29	95		TAKETANI	90	VNS	$m_{\widetilde{\gamma}} < 25$ GeV; $\widetilde{e}^+\widetilde{e}^-$
$>$ 60		[134]	ZHUKOVSKII	90	ASTR	$m_{\widetilde{\gamma}} = 0$
$>$ 28	95	[135]	ADACHI	89	TOPZ	$m_{\widetilde{\gamma}} \lesssim 0.85 m_{\widetilde{e}}$; $\widetilde{e}^+\widetilde{e}^-$
$>$ 41	95	[136]	ADEVA	89B	L3	$m_{\widetilde{\gamma}} < 20$ GeV; $\widetilde{e}^+\widetilde{e}^-$
$>$ 32	90	[137]	ALBAJAR	89	UA1	$p\overline{p} \rightarrow W^{\pm}X$ $(W^{\pm} \rightarrow \widetilde{e}_L\widetilde{\nu})$ $(\widetilde{e}_L \rightarrow e\widetilde{\gamma})$
$>$ 14	90	[138]	ALBAJAR	89	UA1	$Z \rightarrow \widetilde{e}^+\widetilde{e}^-$
$>$ 53	95	[139,140]	HEARTY	89	ASP	$m_{\widetilde{\gamma}}$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 50	95		HEARTY	89	ASP	$m_{\widetilde{\gamma}}$ <5 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 35	95		HEARTY	89	ASP	$m_{\widetilde{\gamma}}$ <10 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 51.5	90	[141,142]	BEHREND	88B	CELL	$m_{\widetilde{\gamma}} = 0$ GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
$>$ 48	90		BEHREND	88B	CELL	$m_{\widetilde{\gamma}} < 5$ GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$

[115] 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.

[116] ACKERSTAFF 98K looked for dielectron+$\not{E}_T$ 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.

[117] ACKERSTAFF 97H searched for acoplanar e^+e^-, assuming the MSSM with universal scalar mass and $\tan\beta$=1.5 but conservatively did not take the possible $\widetilde{e}_L$ production into account. The limit improves to 68 GeV for the lightest allowed $\widetilde{\chi}^0_1$, while it disappears for $\Delta(m) < 3$ GeV. The study includes data from e^+e^- collisions at $\sqrt{s}$=161 GeV, as well as 130–136 GeV (ALEXANDER 97B).

[118] 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.

[119] BARATE 97N limit from ALCARAZ 96 limit on Z invisible-decay width and N_ν=3, independent of decay mode. Limit improves to 41 GeV for degenerate right-handed sleptons.

[120] ABREU 96O bound assumes $|\mu|$ >200 GeV. The limit on $m_{\widetilde{e}_R}$ obtained by assuming a heavy $\widetilde{e}_L$ reduces to below 48 GeV. Data taken at $\sqrt{s}$ = 130–136 GeV.

[121] ACCIARRI 96F searched for acoplanar electron pairs. The limit is on $m_{\widetilde{e}_R}$, under the assumption of a universal scalar mass in the range 0<m<100 GeV. It assumes 0<M<200 GeV, $-200 < \mu < 0$ GeV, $\tan\beta = 1.5$. The corresponding limit for for $m_{\widetilde{e}_L}$ is 64 GeV. The bound on $m_{\widetilde{e}_R}$ ($m_{\widetilde{e}_L}$) improves to 58 GeV (70 GeV) for $m_{\widetilde{\chi}^0_1}$=0. Data taken at $\sqrt{s}$ = 130–136 GeV.

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

[123] BUSKULIC 96K searched for acoplanar electron pairs. The bound disappears for $\Delta(m)$ <10 GeV, while it improves to 59 GeV for $m_{\widetilde{\chi}^0_1}$=0. If μ is small and the LSP higgsino-dominated, no bound beyond $m_Z/2$ exists. Data taken at $\sqrt{s}$ = 130–136 GeV.

[124] SUGIMOTO 96 looked for single photon production from e^+e^- annihilation at $\sqrt{s}=$ 57.8 GeV. The lower bound improves to 65.5 GeV for a massless photino.

[125] SUGIMOTO 96 combined FORD 86, BEHREND 88B, HEARTY 89, HOSODA 94, ABE 95A, and SUGIMOTO 96 results. The lower bound improves to 79.3 GeV for a massless photino.

[126] ABE 95A looked for single photon production from e^+e^- annihilation at $\sqrt{s}=$ 58 GeV. The lower bound improves to 47.2 GeV for a massless photino.

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

[128] ADRIANI 93M used acolinear di-lepton events.

[129] DECAMP 92 limit improves for equal masses. They looked for acoplanar electrons.

[130] AKESSON 90B assume $m_{\widetilde{\gamma}} = 0$. Very similar limits hold for $m_{\widetilde{\gamma}} \lesssim$ 20 GeV.

[131] AKRAWY 90D look for acoplanar electrons. For $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$, limit is 41.5 GeV, for $m_{\widetilde{\gamma}} <$ 30 GeV.

[132] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) $<$ 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[133] DECAMP 90C look for acoplanar electrons. For $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$ limit is 42 GeV, for $m_{\widetilde{\gamma}} <$ 33 GeV.

[134] ZHUKOVSKII 90 set limit by saying the luminosity of a magnetized neutron star due to massless photino emission by electrons be small compared with its neutrino luminosity.

[135] ADACHI 89 assume only photon and photino exchange and $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$. The limit for the nondegenerate case is 26 GeV.

[136] ADEVA 89B look for acoplanar electrons.

[137] ALBAJAR 89 limit applies for $\widetilde{e}_L$ when $m_{\widetilde{e}_L} = m_{\widetilde{\nu}_L}$ and $m_{\widetilde{\gamma}} = 0$. See their Fig. 55 for the 90% CL excluded region in the $m_{\widetilde{e}_L} - m_{\widetilde{\nu}_L}$ plane. For $m_{\widetilde{\nu}} = m_{\widetilde{\gamma}} = 0$, limit is 50 GeV.

[138] ALBAJAR 89 assume $m_{\widetilde{\gamma}} = 0$.

[139] HEARTY 89 assume $m_{\widetilde{\gamma}} = 0$. The limit is very sensitive to $m_{\widetilde{\gamma}}$; no limit can be placed for $m_{\widetilde{\gamma}} \gtrsim$ 13 GeV.

[140] The limit is reduced to 43 GeV if only one $\widetilde{e}$ state is produced ($\widetilde{e}_L$ or $\widetilde{e}_R$ very heavy).

[141] BEHREND 88B limits assume pure photino eigenstate and $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$.

[142] The 95% CL limit for BEHREND 88B is 47.5 GeV for $m_{\widetilde{\gamma}} = 0$. The limit for $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$ is 40 GeV at 90% CL.

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

Limits assume $m_{\widetilde{\mu}_L} = m_{\widetilde{\mu}_R}$ unless otherwise stated.

In the Listings below, we use $\Delta(m) = m_{\widetilde{\mu}} - m_{\widetilde{\chi}^0_1}$. When limits on $m_{\widetilde{\mu}_R}$ are quoted, it is understood that limits on $m_{\widetilde{\mu}_L}$ are usually at least as strong.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>55	95	[143] ACCIARRI	98F	L3	$\Delta m >$ 5 GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>55.6	95	[144] ACKERSTAFF	98K	OPAL	$\Delta(m) >$ 4 GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>59	95	[145] BARATE	97N	ALEP	$\Delta(m) >$ 10 GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$

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

>51	95	[146]	ACKERSTAFF	97H	OPAL	$\Delta(m) > 5$ GeV, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>35	95	[147]	BARATE	97N	RVUE	$\widetilde{\mu}_R$, $\Gamma^{\text{inv}}(Z)$
>51	95	[148]	ABREU	96O	DLPH	$\Delta(m) >5$ GeV, $\widetilde{\mu}^+ \widetilde{\mu}^-$
>45.6	95	[149]	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, $\widetilde{\mu}^+_R \widetilde{\mu}^-_R$
>36	95		ABREU	90G	DLPH	$m_{\widetilde{\gamma}} < 33$ GeV; $\widetilde{\mu}^+ \widetilde{\mu}^-$
>43	95	[150]	AKRAWY	90D	OPAL	$m_{\widetilde{\gamma}} < 30$ GeV; $\widetilde{\mu}^+ \widetilde{\mu}^-$
>38.1	90	[151]	BAER	90	RVUE	$\widetilde{\mu}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>42.6	95	[152]	DECAMP	90C	ALEP	$m_{\widetilde{\gamma}} < 34$ GeV; $\widetilde{\mu}^+ \widetilde{\mu}^-$
>27	95		SAKAI	90	AMY	$m_{\widetilde{\gamma}} < 18$ GeV; $\widetilde{\mu}^+ \widetilde{\mu}^-$
>24.5	95		TAKETANI	90	VNS	$m_{\widetilde{\gamma}} < 15$ GeV; $\widetilde{\mu}^+ \widetilde{\mu}^-$
>24.5	95	[153]	ADACHI	89	TOPZ	$m_{\widetilde{\gamma}} \lesssim 0.8 m_{\widetilde{\mu}}$; $\widetilde{\mu}^+ \widetilde{\mu}^-$
>41	95	[154]	ADEVA	89B	L3	$m_{\widetilde{\gamma}} < 20$ GeV; $\widetilde{\mu}^+ \widetilde{\mu}^-$

[143] 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 $\widetilde{\mu}_R \rightarrow \mu \widetilde{\chi}^0_1$. See their Fig. 6 for the dependence of the limit on Δm.

[144] 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 $\widetilde{\mu}_R \rightarrow \mu \widetilde{\chi}^0_1$. The limit improves to 62.7 GeV for B($\widetilde{\mu}_R \rightarrow \mu \widetilde{\chi}^0_1$)=1.

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

[146] 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).

[147] BARATE 97N limit from ALCARAZ 96 limit on Z invisible-decay width and N_ν=3, independent of decay mode. Limit improves to 41 GeV for degenerate right-handed sleptons.

[148] Data taken at $\sqrt{s}$ = 130–136 GeV.

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

[150] AKRAWY 90D look for acoplanar muons. For $m_{\widetilde{\mu}_L} \gg m_{\widetilde{\mu}_R}$, limit is 41.0 GeV, for $m_{\widetilde{\gamma}} < 30$ GeV.

[151] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[152] DECAMP 90C look for acoplanar muons. For $m_{\widetilde{\mu}_L} \gg m_{\widetilde{\mu}_R}$ limit is 40 GeV, for $m_{\widetilde{\gamma}} <$ 30 GeV.

[153] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m_{\widetilde{\mu}_L} = m_{\widetilde{\mu}_R}$ assumed. The limit for nondegenerate case is 22 GeV.

[154] ADEVA 89B look for acoplanar muons.

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

Limits assume $m_{\widetilde{\tau}_L} = m_{\widetilde{\tau}_R}$ unless otherwise stated.

In the Listings below, we use $\Delta(m)=m_{\widetilde{\tau}} - m_{\widetilde{\chi}^0_1}$. The limits depend on the potentially large mixing angle of the lightest mass eigenstate $\widetilde{\tau}_1 = \widetilde{\tau}_R \sin\theta_\tau + \widetilde{\tau}_L \sin\theta_\tau$. The coupling to the Z vanishes for $\theta_\tau = 0.82$.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>53	95	[155] BARATE	97N	ALEP	$\Delta(m) > 30$ GeV, $\theta_\tau=\pi/2$
>47	95	[155] BARATE	97N	ALEP	$\Delta(m) > 30$ GeV, $\theta_\tau=0.82$
>35	95	[156] BARATE	97N	RVUE	$\widetilde{\tau}_R$, $\Gamma^{\rm inv}(Z)$
>44	95	[157] ADRIANI	93M	L3	$m_{\widetilde{\chi}^0_1}$ <38 GeV, $\widetilde{\tau}^+\widetilde{\tau}^-$
>45	95	[158] DECAMP	92	ALEP	$m_{\widetilde{\chi}^0_1}$ <38 GeV, $\widetilde{\tau}^+\widetilde{\tau}^-$
>43.0	95	[159] AKRAWY	90D	OPAL	$m_{\widetilde{\gamma}} < 23$ GeV; $\widetilde{\tau}^+\widetilde{\tau}^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45.6	95	[160] BUSKULIC	95E	ALEP	$\widetilde{\tau} \rightarrow \tau\nu\ell\overline{\ell}'$
>35	95	ABREU	90G	DLPH	$m_{\widetilde{\gamma}} < 25$ GeV; $\widetilde{\tau}^+\widetilde{\tau}^-$
>38.1	90	[161] BAER	90	RVUE	$\widetilde{\tau}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>40.4	95	[162] DECAMP	90C	ALEP	$m_{\widetilde{\gamma}} < 15$ GeV; $\widetilde{\tau}^+\widetilde{\tau}^-$
>25	95	SAKAI	90	AMY	$m_{\widetilde{\gamma}} < 10$ GeV; $\widetilde{\tau}^+\widetilde{\tau}^-$
>25.5	95	TAKETANI	90	VNS	$m_{\widetilde{\gamma}} < 15$ GeV; $\widetilde{\tau}^+\widetilde{\tau}^-$
>21.7	95	[163] ADACHI	89	TOPZ	$m_{\widetilde{\gamma}}=0$; $\widetilde{\tau}^+\widetilde{\tau}^-$

[155] BARATE 97N uses e^+e^- data collected at $\sqrt{s}$=161 and 172 GeV.

[156] BARATE 97N limit from ALCARAZ 96 limit on Z invisible-decay width and N_ν=3, independent of decay mode. Limit improves to 41 GeV for degenerate right-handed sleptons.

[157] ADRIANI 93M limit is for $m_{\widetilde{\tau}_L} \gg m_{\widetilde{\tau}_R}$.

[158] DECAMP 92 limit is for $m_{\widetilde{\tau}_L} \gg m_{\widetilde{\tau}_R}$; for equal masses the limit would improve. They looked for acoplanar particles.

[159] AKRAWY 90D look for acoplanar particles. For $m_{\widetilde{\tau}_L} \gg m_{\widetilde{\tau}_R}$, limit is 41.0 GeV, for $m_{\widetilde{\gamma}} < 23$ GeV.

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

[161] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) $<$ 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[162] DECAMP 90C look for acoplanar charged particle pairs. Limit is for $m_{\widetilde{\tau}_L} = m_{\widetilde{\tau}_R}$. For $m_{\widetilde{\gamma}} \leq 24$ GeV, the limit is 37 GeV. For $m_{\widetilde{\tau}_L} \gg m_{\widetilde{\tau}_R}$ and $m_{\widetilde{\gamma}} < 15$ GeV, the limit is 33 GeV.

[163] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m_{\widetilde{\tau}_L} = m_{\widetilde{\tau}_R}$ assumed.

Stable $\widetilde{\ell}$ (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. All limits assume $m_{\widetilde{\ell}_L} = m_{\widetilde{\ell}_R}$ unless otherwise stated.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>65	95	[164] ABREU	97D	DLPH	$\widetilde{\mu}_r$ or $\widetilde{\tau}_R$
>67	95	[165] BARATE	97K	ALEP	$\widetilde{\mu}_R$, $\widetilde{\tau}_R$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>40	95	ABREU	90G	DLPH	
>26.3	95	ADACHI	90C	TOPZ	$\widetilde{\mu}$, $\widetilde{\tau}$
>38.8	95	AKRAWY	90O	OPAL	$\widetilde{\ell}_R$
>27.1	95	[166] SAKAI	90	AMY	
>32.6	95	SODERSTROM	90	MRK2	
>24.5	95	[167] ADACHI	89	TOPZ	

[164] ABREU 97D bound applies only to masses above 45 GeV. The mass limit improves to 68 GeV for $\widetilde{\mu}_L$, $\widetilde{\tau}_L$. Data collected in e^+e^- collisions at $\sqrt{s}$=130–172 GeV.

[165] BARATE 97K uses e^+e^- data collected at $\sqrt{s}$ = 130–172 GeV. The mass limit improves to 69 GeV for $\widetilde{\mu}_L$ and $\widetilde{\tau}_L$.

[166] SAKAI 90 limit improves to 30.1 GeV for $\widetilde{e}$ if $m_{\widetilde{\gamma}} \approx m_{\widetilde{e}}$.

[167] ADACHI 89 assume only photon (and photino for $\widetilde{e}$) exchange. The limit for $\widetilde{e}$ improves to 26 GeV for $m_{\widetilde{\gamma}} \approx m_{\widetilde{e}}$.

$\widetilde{q}$ (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. The limits from Z decay do not assume GUT relations and are more model independent.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 224	95	[168] ABE	96D	CDF	$m_{\widetilde{g}} \leq m_{\widetilde{q}}$; with cascade decays
> 176	95	[169] ABACHI	95C	D0	Any $m_{\widetilde{g}}$ <300 GeV; with cascade decays
> 212	95	[169] ABACHI	95C	D0	$m_{\widetilde{g}} \leq m_{\widetilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[170] DATTA	97	THEO	$\widetilde{\nu}$'s lighter than $\widetilde{\chi}^{\pm}_1$, $\widetilde{\chi}^0_2$
> 216	95	[171] DERRICK	97	ZEUS	$ep \rightarrow \widetilde{q}$, $\widetilde{q} \rightarrow \mu j$ or τj, R-parity violation
none 130–573	95	[172] HEWETT	97	THEO	$q\widetilde{g} \rightarrow \widetilde{q}$, $\widetilde{q} \rightarrow q\widetilde{g}$, with a light gluino
none 190–650	95	[173] TEREKHOV	97	THEO	$qg \rightarrow \widetilde{q}\widetilde{g}$, $\widetilde{q} \rightarrow q\widetilde{g}$, with a light gluino
> 215	95	[174] AID	96	H1	$ep \rightarrow \widetilde{q}$, R-parity violation, λ=0.3

>150	95	[174] AID	96	H1	$ep \to \widetilde{q}$, R-parity violation, λ=0.1
>63	95	[175] AID	96C	H1	$m_{\widetilde{q}}$=$m_{\widetilde{e}}$, $m_{\widetilde{\chi}^0_1}$=35 GeV
none 330–400	95	[176] TEREKHOV	96	THEO	$ug \to \widetilde{u}\widetilde{g}$, $\widetilde{u} \to u\widetilde{g}$ with a light gluino
		[177] ABE	95T	CDF	$\widetilde{q} \to \widetilde{\chi}^0_2 \to \widetilde{\chi}^0_1\gamma$
>45.3	95	[178] BUSKULIC	95E	ALEP	$\widetilde{q} \to q\nu\ell\overline{\ell}'$
>239	95	[179] AHMED	94B	H1	$ep \to \widetilde{q}$; R-parity violation, λ=0.30
>135	95	[179] AHMED	94B	H1	$ep \to \widetilde{q}$; R-parity violation, λ=0.1
>35.3	95	[180] ADRIANI	93M	L3	$Z \to \widetilde{u}\overline{\widetilde{u}}$, $\Gamma(Z)$
>36.8	95	[180] ADRIANI	93M	L3	$Z \to \widetilde{d}\overline{\widetilde{d}}$, $\Gamma(Z)$
>90	90	[181] ABE	92L	CDF	Any $m_{\widetilde{g}}$ <410 GeV; with cascade decay
>218	90	[182] ABE	92L	CDF	$m_{\widetilde{g}} = m_{\widetilde{q}}$; with cascade decay
>180	90	[181] ABE	92L	CDF	$m_{\widetilde{g}} < m_{\widetilde{q}}$; with cascade decay
>100		[183] ROY	92	RVUE	$p\overline{p} \to \widetilde{q}\widetilde{q}$; R-parity violating
		[184] NOJIRI	91	COSM	
>45	95	[185] ABREU	90F	DLPH	$Z \to \widetilde{q}\overline{\widetilde{q}}$, $m_{\widetilde{\gamma}} < 20$ GeV
>43	95	[186] ABREU	90F	DLPH	$Z \to \widetilde{d}\overline{\widetilde{d}}$, $m_{\widetilde{\gamma}} < 20$ GeV
>42	95	[187] ABREU	90F	DLPH	$Z \to \widetilde{u}\overline{\widetilde{u}}$, $m_{\widetilde{\gamma}} < 20$ GeV
>27.0	95	ADACHI	90C	TOPZ	Stable $\widetilde{u}$, $\widetilde{u}\overline{\widetilde{u}}$
>74	90	[188] ALITTI	90	UA2	Any $m_{\widetilde{q}}$; B($\widetilde{q} \to q\widetilde{g}$ or $q\widetilde{\gamma}$) = 1
>106	90	[188] ALITTI	90	UA2	$m_{\widetilde{q}} = m_{\widetilde{g}}$; B($\widetilde{q} \to q\widetilde{\gamma}$) = 1
>39.2	90	[189] BAER	90	RVUE	$\widetilde{d}_L$; $\Gamma(Z)$
>45	95	[190,191] BARKLOW	90	MRK2	$Z \to \widetilde{q}\overline{\widetilde{q}}$
>40	95	[190,192] BARKLOW	90	MRK2	$Z \to \widetilde{d}\overline{\widetilde{d}}$
>39	95	[190,193] BARKLOW	90	MRK2	$Z \to \widetilde{u}\overline{\widetilde{u}}$
>1100		GRIFOLS	90	ASTR	$m_{\widetilde{\gamma}} < 1$ MeV
>24	95	SAKAI	90	AMY	$e^+e^- \to \widetilde{d}\overline{\widetilde{d}} \to d\overline{d}\widetilde{\gamma}\widetilde{\gamma}$; $m_{\widetilde{\gamma}} < 10$ GeV
>26	95	SAKAI	90	AMY	$e^+e^- \to \widetilde{u}\overline{\widetilde{u}} \to u\overline{u}\widetilde{\gamma}\widetilde{\gamma}$; $m_{\widetilde{\gamma}} < 10$ GeV
>26.3	95	[194] ADACHI	89	TOPZ	$e^+e^- \to \widetilde{q}\overline{\widetilde{q}} \to q\overline{q}\widetilde{\gamma}\widetilde{\gamma}$
		[195] NATH	88	THEO	$\tau(p \to \nu K)$ in supergravity GUT
>45	90	[196] ALBAJAR	87D	UA1	Any $m_{\widetilde{g}} > m_{\widetilde{q}}$
>75	90	[196] ALBAJAR	87D	UA1	$m_{\widetilde{g}} = m_{\widetilde{q}}$

[168] 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.

[169] 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 tanβ = 2.0 $\mu = -250$ GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space. No limit is given for m_{gluino} >547 GeV.

[170] 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 $\widetilde{\chi}_1^{\pm}$,$\widetilde{\chi}_2^0$ in the squark cascade decays have dominant and invisible decays to $\widetilde{\nu}$.

[171] 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.

[172] 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.

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

[174] AID 96 looked for first-generation squarks as s-channel resonances singly produced in ep collision via the R-parity violating coupling in the superpotential W=$\lambda L_1 Q_1 d_1$. The degeneracy of squarks $\widetilde{Q}_1$ and $\widetilde{d}_1$ is assumed. Eight different channels of possible squark decays are considered.

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

[176] 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.

[177] 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, tanβ = 1.5, and heavy gluinos, the range 50<$m_{\widetilde{q}}$ (GeV)<110 is excluded at 90% CL. See the paper for details.

[178] 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.

[179] AHMED 94B looked for squarks as s-channel resonance in ep collision via R-parity violating coupling in the superpotential $W = \lambda L_1 Q_1 d_1$. The degeneracy of all squarks Q_1 and d_1 is assumed. The squarks decay dominantly via the same R-violating coupling into eq or νq if $\lambda \gtrsim 0.2$. For smaller λ, decay into photino is assumed which subsequently decays into $eq\overline{q}$, and the bound depends on $m_{\widetilde{\gamma}}$. See paper for excluded region on ($m_{\widetilde{q}}$,λ) plane.

[180] ADRIANI 93M limit from $\Delta\Gamma(Z)$< 35.1 MeV and assumes $m_{\widetilde{q}_L} \gg m_{\widetilde{q}_R}$.

[181] ABE 92L assume five degenerate squark flavors and $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$. ABE 92L includes the effect of cascade decay, for a particular choice of parameters, $\mu = -250$ GeV, $\tan\beta = 2$. Results are weakly sensitive to these parameters over much of parameter space. No limit for $m_{\widetilde{q}} \leq 50$ GeV (but other experiments rule out that region). Limits are 10–20 GeV higher if $B(\widetilde{q} \rightarrow q\widetilde{\gamma}) = 1$. Limit assumes GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\widetilde{\chi}^0_1} \approx m_{\widetilde{g}}/6$. This last relation implies that as $m_{\widetilde{g}}$ increases, the mass of $\widetilde{\chi}^0_1$ will eventually exceed $m_{\widetilde{q}}$ so that no decay is possible. Even before that occurs, the signal will disappear; in particular no bounds can be obtained for $m_{\widetilde{g}} >410$ GeV. m_{H^+}=500 GeV.

[182] ABE 92L bounds are based on similar assumptions as ABACHI 95C. No limits for $m_{gluino} >410$ GeV.

[183] 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.

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

[185] ABREU 90F assume six degenerate squarks and $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$. $m_{\widetilde{q}} < 41$ GeV is excluded at 95% CL for $m_{\text{LSP}} < m_{\widetilde{q}} - 2$ GeV.

[186] ABREU 90F exclude $m_{\widetilde{d}} < 38$ GeV at 95% for $m_{\text{LSP}} < m_{\widetilde{d}} - 2$ GeV.

[187] ABREU 90F exclude $m_{\widetilde{u}} < 36$ GeV at 95% for $m_{\text{LSP}} < m_{\widetilde{u}} - 2$ GeV.

[188] ALITTI 90 searched for events having $\geq$ 2 jets with $E^1_T > 25$ GeV, $E^2_T > 15$ GeV, $|\eta| < 0.85$, and $\Delta\phi < 160°$, with a missing momentum $>$ 40 GeV and no electrons. They assume $\widetilde{q} \rightarrow q\widetilde{\gamma}$ (if $m_{\widetilde{q}} < m_{\widetilde{g}}$) or $\widetilde{q} \rightarrow q\widetilde{g}$ (if $m_{\widetilde{q}} > m_{\widetilde{g}}$) decay and $m_{\widetilde{\gamma}} \lesssim$ 20 GeV. Five degenerate squark flavors and $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$ are assumed. Masses below 50 GeV are not excluded by the analysis.

[189] BAER 90 limit from $\Delta\Gamma(Z) <$ 120 MeV, assuming $m_{\widetilde{d}_L} = m_{\widetilde{u}_L} = m_{\widetilde{e}_L} = m_{\widetilde{\nu}}$. Independent of decay modes. Minimal supergravity assumed.

[190] BARKLOW 90 assume 100% $\widetilde{q} \rightarrow q\widetilde{\gamma}$.

[191] BARKLOW 90 assume five degenerate squarks (left- and right-handed). Valid up to $m_{\widetilde{\chi}^0_1} \lesssim [m_{\widetilde{q}} - 4$ GeV].

[192] BARKLOW 90 result valid up to $m_{\widetilde{\chi}^0_1} \lesssim [m_{\widetilde{d}} - 5$ GeV].

[193] BARKLOW 90 result valid up to $m_{\widetilde{\chi}^0_1} \lesssim [m_{\widetilde{u}} - 6$ GeV].

[194] ADACHI 89 assume only photon exchange, which gives a a conservative limit. The limit is only for one flavor of charge 2/3 $\widetilde{q}$. $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$ and $m_{\widetilde{\gamma}} = 0$ assumed. The limit decreases to 26.1 GeV for $m_{\widetilde{\gamma}} = 15$ GeV. The limit for nondegenerate case is 24.4 GeV.

[195] NATH 88 uses Kamioka limit of $\tau(p \rightarrow \overline{\nu} K^+) > 7 \times 10^{31}$ yrs to constrain squark mass $m_{\widetilde{q}} > 1000$ GeV by assuming that the proton decay proceeds via an exchange of a color-triplet Higgsino of mass $< 10^{16}$ GeV in the supersymmetric SU(5) GUT. The limit applies for $m_{\widetilde{\gamma}} \equiv (8/3) \sin^2\theta_W \widetilde{m}_2 > 10$ GeV ($\widetilde{m}_2$ is the SU(2) gaugino mass) and for a very conservative value of the three-quark proton wave function, barring cancellation between second and third generations. Lower squark mass is allowed if $m_{\widetilde{\gamma}}$ as defined above is smaller.

[196] The limits of ALBAJAR 87D are from $p\overline{p} \rightarrow \widetilde{q}\overline{\widetilde{q}}X$ ($\widetilde{q} \rightarrow q\widetilde{\gamma}$) and assume 5 flavors of degenerate mass squarks each with $m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$. They also assume $m_{\widetilde{g}} > m_{\widetilde{q}}$. These limits apply for $m_{\widetilde{\gamma}} \lesssim$ 20 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 $\theta_b \sim 1.17$. In the Listings below, we use $\Delta m = m_{\widetilde{b}_1} - m_{\widetilde{\chi}^0_1}$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>69.7	95	[197] ACKERSTAFF	97Q	OPAL	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta(m) > 8$ GeV
>73	95	[198] BARATE	97Q	ALEP	$\widetilde{b} \to b\widetilde{\chi}^0_1$, θ_b=0, $\Delta(m) > 10$ GeV
>53	95	[199] ABREU	96O	DLPH	$\widetilde{b} \to b\widetilde{\chi}^0$, θ_b=0, $\Delta(m) >20$ GeV
>61.8	95	[200] ACKERSTAFF	96	OPAL	$\widetilde{b} \to b\widetilde{\chi}^0$, θ_b=0, $\Delta(m) >8$ GeV

[197] ACKERSTAFF 97Q data taken at $\sqrt{s}$=130–172 GeV. See paper for dependence on θ_b. No limit for $\theta_b \approx 1.17$.

[198] BARATE 97Q uses data at $\sqrt{s}$=161, 170, and 172 GeV. The limit disappears when $\theta_b \approx 1.17$.

[199] Data taken at $\sqrt{s}$ = 130–136 GeV.

[200] ACKERSTAFF 96 also studied θ_b dependence when there is a mixing $\widetilde{b}_1 = \widetilde{b}_L\cos\theta_b + \widetilde{b}_R\sin\theta_b$. Data taken at $\sqrt{s}$ = 130, 136, and 161 GeV. See the paper for dependence on θ_b. No limit for $\theta_b \approx 1.17$.

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

Limit depends on decay mode. In e^+e^- collisions they also depend on the mixing angle of the mass eigenstate $\widetilde{t}_1 = \widetilde{t}_L\cos\theta_t + \widetilde{t}_R\sin\theta_t$. Coupling to 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."

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 73.3	95	[201] ACKERSTAFF	97Q	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m) > 10$ GeV
$>$ 65.0	95	[201] ACKERSTAFF	97Q	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta(m) >$ 10 GeV
$>$ 67.9	95	[201] ACKERSTAFF	97Q	OPAL	$\widetilde{t} \to b\ell\widetilde{\nu}$, θ_t=0, $\Delta(m) > 10$ GeV
$>$ 56.2	95	[201] ACKERSTAFF	97Q	OPAL	$\widetilde{t} \to b\ell\widetilde{\nu}$, θ_t=0.98, $\Delta(m) >$ 10 GeV
$>$ 66.3	95	[201] ACKERSTAFF	97Q	OPAL	$\widetilde{t} \to b\tau\widetilde{\nu}_\tau$, θ_t=0, $\Delta(m) > 10$ GeV
$>$ 54.4	95	[201] ACKERSTAFF	97Q	OPAL	$\widetilde{t} \to b\tau\widetilde{\nu}_\tau$, θ_t=0.98, $\Delta(m) >$ 10 GeV
> 67	95	[202] BARATE	97Q	ALEP	$\widetilde{t} \to c\widetilde{\chi}^0_1$, any θ_t, $\Delta(m) > 10$ GeV
$>$ 70	95	[202] BARATE	97Q	ALEP	$\widetilde{t} \to b\ell\widetilde{\nu}$, any θ_t, $\Delta(m) > 10$ GeV
$>$ 64	95	[202] BARATE	97Q	ALEP	$\widetilde{t} \to b\tau\widetilde{\nu}_\tau$, any θ_t, $\Delta(m) >$ 10 GeV

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

none 61–91	95	[203] ABACHI	96B	D0	$\widetilde{t} \to c\widetilde{\chi}^0_1$, $m_{\widetilde{\chi}^0_1}$ <30 GeV
> 54	95	[204] ABREU	96O	DLPH	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >5 GeV
> 52	95	[204] ACCIARRI	96F	L3	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >8 GeV
> 65.4	95	[205] ACKERSTAFF	96	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >10 GeV
> 56.8	95	[205] ACKERSTAFF	96	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >10 GeV
> 60.6	95	[205] ACKERSTAFF	96	OPAL	$\widetilde{t} \to b\ell\widetilde{\nu}$, θ_t=0, $\Delta(m)$ >10 GeV
none 9–24.4	95	[206] AID	96	H1	$ep \to \widetilde{t}\widetilde{t}$, R-parity violating decays
>138	95	[207] AID	96	H1	$ep \to \widetilde{t}$, R-parity violation, $\lambda\cos\theta_t > 0.03$
> 48	95	[204] BUSKULIC	96K	ALEP	$t \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >18 GeV
> 57	95	[204] BUSKULIC	96K	ALEP	$t \to c\widetilde{\chi}^0_1$, θ_t=π/2, $\Delta(m)$ >14 GeV
> 45		[208] CHO	96	RVUE	B^0-$\overline{B}^0$ and ϵ, θ_t= 0.98, $\tan\beta$ <2
none 11–41	95	[209] BUSKULIC	95E	ALEP	θ_t=0.98, $\widetilde{t} \to c\nu\ell\overline{\ell}'$
none 6.0–41.2	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >2 GeV
none 5.0–46.0	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >5 GeV
none 11.2–25.5	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >2 GeV
none 7.9–41.2	95	AKERS	94K	OPAL	$\widetilde{t} \to c\widetilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >5 GeV
none 7.6–28.0	95	[210] SHIRAI	94	VNS	$\widetilde{t} \to c\widetilde{\chi}^0_1$, any θ_t, $\Delta(m)$ >10 GeV
none 10–20	95	[210] SHIRAI	94	VNS	$\widetilde{t} \to c\widetilde{\chi}^0_1$, any θ_t, $\Delta(m)$ > 2.5 GeV

[201] ACKERSTAFF 97Q looked for $\widetilde{t}$ pair production. Data taken at $\sqrt{s}$=130, 136, 161, 170, and 172 GeV. Unless the ℓ=τ decay mode is explicitly indicated, the same branching fractions to ℓ=e, μ, and τ are assumed for $b\ell\widetilde{\nu}_\ell$ modes. See Table 7 and Figs. 8–10 for other choices of θ_t, $\Delta(m)$, and leptonic branching ratios.

[202] BARATE 97Q uses e^+e^- data at $\sqrt{s}$=161, 170, and 172 GeV. Unless the ℓ=τ decay mode is explicitly indicated, the same branching fractions to ℓ=e, μ, and τ are assumed for $b\ell\widetilde{\nu}_\ell$ modes. See their Figs. 4 and 5 for other choices of θ_t, $\Delta(m)$, and leptonic branching ratios.

[203] 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.

[204] Data taken at $\sqrt{s}$ = 130–136 GeV.

[205] ACKERSTAFF 96 looked for $\widetilde{t}$ pair production. See the paper for θ_t and $\Delta(m)$ dependece of the limits. Data taken at $\sqrt{s}$ = 130, 136, and 161 GeV.

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

[207] AID 96 considers production and decay of $\widetilde{t}$ via the R-parity violating coupling in the superpotential W=$\lambda L_1 Q_3 d_1$.

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

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

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

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

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>173	95	[211] ABE	97K	CDF	Any $m_{\widetilde{q}}$; with cascade decays
>216	95	[211] ABE	97K	CDF	$m_{\widetilde{q}}=m_{\widetilde{g}}$; with cascade decays
>224	95	[212] ABE	96D	CDF	$m_{\widetilde{q}} = m_{\widetilde{g}}$; with cascade decays
>154	95	[212] ABE	96D	CDF	$m_{\widetilde{g}} < m_{\widetilde{q}}$; with cascade decays
>212	95	[213] ABACHI	95C	D0	$m_{\widetilde{g}} \geq m_{\widetilde{q}}$; with cascade decays
>144	95	[213] ABACHI	95C	D0	Any $m_{\widetilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[214] ABE	95T	CDF	$\widetilde{g} \rightarrow \widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0\gamma$
		[215] HEBBEKER	93	RVUE	e^+e^- jet analyses
>218	90	[216] ABE	92L	CDF	$m_{\widetilde{q}} \leq m_{\widetilde{g}}$; with cascade decay
>100	90	[216] ABE	92L	CDF	Any $m_{\widetilde{q}}$; with cascade decay
>100		[217] ROY	92	RVUE	$p\overline{p} \rightarrow \widetilde{g}\widetilde{g}$; R-parity violating
>132	90	[218] HIDAKA	91	RVUE	
		[219] NOJIRI	91	COSM	
> 79	90	[220] ALITTI	90	UA2	Any $m_{\widetilde{g}}$; B($\widetilde{g} \rightarrow q\overline{q}\widetilde{\gamma}$) = 1
>106	90	[220] ALITTI	90	UA2	$m_{\widetilde{q}} = m_{\widetilde{g}}$; B($\widetilde{g} \rightarrow q\overline{q}\widetilde{\gamma}$) = 1
		[221] NAKAMURA	89	SPEC	R-Δ^{++}
none 4–53	90	[222] ALBAJAR	87D	UA1	Any $m_{\widetilde{q}} > m_{\widetilde{g}}$
none 4–75	90	[222] ALBAJAR	87D	UA1	$m_{\widetilde{q}} = m_{\widetilde{g}}$
none 16–58	90	[223] ANSARI	87D	UA2	$m_{\widetilde{q}} \lesssim 100$ GeV

[211] 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 $m_{\widetilde{q}}$ is for μ=−200 GeV and tanβ=2, and that for $m_{\widetilde{q}}$=$m_{\widetilde{g}}$ is for μ=−400 GeV and tanβ=4. Different choices for tanβ and μ lead to changes of the order of ±10 GeV in the limits. See Footnote [16] of the paper for more details on the assumptions.

[212] 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.

[213] 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.

[214] 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.

[215] 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.

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

[217] 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.

[218] HIDAKA 91 limit obtained from LEP and preliminary CDF results within minimal supersymmetry with gaugino-mass unification condition. HIDAKA 91 limit extracted from BAER 91 analysis.

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

[220] ALITTI 90 searched for events having ≥ 2 jets with $E^1_T > 25$ GeV, $E^2_T > 15$ GeV, $|\eta| < 0.85$, and $\Delta\phi < 160°$, with a missing momentum > 40 GeV and no electrons. They assume $\widetilde{g} \rightarrow q\overline{q}\widetilde{\gamma}$ decay and $m_{\widetilde{\gamma}} \lesssim 20$ GeV. Masses below 50 GeV are not excluded by the analysis.

[221] 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 $\widetilde{g}uuu$ state) lighter than 1.6 GeV.

[222] 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.

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

NOTE ON 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 $R^0 \to \rho^0\tilde{\gamma}$, if allowed, must be outside the ADAMS 97B range. 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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   in SUSY 97, Proceedings of the Fifth International Conference on Supersymmetries in Physics," 27-31 May 1997, Philadelphia, USA, edited by M. Cvetic and P. Langacker (Nuc. Phys. B (Proc. Suppl.) 62 (1998)) p. 485. `hep-ph/9710277`.
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.
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Long-lived/light $\widetilde{g}$ (Gluino) MASS LIMIT

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[224] ADAMS	97B	KTEV	$pN \to R^0 \to \rho^0 \widetilde{\gamma}$
		[225] 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	[226] BARATE	97L	ALEP	Color factors
>5	99	[227] CSIKOR	97	RVUE	β function, $Z \to$ jets
>1.5	90	[228] DEGOUVEA	97	THEO	$Z \to jjjj$
		[229] FARRAR	96	RVUE	$R^0 \to \pi^0 \widetilde{\gamma}$
none 1.9–13.6	95	[230] AKERS	95R	OPAL	Z decay into a long-lived $(\widetilde{g}q\overline{q})^{\pm}$
<0.7		[231] CLAVELLI	95	RVUE	quarkonia
none 1.5–3.5		[232] CAKIR	94	RVUE	$\Upsilon(1S) \to \gamma +$ gluinonium
not 3–5		[233] LOPEZ	93C	RVUE	LEP
≈ 4		[234] CLAVELLI	92	RVUE	α_s running
		[235] ANTONIADIS	91	RVUE	α_s running
>1		[236] ANTONIADIS	91	RVUE	$pN \to$ missing energy
>3.8	90	[237] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^1$
>3.2	90	[237] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^{0.72}$
none 0.6–2.2	90	[238] TUTS	87	CUSB	$\Upsilon(1S) \to \gamma +$ gluinonium
none 1 –4.5	90	[239] ALBRECHT	86C	ARG	$1 \times 10^{-11} \lesssim \tau \lesssim 1 \times 10^{-9}$s
none 1–4	90	[240] BADIER	86	BDMP	$1 \times 10^{-10} < \tau < 1 \times 10^{-7}$s
none 3–5		[241] BARNETT	86	RVUE	$p\overline{p} \to$ gluino gluino gluon
none		[242] VOLOSHIN	86	RVUE	If (quasi) stable; $\widetilde{g}uud$
none 0.5–2		[243] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$=300 GeV
none 0.5–4		[243] COOPER-...	85B	BDMP	For $m_{\widetilde{q}} <$65 GeV
none 0.5–3		[243] COOPER-...	85B	BDMP	For $m_{\widetilde{q}}$=150 GeV
none 2–4		[244] DAWSON	85	RVUE	$\tau > 10^{-7}$ s
none 1–2.5		[244] DAWSON	85	RVUE	For $m_{\widetilde{q}}$=100 GeV
none 0.5–4.1	90	[245] FARRAR	85	RVUE	FNAL beam dump
>1		[246] GOLDMAN	85	RVUE	Gluononium
$>$1–2		[247] HABER	85	RVUE	
		[248] BALL	84	CALO	
		[249] BRICK	84	RVUE	
		[250] FARRAR	84	RVUE	
>2		[251] BERGSMA	83C	RVUE	For $m_{\widetilde{q}}$ <100 GeV
		[252] CHANOWITZ	83	RVUE	$\widetilde{g}u\overline{d}$, $\widetilde{g}uud$
$>$2–3		[253] KANE	82	RVUE	Beam dump
$>$1.5–2		FARRAR	78	RVUE	R-hadron

[224] ADAMS 97B looked for $\rho^0 \to \pi^+\pi^-$ as a signature of R^0=$(\widetilde{g}g)$ bound states. The experiment is sensitive to an R^0 mass range of 1.2–4.5 GeV and to a lifetime range of

10^{-10}–10^{-3} sec. Precise limits depend on the assumed value of $m_{R^0}/m_{\widetilde{\gamma}}$. See Fig. 7 for the excluded mass and lifetime region.

[225] 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.

[226] 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.

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

[228] 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.

[229] FARRAR 96 studied the possible R^0=$(\widetilde{g}\,g)$ component in Fermilab E799 experiment and used its bound B($K^0_L \rightarrow \pi^0 \nu \overline{\nu}$) $\leq 5.8 \times 10^{-5}$ to place constraints on the combination of R^0 production cross section and its lifetime.

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

[231] 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.

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

[233] 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.

[234] 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.

[235] 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.

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

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

[238] The gluino mass is defined by half the bound $\widetilde{g}\widetilde{g}$ mass. If zero gluino mass gives a $\widetilde{g}\widetilde{g}$ 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.

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

[240] BADIER 86 looked for secondary decay vertices from long-lived $\widetilde{g}$-hadrons produced at 300 GeV π^- beam dump. The quoted bound assumes $\widetilde{g}$-hadron nucleon total cross

section of 10μb. See their figure 7 for excluded region in the $m_{\widetilde{g}} - m_{\widetilde{q}}$ plane for several assumed total cross-section values.

[241] 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.

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

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

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

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

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

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

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

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

[250] 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.

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

[252] 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.

[253] 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.

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

[254] 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.

[255] 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.

[256] 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.

REFERENCES FOR Supersymmetric Particle Searches

ABBOTT	98	PRL 80 442	B. Abbott+	(D0 Collab.)
ABBOTT	98C	PRL 80 1591	B. Abbott+	(D0 Collab.)
ABREU	98	EPJ C1 1	P. Abreu+	(DELPHI Collab.)
ACCIARRI	98F	EPJ C (to be publ.)	M. Acciarri+	(L3 Collab.)
CERN-PPE/97-130				
ACKERSTAFF	98J	EPJ C (to be publ.)	K. Ackerstaff+	(OPAL Collab.)
CERN-PPE/97-132				
ACKERSTAFF	98K	EPJ C (to be publ.)	K. Ackerstaff+	(OPAL Collab.)
CERN-PPE/97-124				
ACKERSTAFF	98L	EPJ C2 213	K. Ackerstaff+	(OPAL Collab.)
ABACHI	97	PRL 78 2070	S. Abachi+	(D0 Collab.)
ABE	97K	PR D56 R1357	F. Abe+	(CDF Collab.)
ABREU	97D	PL B396 315	P. Abreu+	(DELPHI Collab.)
ABREU	97J	ZPHY C74 577	P. Abreu+	(DELPHI Collab.)
ACCIARRI	97U	PL B414 373	M. Acciarri+	(L3 Collab.)
ACCIARRI	97V	PL B415 299	M. Acciarri+	(L3 Collab.)
ACKERSTAFF	97H	PL B396 301	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97Q	ZPHY C75 409	K. Ackerstaff+	(OPAL Collab.)
ADAMS	97B	PRL 79 4083	J. Adams+	(KTeV Collab.)
ALBUQUERQ...	97	PRL 78 3252	I.F. Albuquerque+	(FNAL E761 Collab.)
ALEXANDER	97B	ZPHY C73 201	G. Alexander+	(OPAL Collab.)
BARATE	97K	PL B405 379	R. Barate+	(ALEPH Collab.)
BARATE	97L	ZPHY C76 1	R. Barate+	(ALEPH Collab.)
BARATE	97N	PL B407 377	R. Barate+	(ALEPH Collab.)
BARATE	97Q	PL B413 431	R. Barate+	(ALEPH Collab.)
BOTTINO	97	PL B402 113	+	(TORI, LAPP, GENO, ROMA, ROMA2, INFN)
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+	(ZEUS Collab.)
ELLIS	97	PL B394 354	J. Ellis, J.L. Lopez, D.V. Nanopoulos	
ELLIS	97C	PL B413 355	J. Ellis, Falk, Olive, Schmitt	
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	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABACHI	96B	PRL 76 2222	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	96	PRL 77 438	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96D	PRL 76 2006	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96K	PRL 76 4307	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABREU	96L	PL B382 323	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	96O	PL B387 651	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	96F	PL B377 289	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACKERSTAFF	96	PL B389 197	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ACKERSTAFF	96C	PL B389 616	+Alexander, Allison, Altekamp+	(OPAL Collab.)
AID	96	ZPHY C71 211	+Andreev, Andrieu, Appuhn+	(H1 Collab.)
AID	96C	PL B380 461	+Andreev, Andrieu, Appuhn+	(H1 Collab.)
ALCARAZ	96	CERN-PPE/96-183	J. Alcaraz+	
The ALEPH, DELPHI, L3, OPAL, and SLD Collaborations and the LEP Electroweak Working Group				
ALEXANDER	96J	PL B377 181	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	96L	PL B377 273	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BUSKULIC	96A	ZPHY C72 549	D. Buskulic+	(ALEPH Collab.)
BUSKULIC	96K	PL B373 246	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	96U	PL B384 461	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
CHO	96	PL B372 101	+Kizukuri, Oshimo	(TOKAH, OCH)
ELLIS	96B	PL B388 97	+Falk, Olive, Schmitt	(CERN, MINN)

FARRAR	96	PRL 76 4111	G.R. Farrar	(RUTG)
SUGIMOTO	96	PL B369 86	+Abe, Fujii, Igarashi+	(AMY Collab.)
TEREKHOV	96	PL B385 139	I. Terkhov, L. Clavelli	(ALAT)
ABACHI	95C	PRL 75 618	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	95A	PL B361 199	+Fujii, Sugiyama, Fujimoto+	(TOPAZ Collab.)
ABE	95N	PRL 74 3538	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ABE	95T	PRL 75 613	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ACCIARRI	95E	PL B350 109	+Adam, Adraiani, Aguilar-Benitez+	(L3 Collab.)
AKERS	95A	ZPHY C65 367	R. Akers+	(OPAL Collab.)
AKERS	95R	ZPHY C67 203	+Alexander, Allison, Ametewee, Anderson+	(OPAL Collab.)
BUSKULIC	95E	PL B349 238	+Casper, DeBonis, Decamp+	(ALEPH Collab.)
CLAVELLI	95	PR D51 1117	+Coulter	(ALAT)
FALK	95	PL B354 99	+Olive, Srednicki	(MINN, UCSB)
LOSECCO	95	PL B342 392		(NDAM)
AHMED	94B	ZPHY C64 545	+Aid, Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
AKERS	94K	PL B337 207	+Alexander, Allison, Anderson+	(OPAL Collab.)
BECK	94	PL B336 141	+Bensch, Bockholt+	(MPIH, KIAE, SASSO)
CAKIR	94	PR D50 3268	M.B. Cakir, G.R. Farrar	(RUTG)
FALK	94	PL B339 248	+Olive, Srednicki	(UCSB, MINN)
FRANKE	94	PL B336 415	+Fraas, Bartl	(WURZ, WIEN)
HOSODA	94	PL B331 211	+Abe, Amako, Arai+	(VENUS Collab.)
SHIRAI	94	PRL 72 3313	+Ohmoto, Abe, Amako+	(VENUS Collab.)
ACTON	93G	PL B313 333	+Akers, Alexander, Allison, Anderson+	(OPAL Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALITTI	93	NP B400 3	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
CLAVELLI	93	PR D47 1973	+Coulter, Yuan	(ALAT)
DREES	93	PR D47 376	+Nojiri	(DESY, SLAC)
FALK	93	PL B318 354	+Madden, Olive, Srednicki	(UCB, UCSB, MINN)
HEBBEKER	93	ZPHY C60 63		(CERN)
KELLEY	93	PR D47 2461	+Lopez, Nanopoulos, Pois, Yuan	(TAMU, ALAH)
LAU	93	PR D47 1087		(HOUS)
LOPEZ	93C	PL B313 241	+Nanopoulos, Wang	(TAMU, HARC, CERN)
MIZUTA	93	PL B298 120	+Yamaguchi	(TOHO)
MORI	93	PR D48 5505	+(KEK, NIIG, TOKY, TOKA, KOBE, OSAK, TINT, GIFU)	
ABE	92L	PRL 69 3439	+Amidei, Anway-Wiese, Apollinari, Atac+	(CDF Collab.)
BOTTINO	92	MPL A7 733	+DeAlfaro, Fornengo, Morales, Puimedon+	(TORI, ZARA)
Also	91	PL B265 57	Bottino, de Alfaro, Fornengo, Mignola+	(TORI, INFN)
CLAVELLI	92	PR D46 2112		(ALAT)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
ELLIS	92F	PL B283 252	+Roszkowski	(CERN)
KAWASAKI	92	PR D46 1634	+Mizuta	(OSU, TOHO)
LOPEZ	92	NP B370 445	+Nanopoulos, Yuan	(TAMU)
MCDONALD	92	PL B283 80	+Olive, Srednicki	(LISB, MINN, UCSB)
ROY	92	PL B283 270		(CERN)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
AKESSON	91	ZPHY C52 219	+Almehed, Angelis, Atherton, Aubry+	(HELIOS Collab.)
ALEXANDER	91F	ZPHY C52 175	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
ANTONIADIS	91	PL B262 109	+Ellis, Nanopoulos	(EPOL, CERN, TAMU, HARC)
BAER	91	PR D44 207	+Tata, Woodside	(FSU, HAWA, ISU)
BOTTINO	91	PL B265 57	+de Alfaro, Fornengo, Mignola+	(TORI, INFN)
GELMINI	91	NP B351 623	+Gondolo, Roulet	(UCLA, TRST)
HIDAKA	91	PR D44 927		(TGAK)
KAMIONKOW...	91	PR D44 3021	Kamionkowski	(CHIC, FNAL)
MORI	91B	PL B270 89	+Nojiri, Oyama, Suzuki+	(Kamiokande Collab.)
NOJIRI	91	PL B261 76		(KEK)
OLIVE	91	NP B355 208	+Srednicki	(MINN, UCSB)
ROSZKOWSKI	91	PL B262 59		(CERN)
SATO	91	PR D44 2220	+Hirata, Kajita, Kifune, Kihara+	(Kamioka Collab.)
ABREU	90F	PL B247 148	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90G	PL B247 157	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ADACHI	90C	PL B244 352	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
ADEVA	90I	PL B249 341	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
AKESSON	90B	PL B238 442	+Alitti, Ansari, Ansorge+	(UA2 Collab.)
AKRAWY	90D	PL B240 261	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90N	PL B248 211	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90O	PL B252 290	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALITTI	90	PL B235 363	+Ansari, Ansorge, Bagnaia, Bareyre+	(UA2 Collab.)
BAER	90	PR D41 3414	+Drees, Tata	(FSU, CERN, HAWA)
BARKLOW	90	PRL 64 2984	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)

DECAMP	90C	PL B236 86	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90K	PL B244 541	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ELLIS	90	PL B245 251	+Nanopoulos, Roszkowski, Schramm	(CERN, HARC, TAMU)
GRIEST	90	PR D41 3565	+Kamionkowski, Turner	(UCB, CHIC, FNAL)
GRIFOLS	90	NP B331 244	+Masso	(BARC)
KRAUSS	90	PRL 64 999		(YALE)
SAKAI	90	PL B234 534	+Gu, Low, Abe, Fujii+	(AMY Collab.)
SODERSTROM	90	PRL 64 2980	+McKenna, Abrams, Adolphsen, Averill+	(Mark II Collab.)
TAKETANI	90	PL B234 202	+Odaka, Abe, Amako+	(VENUS Collab.)
ZHUKOVSKII	90	SJNP 52 931	+Eminov	(MOSU)
		Translated from YAF 52 1473.		
ABE	89J	ZPHY C45 175	+Amako, Arai, Fukawa+	(VENUS Collab.)
ADACHI	89	PL B218 105	+Aihara, Dijkstra, Enomoto, Fujii+	(TOPAZ Collab.)
ADEVA	89B	PL B233 530	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
HEARTY	89	PR D39 3207	+Rothberg, Young, Johnson, Whitaker+	(ASP Collab.)
Also	87	PRL 58 1711	Hearty, Rothberg, Young, Johnson+	(ASP Collab.)
Also	86	PRL 56 685	Bartha, Burke, Extermann+	(ASP Collab.)
NAKAMURA	89	PR D39 1261	+Kobayashi, Konaka, Imai, Masaike+	(KYOT, TMTC)
OLIVE	89	PL B230 78	+Srednicki	(MINN, UCSB)
BEHREND	88B	PL B215 186	+Criegee, Dainton, Field+	(CELLO Collab.)
ELLIS	88B	PL B215 404	+Olive, Sarkar, Sciama	(CERN, MINN, RAL, CAMB)
NATH	88	PR D38 1479	+Arnowitt	(NEAS, TAMU)
OLIVE	88	PL B205 553	+Srednicki	(MINN, UCSB)
SREDNICKI	88	NP B310 693	+Watkins, Olive	(MINN, UCSB)
ALBAJAR	87D	PL B198 261	+Albrow, Allkofer+	(UA1 Collab.)
ANSARI	87D	PL B195 613	+Bagnaia, Banner+	(UA2 Collab.)
ARNOLD	87	PL B186 435	+Barth+	(BRUX, DUUC, LOUC, BARI, AICH, CERN+)
BEHREND	87B	ZPHY C35 181	+Buerger, Criegee, Dainton+	(CELLO Collab.)
NG	87	PL B188 138	+Olive, Srednicki	(MINN, UCSB)
TUTS	87	PL B186 233	+Franzini, Youssef, Zhao+	(CUSB Collab.)
ALBRECHT	86C	PL 167B 360	+Binder, Harder+	(ARGUS Collab.)
BADIER	86	ZPHY C31 21	+Bemporad, Boucrot, Callot+	(NA3 Collab.)
BARNETT	86	NP B267 625	+Haber, Kane	(LBL, UCSC, MICH)
FORD	86	PR D33 3472	+Qi, Read+	(MAC Collab.)
GAISSER	86	PR D34 2206	+Steigman, Tilav	(BART, DELA)
VOLOSHIN	86	SJNP 43 495	+Okun	(ITEP)
		Translated from YAF 43 779.		
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
Also	84C	PRPL 109 131	Adeva, Barber, Becker+	(Mark-J Collab.)
AKERLOF	85	PL 156B 271	+Bonvicini, Chapman, Errede+	(HRS Collab.)
BARTEL	85L	PL 155B 288	+Becker, Cords, Felst, Hagiwara+	(JADE Collab.)
BEHREND	85	PL 161B 182	+Burger, Criegee, Fenner+	(CELLO Collab.)
COOPER-...	85B	PL 160B 212	Cooper-Sarkar, Parker, Sarkar+	(WA66 Collab.)
DAWSON	85	PR D31 1581	+Eichten, Quigg	(LBL, FNAL)
FARRAR	85	PRL 55 895		(RUTG)
GOLDMAN	85	Physica 15D 181	+Haber	(LANL, UCSC)
HABER	85	PRPL 117 75	+Kane	(UCSC, MICH)
ADEVA	84B	PRL 53 1806	+Barber, Becker, Berdugo+	(Mark-J Collab.)
BALL	84	PRL 53 1314	+Coffin, Gustafson+	(MICH, FIRZ, OSU, FNAL, WISC)
BARBER	84B	PL 139B 427	+Shrock	(STON)
BARTEL	84B	PL 139B 327	+Becker, Bowdery, Cords+	(JADE Collab.)
BARTEL	84C	PL 146B 126	+Becker, Bowdery, Cords+	(JADE Collab.)
BRICK	84	PR D30 1134	+	(BROW, CAVE, IIT, IND, MIT, MONS, NIJM+)
ELLIS	84	NP B238 453	+Hagelin, Nanopoulos, Olive, Srednicki	(CERN)
FARRAR	84	PRL 53 1029		(RUTG)
BEHREND	83	PL 123B 127	+Chen, Fenner, Gumpel+	(CELLO Collab.)
BERGSMA	83C	PL 121B 429	+Dorenbosch, Jonker+	(CHARM Collab.)
CHANOWITZ	83	PL 126B 225	+Sharpe	(UCB, LBL)
GOLDBERG	83	PRL 50 1419		(NEAS)
HOFFMAN	83	PR D28 660	+Frank, Mischke, Moir, Schardt	(LANL, ARZS)
KRAUSS	83	NP B227 556		(HARV)
VYSOTSKII	83	SJNP 37 948		(ITEP)
		Translated from YAF 37 1597.		
KANE	82	PL 112B 227	+Leveille	(MICH)
CABIBBO	81	PL 105B 155	+Farrar, Maiani	(ROMA, RUTG)
FARRAR	78	PL 76B 575	+Fayet	(CIT)
Also	78B	PL 79B 442	Farrar, Fayet	(CIT)