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SUPERSYMMETRY AT VERY HIGH ENERGIES*

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Abstract

I summarize the case for new physics at the TeV scale, and review basic elements of the supersymmetry option. Constraints on the spectrum of superpartners are recorded, and the signatures for the strongly interacting superpartners are listed. I then discuss prospects and detection requirements for superparticle searches in $p^{\pm}p$ collisions.

1 Introduction

The standard model is incomplete[1]; it does not explain how the scale of electroweak symmetry breaking is maintained in the presence of quantum corrections. The problem of the scalar sector can be summarized neatly as follows.[2] The Higgs potential of the $SU(2)_L \otimes U(1)_Y$ electroweak theory is

$$V(\phi^+\phi) = \mu_0^2\phi^+\phi + |\lambda|(\phi^+\phi)^2 \ . \tag{1}$$

With μ_0^2 chosen less than zero, the electroweak symmetry is spontaneously broken down to the $U(1)$ of electromagnetism, as the scalar field acquires a vacuum expectation value fixed by the low energy phenomenology,

$$<\phi>=\sqrt{-\mu_0^2/2|\lambda|} \equiv (G_F\sqrt{8})^{-1/2} \approx 175 \text{ GeV} \ . \tag{2}$$

Beyond the classical approximation, scalar mass parameters receive quantum corrections involving loops containing particles of spins $J = 1, 1/2$, and 0:

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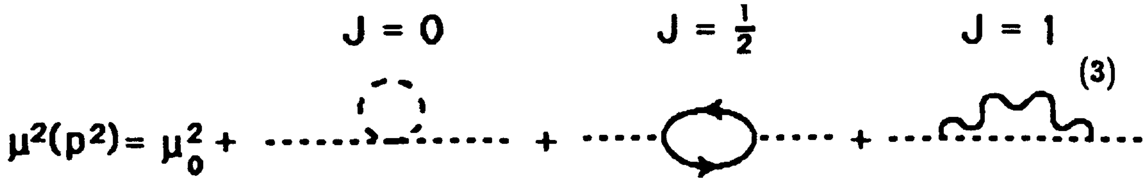

The loop integrals are potentially divergent. Symbolically, we may summarize the content of Eq. (3) as

$$\mu^2(p^2) = \mu^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots , \tag{4}$$

where Λ defines a reference scale at which the value of μ^2 is known, g is the coupling constant of the theory, and C is a constant of proportionality, calculable in any particular theory. Instead of dealing with the relationship between observables and parameters of the Lagrangian, we choose to describe the variation of an observable with the momentum scale. In order for the mass shifts induced by radiative corrections to remain under control (*i.e.*, not to greatly exceed the value measured on the laboratory scale), either

- Λ must be small, so the range of integration is not enormous; or
- new physics must intervene to cut off the integral.

In the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model, the natural reference scale is the Planck mass,

$$\Lambda \sim M_{Planck} \approx 10^{19}\ \text{GeV} . \tag{5}$$

In a unified theory of the strong, weak, and electromagnetic interactions, the natural scale is the unification scale

$$\Lambda \sim M_U \approx 10^{15}\ \text{GeV} . \tag{6}$$

Both estimates are very large compared to the scale of electroweak symmetry breaking (2). We are therefore assured that new physics must intervene at an energy of approximately 1 TeV, in order that the shifts in μ^2 not be much larger than (2).

Only a few distinct classes of scenarios for controlling the contribution of the integral in (4) can be envisaged. The supersymmetric solution is especially elegant. Exploiting the fact that fermion loops contribute with an overall minus sign (because of Fermi statistics), supersymmetry balances the contributions of fermion and boson loops. In the limit of unbroken supersymmetry, in which the masses of bosons are degenerate with those of their fermion counterparts, the cancellation is exact:

$$\sum_{\substack{i=fermions\\+bosons}} C_i \int dk^2 = 0 \,. \tag{7}$$

If the supersymmetry is broken (as it must be in our world), the contribution of the integrals may still be acceptably small if the fermion-boson mass splittings ΔM are not too large. The condition that $g^2 \Delta M^2$ be "small enough" leads to the requirement[3] that superpartner masses be less than about 1 TeV/c^2.

In addition to stability problem for the scalar sector, there is other unfinished business of the standard model. Among the important issues, let us mention

- The arbitrariness of Higgs and fermion representations;
- The multiplicity of apparently free parameters required to specify the model: more than 18 for $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$, and a similar count for unified theories such as $SU(5)$;
- The omission of gravitation, and the absence of a quantum theory of gravitation.

The possibility that supersymmetry, in the setting of superstring theories, might respond to these objections is discussed in the talk by David Gross[4] at this meeting.

2 What is Supersymmetry?[5]

In relativistic quantum field theory, continuous symmetries of the S-matrix normally are based on Lie algebras. A familiar example is the $SU(2)$ symmetry of isospin, generated by the algebra

$$[T^j, T^k] = i\varepsilon^{jkl} T_l \; , \tag{8}$$

where ε^{jkl} is the antisymmetric three-index symbol. The most general form[6] of symmetries of the S-matrix is the combination of Poincaré invariance plus internal symmetries. The space-time symmetries are generated by the momentum operator P^μ, the generator of translations, and by $M^{\mu\nu}$, the generator of Lorentz boosts and rotations. This leads to the familiar classification of particles by mass and spin. Internal symmetries are generated by the generators of the symmetry group G, which we denote generically as X_a. These objects commute with the generators of space-time symmetries,

$$\left.\begin{aligned} [X_a, P^\mu] &= 0 \\ [X_a, M^{\mu\nu}] &= 0 \end{aligned}\right\} \; , \tag{9}$$

and with the Hamiltonian $\mathcal{H}$ of the world,

$$[X_a, \mathcal{H}] = 0 \; , \tag{10}$$

so we may simultaneously specify internal quantum numbers along with masses and spins. This leads to the useful classification of particles by representations of the symmetry group G. Examples of internal symmetries are global symmetries such as the flavor symmetries and the $U(1)$ symmetry associated with baryon number conservation, and the local (gauged) symmetries such as $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.

The notion of Lie algebras may be generalized to the *graded Lie algebras* defined by both commutators and anticommutators:

$$\left.\begin{aligned} [X, X'] &\sim X'' \\ \{Q, Q'\} &\sim X \\ [Q, X] &\sim Q'' \end{aligned}\right\} . \qquad (11)$$

The generators of the graded Lie algebras are of two kinds. The scalar charges X_a make up the odd part of the algebra, while the spinorial charges Q_a make up the even part. Among the graded Lie algebras, the only ones consistent with relativistic quantum field theory are the supersymmetry algebras,[7] in simplest form

$$\left.\begin{aligned} \{Q_a, \bar{Q}^b\} &\sim \delta_a^b \gamma \cdot P \\ \{Q, Q\} &= 0 = \{\bar{Q}, \bar{Q}\} \\ [P, Q] &= 0 = [P, \bar{Q}] \end{aligned}\right\} , \qquad (12)$$

where $\bar{Q}$ is the Hermitian conjugate of Q, a and b are internal symmetry labels, and P is a momentum 4-vector.

A particle is transformed by a scalar charge into a partner with the same mass and spin. An example is the action of T_i, which generates isospin rotations about the i–axis. A particle is transformed by a spinorial charge into a superpartner whose spin differs by $1/2$ unit, but otherwise has identical quantum numbers. Thus arises a connection between fermions and bosons.

In a supersymmetric theory, particles fall into multiplets which are representations of the supersymmetry algebra. Superpartners share all quantum numbers except spin; if the supersymmetry is unbroken, they are degenerate in mass. The number of fermion states (counted as degrees of freedom) is identical with the number of boson states. In nearly all supersymmetric theories, the superpartners carry a new fermionic quantum number R which is exactly conserved. This means that the lightest superpartner will be absolutely stable. In Table 1 we list the fundamental fields of the standard model and their superpartners. By examining the quantum numbers of known particles, we readily see that there are no candidates for supersymmetric pairs among them. Supersymmetry therefore means doubling the particle spectrum, compared with the standard model. In fact, we must expand the spectrum slightly further, because the minimal supersymmetric extension of the standard model requires at least two doublets of Higgs bosons.[8] The interactions among old and new particles are prescribed by the supersymmetric extension of the usual interaction Lagrangian, which we shall take to be the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ theory. If supersymmetry is an invariance of the Lagrangian, it is evidently a broken symmetry, because observationally boson masses are not equal to the masses of their fermion counterparts. For supersymmetry to resolve the hierarchy problem, we have seen in §1 that it must be effectively unbroken above the electroweak scale of $O(1\ \text{TeV})$. This suggests that superpartner masses will themselves be $\lesssim 1\ \text{TeV}/c^2$.

There is no convincing theory for masses of the superpartners. (This is not worse than the situation for the masses of the usual fermions or scalars.) As for the ordinary particles, however, we can derive relations among superparticle masses, and infer restrictions on the masses. Three kinds of indirect methods yield interesting relations:

Table 1: Fundamental Fields of the Standard Model and their Superpartners

Particle	Spin	Color	Charge
g gluon	1	8	0
$\tilde{g}$ gluino	1/2	8	0
γ photon	1	0	0
$\tilde{\gamma}$ photino	1/2	0	0
$W^{\pm}, Z^0$ intermediate bosons	1	0	$\pm 1,0$
$\tilde{W}^{\pm}, \tilde{Z}^0$ wino and zino	1/2	0	$\pm 1,0$
q quark	1/2	3	2/3, -1/3
$\tilde{q}$ squark	0	3	2/3, -1/3
e electron	1/2	0	-1
$\tilde{e}$ selectron	0	0	-1
ν neutrino	1/2	0	0
$\tilde{\nu}$ sneutrino	0	0	0
$H^+ \;\; H'^0$ $H^0 \;\; H'^-$ Higgs bosons	0	0	$\pm 1,0$
$\tilde{H}^+ \;\; \tilde{H}'^0$ $\tilde{H}^0 \;\; \tilde{H}'^-$ Higgsinos	1/2	0	$\pm 1,0$

- The role of virtual superpartners in rare processes. An example within the standard model is the limit on the $m_c - m_u$ mass splitting inferred from the magnitude of the $K^0 - \overline{K}^0$ transition amplitude.

- Cosmological constraints. A standard model example is the bound on the sum of light neutrino masses inferred from the limits on the mass density of the Universe.

- The distortion of standard model predictions. A conventional example is the bound on the number of light neutrino species inferred from the total width of the Z^0.

It is instructive to consider one example of each of these approaches.

Barbieri and collaborators[9] have studied the deviations from quark–lepton universality in charged-current weak interactions that would arise from the exchange of superpartners. In lowest contributing order, corrections to the muon decay rate are due to diagrams containing sleptons and gauginos, whereas corrections to the β–decay rate are due to diagrams containing squarks and gauginos. The requirement that the Fermi constant inferred from β–decay agree with that determined from muon decay within experimental errors, so that

$$\left|\frac{\delta G^\beta}{G^\beta} - \frac{\delta G^\mu}{G^\mu}\right| < 2 \times 10^{-3} , \tag{13}$$

then leads to constraints on the squark-slepton mass difference. These are quite restrictive if the wino mass is small ($\lesssim M_W/2$). If the wino mass is comparable to the W-boson mass, this calculation suggests that deviations from universality are to be found just inside the present experimental limits.

Constraints on the mass of a stable photino may be derived from the observed mass density of the Universe using methods[10] developed to bound the masses of stable neutrinos. If the photino is light, it is straightforward to compare the contribution of photinos to the mass density of a 2.7–K Universe,

$$\rho_{\tilde{\gamma}} \approx 109 \, m_{\tilde{\gamma}} \, \mathrm{cm}^{-3} \tag{14}$$

with the critical (closure) density

$$\rho_{crit} = (3.2 - 10.3)(\mathrm{keV}/c^2)\mathrm{cm}^{-3} \tag{15}$$

(a reasonable upper bound on the observed density), to find

$$m_{\tilde{\gamma}} \lesssim 100 \, \mathrm{eV}/c^2 \, . \tag{16}$$

When the photino mass exceeds about 1 MeV/c^2, it is necessary to take into account the annihilation of photinos into light fermions by the exchange of a scalar partner of the fermions. The results of this analysis[11] yield a lower bound on the mass of a "heavy" photino, which is shown together with (16) in Fig. 1.

Gauge boson decays may within a few years provide useful sources of superpartners. The principal decays and the anticipated rates at existing and future colliders are given in Table 2. These have interesting consequences for

- Direct searches, e.g.

$$\begin{array}{lcl} W & \rightarrow & \tilde{e}\tilde{\nu} \\ & & \hookrightarrow e\tilde{\gamma} \end{array} \tag{17}$$

- The widths of W and Z;

- Distortion of the ratio

$$R \equiv \frac{\sigma(\bar{p}p \rightarrow W^{\pm} + \mathrm{anything}) B(W \rightarrow e\nu)}{\sigma(\bar{p}p \rightarrow Z^0 + \mathrm{anything}) B(Z^0 \rightarrow e^+e^-)} \, . \tag{18}$$

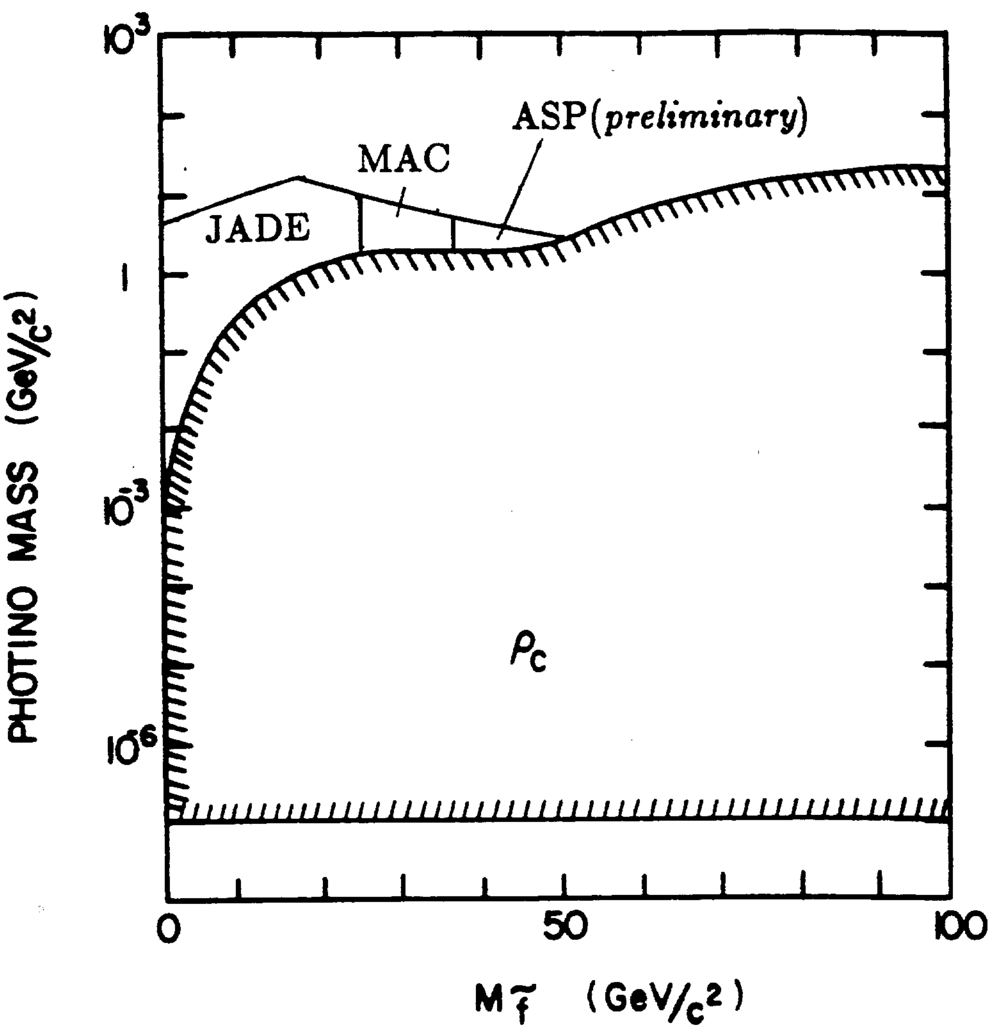

Figure 1: Cosmological limits on the allowed photino mass as a function of the mass of the lightest scalar partner of a charged fermion. The photino is assumed to be stable, and the lightest superparticle. Shown for comparison are the limits from three accelerator experiments (Refs. 12–14).

Table 2: Gauge Boson Decays as Sources of Superpartners

$W^{\pm}$		Z^0
	Decay Modes	
$\tilde{\omega}_i\tilde{\gamma}$		$\tilde{\omega}_i^+\tilde{\omega}_j^-$
$\tilde{\omega}_i\tilde{Z}^0$		$\tilde{Z}\tilde{H}$
$\tilde{\omega}_i\tilde{H}^0$		$\tilde{q}\tilde{q}^*$
$\tilde{q}\tilde{q}'^*$		$\tilde{\ell}^+\tilde{\ell}^-$
$\tilde{\ell}\tilde{\nu}$		$\tilde{\nu}\tilde{\nu}^*$
	Production per year	
$10^4 - 10^5$	$\bar{p}p$ colliders	$3\times10^3 - 3\times10^4$
—	SLC	3×10^5
—	LEP	3×10^6
2×10^9	SSC	5×10^8

We denote by $\tilde{\omega}_i$ the mass eigenstates resulting from $\tilde{W}-\tilde{H}$ mixing. Mixing among both charged and neutral gauginos and higgsinos is treated in detail in Ref. 17.

The last of these has been analyzed recently by Deshpande, et al.[15] QCD corrections to the "Drell-Yan" production cross sections are believed to cancel to good approximation in the ratio, so that knowledge of the proton structure functions implies a prediction of R which depends upon the branching ratios for leptonic decay. The ratio grows as the number of light neutrino species is increased, or as generations of superpartners are added. Typical expectations are shown in Fig. 2. The experimental results reported[16] at the Kyoto conference,

$$R = \begin{cases} 8.47 \pm 2.08 & [\mathrm{UA}-1] \\ 7.35 {+1.78 \atop -2.16} & [\mathrm{UA}-2] \end{cases} \tag{19}$$

must still be regarded as provisional, because of the limited statistics on Z^0-production. One can already see that interesting limits on the number of light neutrino species and useful constraints on the superpartner spectrum will soon emerge.

We have already noted that there is no convincing theory for the masses of superpartners. Indeed, even the *ordering* of superpartner masses is quite model dependent. What this means for direct searches is that one must consider all reasonable possibilities. In practice, this entails

- Searching for all superpartners;
- Considering all plausible decay modes of each one;
- Making use of existing experimental constraints.

As an example of direct searches, let us consider the limits on selectron and photino masses derived from e^+e^- collisions. We distinguish the cases of stable and unstable selectrons, corresponding to

$$m_{\tilde{e}} \lesseqgtr m_{\tilde{\gamma}} + m_e \, . \tag{20}$$

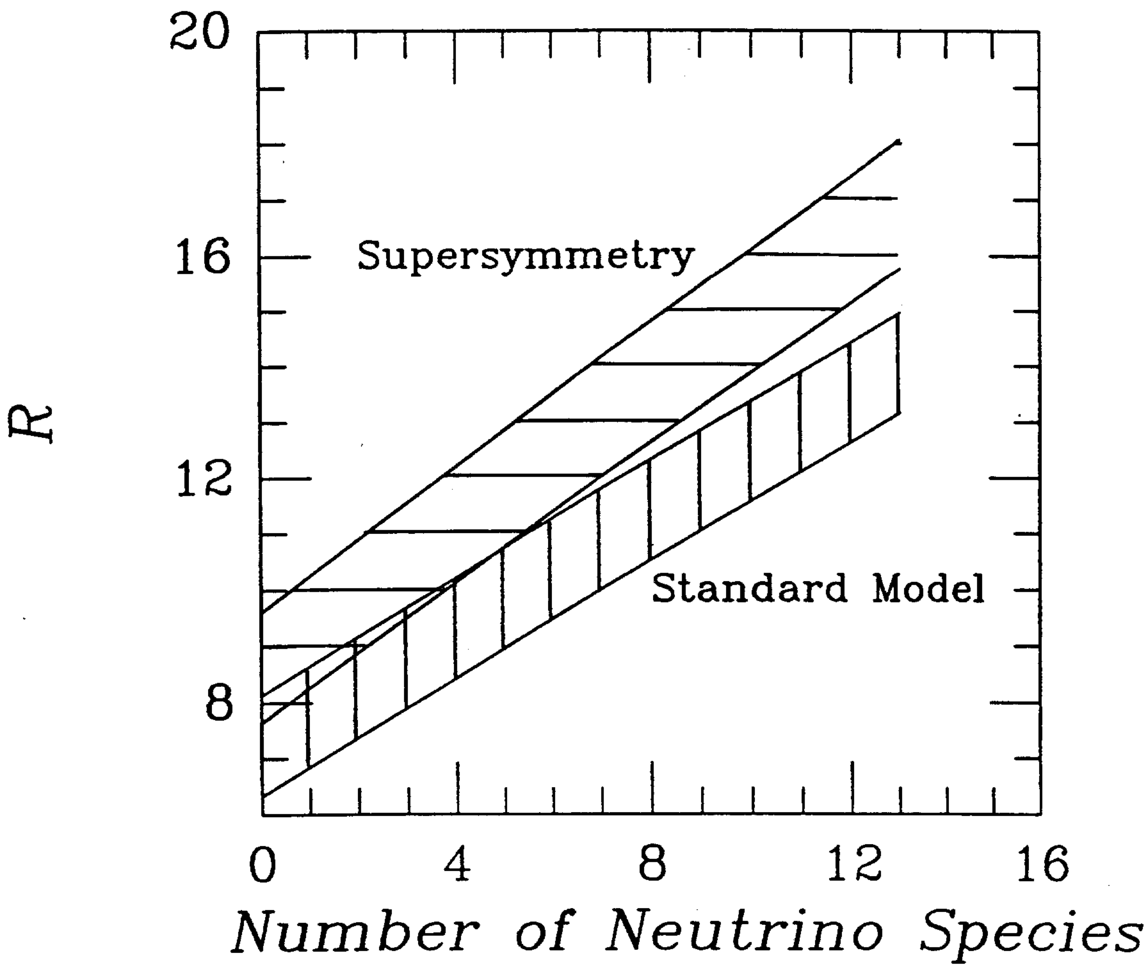

Figure 2: The ratio R defined in eqn. (18) versus the number of light neutrino species (after Deshpande, et al., Ref. 15). The upper band gives the result for a supersymmetry model, with parameters chosen to maximize the effect. The lower band shows the result for the standard model. I have enlarged the uncertainties to better reflect ambiguities in the structure functions.

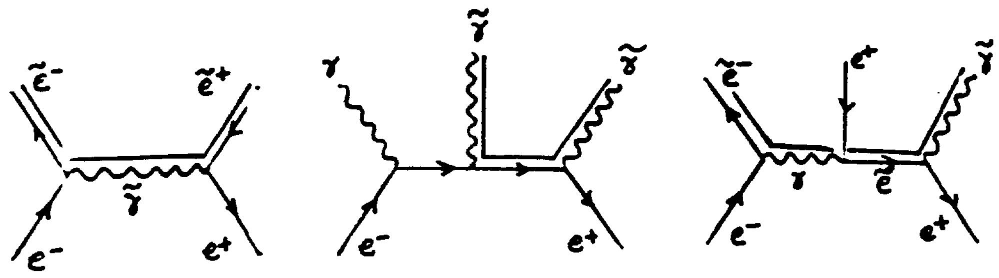

Figure 3: Representative Feynman graphs for the processes used to limit the photino and selectron masses.

If the selectron is stable, a search for stable charged particles produced in

$$e^+e^- \to \tilde{e}^+\tilde{e}^- \tag{21}$$

is appropriate. If the selectron is unstable but the photino is stable, there are two distinct possibilities:

$$\begin{array}{lll} e^+e^- & \to & \tilde{e}^+\ \tilde{e}^- \\ & & \ \ \ \ \ \ \hookrightarrow e^-\tilde{\gamma} \\ & & \hookrightarrow e^+\tilde{\gamma} \end{array} \tag{22}$$

and

$$e^+e^- \to e\tilde{e}\tilde{\gamma}. \tag{23}$$

Whether or not the selectron is unstable, it can mediate the reaction

$$e^+e^- \to \gamma\tilde{\gamma}\tilde{\gamma}. \tag{24}$$

Examples of the Feynman graphs leading to all of these final states are shown in Fig. 3. The limits derived from searches for reactions (21)–(24) are displayed in Fig. 4. If the photino is very light, the lower bound on the mass of the selectron is impressively large: $\approx 50\ \mathrm{GeV}/c^2$. On this compressed scale, the cosmological constraints appear less imposing than in Fig. 1.

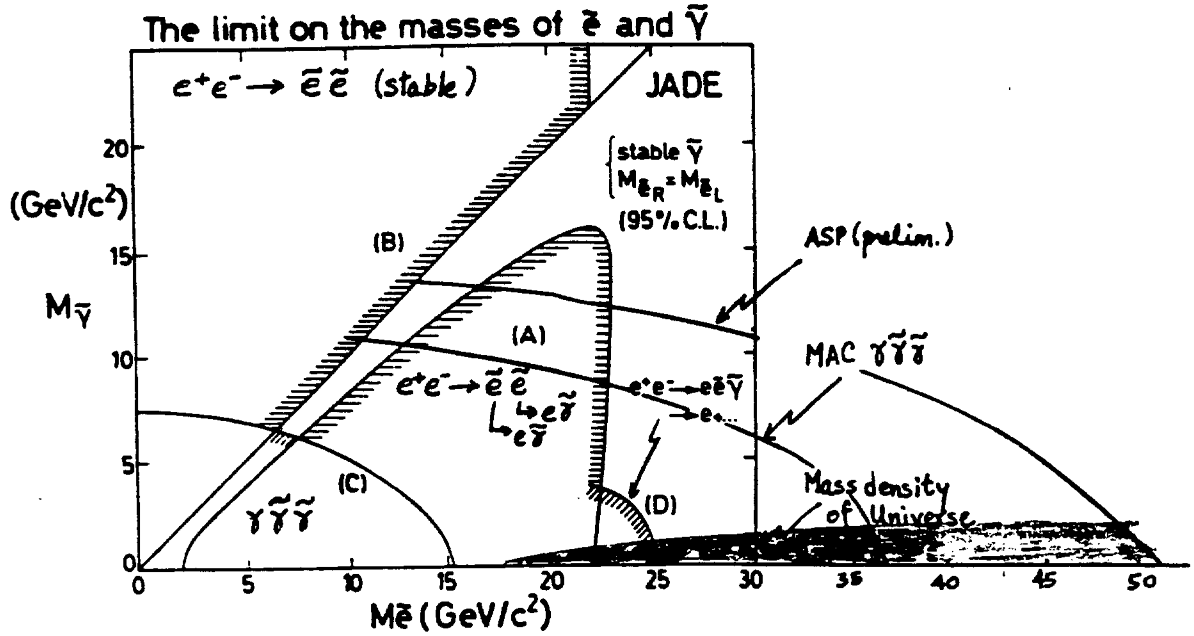

Figure 4: Limits [refs. 12–14] on the allowed masses of photinos and selectrons, from studies of e^+e^- interactions. The photino is assumed to be stable and noninteracting, and the masses of "left-handed" and "right-handed" selectrons are assumed equal. Shown for comparison are the bounds from the mass density of the Universe.

It is generally expected that the photino $\tilde{\gamma}$ is the lightest superpartner, and hence is stable. If global supersymmetry is spontaneously broken, the theory acquires a massless Goldstone *fermion*, the Goldstino $\tilde{\mathcal{G}}$. Decays of the form

$$\tilde{\gamma} \rightarrow \gamma \tilde{\mathcal{G}} \tag{25}$$

are then allowed. In supergravity theories, based upon spontaneously broken *local* supersymmetry, the Goldstino becomes the helicity $\pm 1/2$ components of the massive, spin-3/2 gravitino, and is not available as a decay product of a light photino. The other popular candidate for the lightest superpartner is the *sneutrino*, $\tilde{\nu}$. Any of these candidates is a weakly interacting neutral particle, which will result in undetected energy. Although it is important to consider all possibilities systematically, we shall assume for most of today's discussion that the lightest superpartner is the photino.

The strongly interacting superparticles are of particular interest because they are produced at substantial rates in hadron-hadron collisions. Possible decay chains and signatures for squarks and gluinos are indicated in Fig. 5. For each unstable strongly interacting superpartner produced, we expect one, two, or three jets, accompanied by missing energy.

Before we turn to our main subject, the search for supersymmetry at high energies, it will be useful to have in mind a rough summary of the limits on masses of superpartners as they stand before the analysis of data from the $S\bar{p}pS$ collider. I caution that every entry hangs on assumptions about decay chains, *etc.*, and that few categorical statements are reliable. For thorough discussions of the limits, see the papers by Haber and Kane, and by Dawson, *et al.*, in Ref. 5. An abbreviated statement of existing limits is given in Table 3.

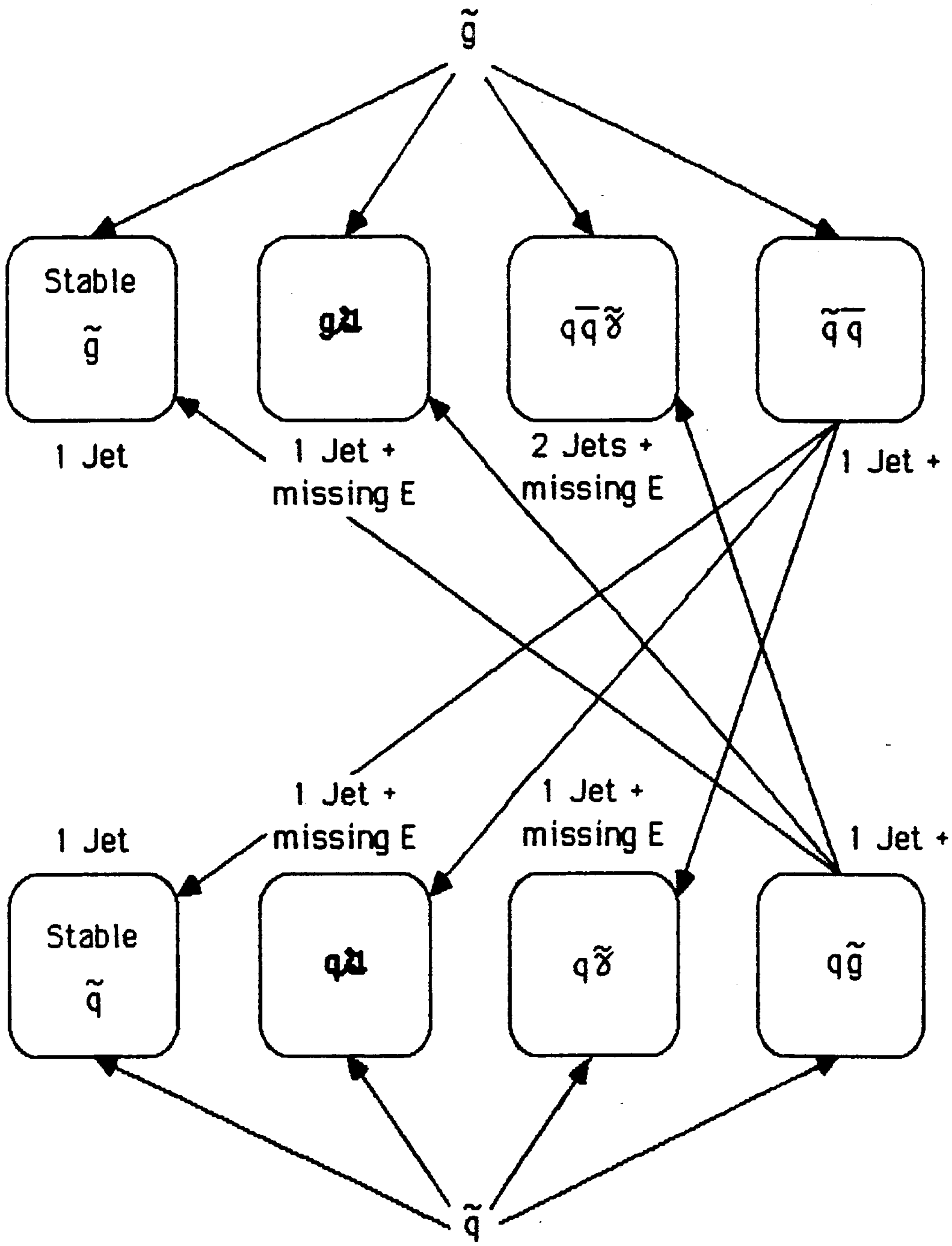

Figure 5: Signatures of the strongly interacting superpartners.

Table 3: Limits on the Masses of Superpartners

Particle	Limit
$\tilde{\gamma}$	could be as light as a few GeV/c^2, or massless
$\tilde{g}$	could be as light as a few GeV/c^2
$\tilde{W}$	$\gtrsim$ 25 GeV/c^2 for massless $\tilde{\gamma}$ and $\tilde{\nu}$
$\tilde{Z}$	$>$ 41 GeV/c^2 for massless $\tilde{\gamma}$ and $M(e) = 22$ GeV/c^2 (but see Fig. 4)
$\tilde{q}$	if stable: $>$ 14 GeV/c^2; if unstable (and photino is massless): $>$ 17.8 GeV/c^2 for $e_{\tilde{q}} = 2/3$; 3 GeV/$c^2 \lesssim M \lesssim 7.4$ GeV/c^2 or $\gtrsim$ 16 GeV/c^2 for $e_{\tilde{q}} = -1/3$
$\tilde{\ell}^{\pm}$	$\gtrsim$ 20 GeV/c^2

3 Superparticle Searches in $p^{\pm}p$ Collisions

Over the past few years, a great deal of effort has gone into estimating production rates for superpartners. Sally Dawson, Estia Eichten, and I[17] have evaluated all the lowest–order (Born diagram) cross sections $d\hat{\sigma}/d\hat{t}$ and $\hat{\sigma}$ for the production of

$$(\tilde{q}, \tilde{\ell}^{\pm}, \tilde{\nu}, \tilde{g}, \tilde{\gamma}, \tilde{Z}^0, \tilde{H}^0, \tilde{H}^{0\prime}, \tilde{W}^{\pm}, \tilde{H}^{\pm})^2 \tag{26}$$

final states in parton–parton collisions, including the possibility of mixing among $(\tilde{\gamma}, \tilde{Z}, \tilde{H}^0, \tilde{H}^{0\prime})$ or $(\tilde{W}^{\pm}, \tilde{H}^{\pm})$. We have also calculated the processes initiated by e^+e^- collisions. Many of these reactions have been studied by others as well; complete references are given in Ref. 17. The approximate magnitudes of the cross sections are indicated in Table 4.

We have studied the implications of these elementary cross sections for $p^{\pm}p$

Table 4: Hierarchy of Superpartner Production Rates

Final States	Mechanism	Magnitude
$(\tilde{g},\tilde{q})^2$	QCD	α_s^2
$(\tilde{g},\tilde{q})\cdot(\tilde{\gamma},\tilde{Z}^0,\tilde{H}^0,\tilde{H}'^0,\tilde{W}^\pm,\tilde{H}^\pm)$	electroweak/QCD	$\alpha\cdot\alpha_s$
$\tilde{\ell}\tilde{\nu},\tilde{\ell}\tilde{\ell}^*,\tilde{\nu}\tilde{\nu}^*$	{ decay of $W^\pm,Z^0$ virtual $W^\pm,Z^0$	α α^2
$(\tilde{\gamma},\tilde{Z}^0,\tilde{H}^0,\tilde{H}'^0,\tilde{W}^\pm,\tilde{H}^\pm)^2$	electroweak	α^2

collisions using standard models of the QCD-improved parton model and the *EHLQ* structure functions.[1] I will show example calculations for three representative spectra:

- *Spectrum 1:* $M(\tilde{\gamma}) = 10^{-7}$ GeV/c^2, $M(\tilde{g}) = 3$ GeV/c^2, $M(\tilde{q}) = M(\tilde{W}) = M(\tilde{Z}) = M(\tilde{\ell}) = 20$ GeV/c^2;
- *Spectrum 2:* all masses = 50 GeV/c^2;
- *Spectrum 3:* all masses = 100 GeV/c^2.

It is worth remarking that the squark and gluino production rates depend mainly on the masses of the produced (not exchanged) superparticles, so that one may hope to obtain "model-independent" limits on $\tilde{g}$ and $\tilde{q}$ masses from experiments at hadron colliders. For gluino pair production, the three diagrams shown in Fig. 6(a)–(c) depend only on the gluino mass. The squark-exchange graph of Fig. 6(d) depends on the squark mass as well, but is numerically unimportant in most circumstances. The situation is similar for squark pair production, and necessarily the cross section for associated squark–gluino production depends

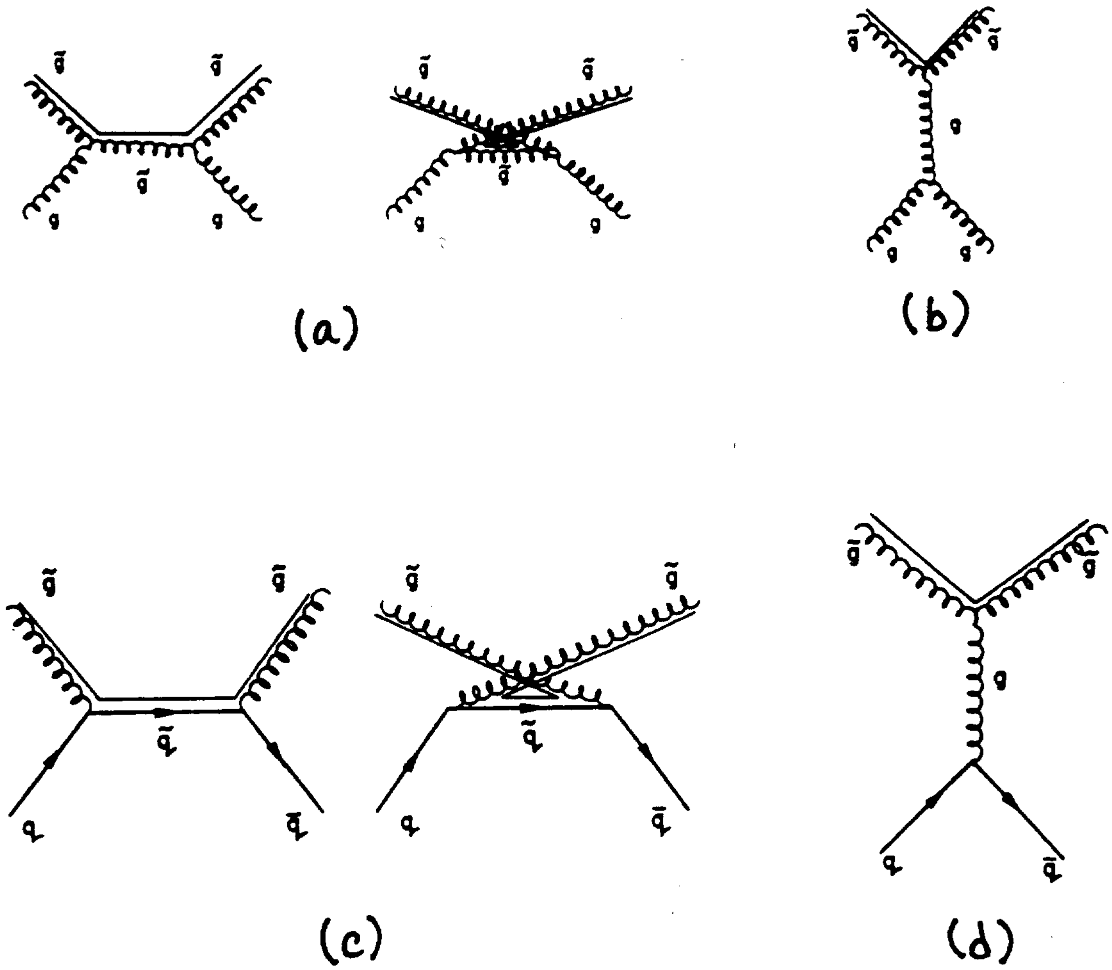

Figure 6: Feynman diagrams for gluino production in gluon-gluon (a,b) and quark-antiquark (c,d) collisions.

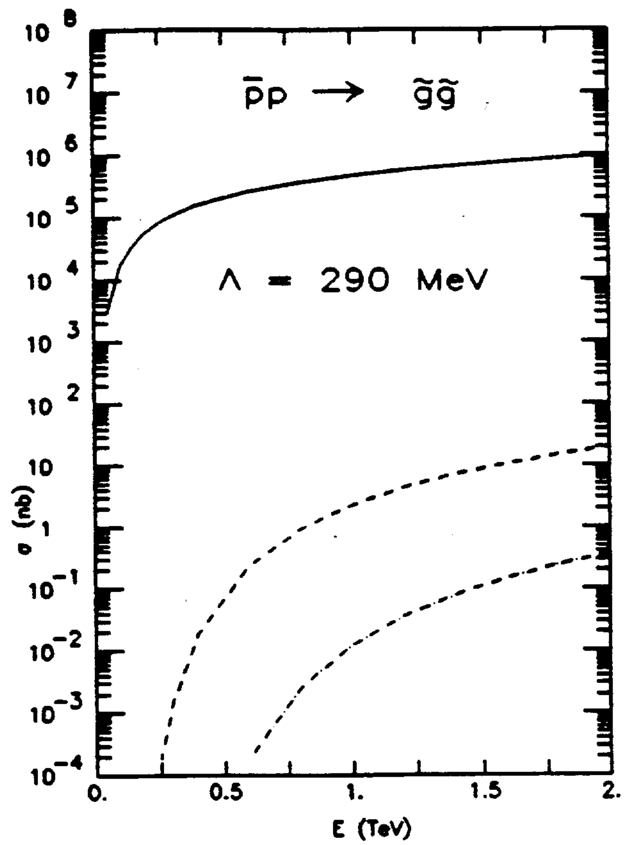

Figure 7: Total cross sections for the reaction $\bar{p}p \to \tilde{g}\tilde{g}$ + anything for the three superparticle mass spectra described in the text. This corrects a plotting error in Fig. 33 of Ref. 17.

only on the squark and gluino masses.

The cross sections for the production of gluino pairs in $\bar{p}p$ collisions are shown in Fig. 7. Gluino pair production has the largest cross section among the processes we have considered. If the gluino is light on the scale set by the $\bar{p}p$ collider energy $\sqrt{s}$, an additional production mechanism may become significant or even dominant: the reaction

$$\begin{array}{rcl}\bar{p}p & \to & gg + \text{anything} \\ & & \hookrightarrow \tilde{g}\tilde{g}\end{array} \tag{27}$$

Because the $gg \to gg$ cross section is so large, the branching of a gluon into gluino pairs may still leave a substantial rate.[18] We shall return shortly to the detectability of gluino pairs.

An interesting comment on the light–gluino possibility has been made by Robinett.[19] He notes that ultrahigh–energy ($\sim 10^{15}$ eV) cosmic rays imply c.m. energies of $\sqrt{s} \gtrsim 1$ TeV, at which cross sections for the production of light gluinos are large, approaching 1 mb. The decay of these gluinos leads to fluxes of weakly interacting neutrals (photinos or sneutrinos) which are comparable to the flux of cosmic neutrinos. The rates of the secondary interactions of $\tilde{\gamma}$ or $\tilde{\nu}$ may then be observably large in the high–volume detectors dedicated to the search for proton decay, or in cosmic ray detectors such as the Fly's Eye. This is a useful reminder that if the gluino is light, indications should be all around us.

If the gluino or (less likely) the squarks should be light, it may be practical to sacrifice some production cross section in the interest of a characteristic topology, by searching for the production of a photino in association with a strongly interacting superpartner. Some example cross sections are shown in Figs. 8 and 9. In Fig. 8 we display the energy dependence of the cross sections for the reaction

$$\bar{p}p \rightarrow \tilde{\gamma}\tilde{g} + \text{anything} \tag{28}$$

for Spectra 1–3. The dependence on squark mass of the cross section for the reaction

$$\bar{p}p \rightarrow \tilde{\gamma}\tilde{q} + \text{anything} \tag{29}$$

is shown in Fig. 9 for $\sqrt{s} = 540$ GeV and 2 TeV.

From Fig. 5, we see that the event topology will consist of 1, 2, or 3 jets on one side of the beam direction, and nothing (which is to say the undetected

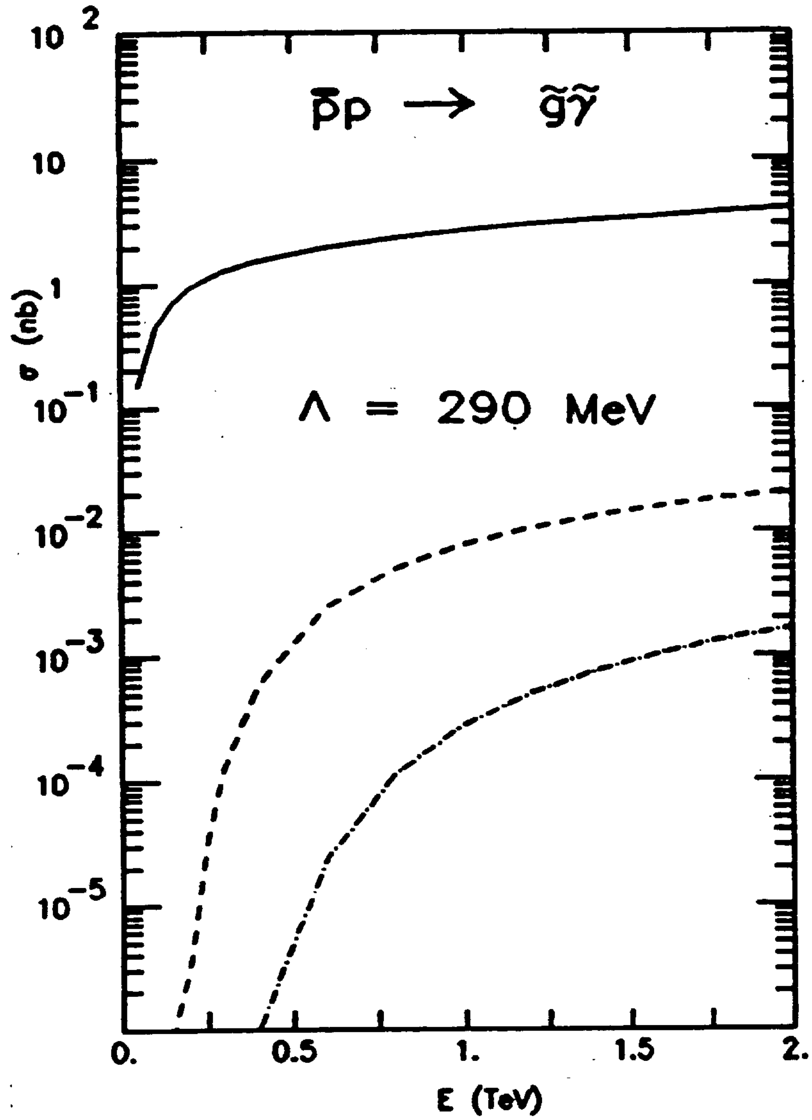

Figure 8: Total cross sections for the reaction $\bar{p}p \to \tilde{\gamma}\tilde{g}$ + anything for the three superparticle mass spectra described in the text (from Ref. 17).

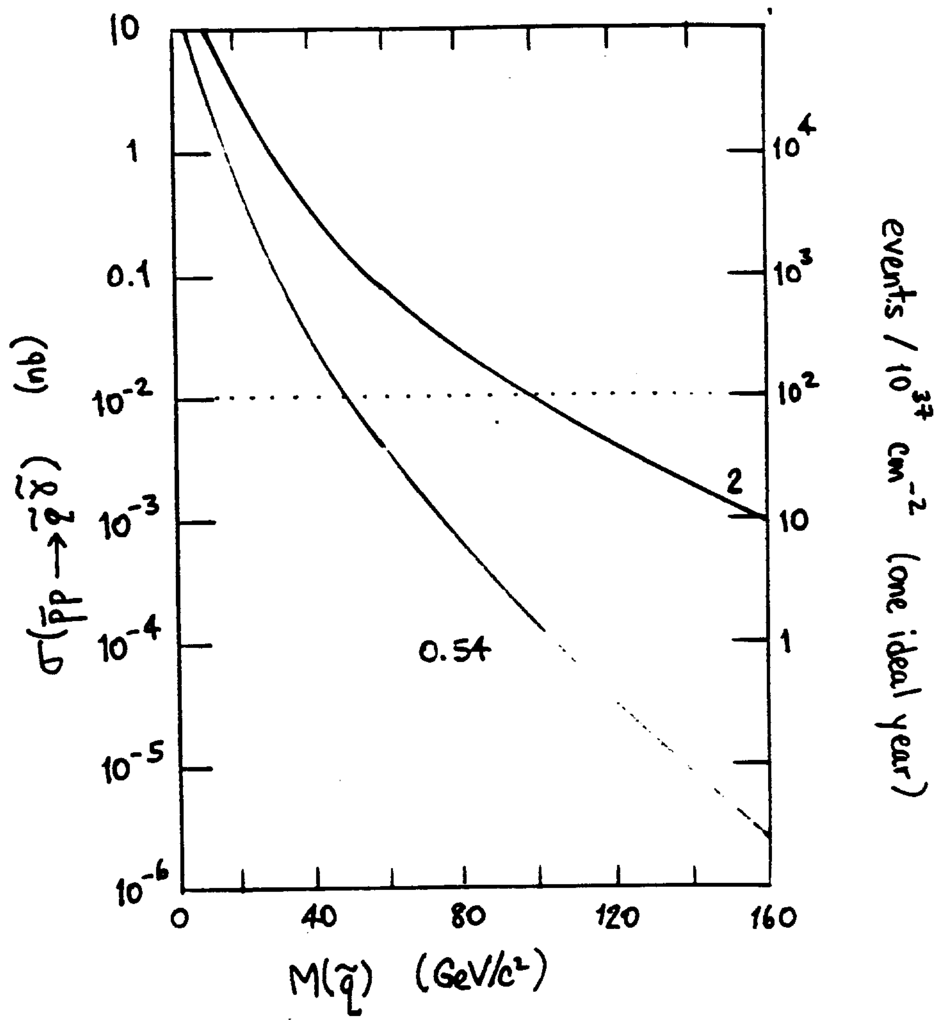

Figure 9: Total cross sections for the reaction $\bar{p}p \rightarrow \tilde{\gamma}\tilde{q}$ + anything at $\sqrt{s}$ = 540 GeV and 2 TeV (from Ref. 20).

photino) on the other side. The only significant standard model background should be from

$$\bar{p}p \;\rightarrow\; Z^0 + \text{jets} \qquad (30)$$
$$\hookrightarrow \nu\bar{\nu}$$

which can be calibrated using $Z^0 \rightarrow e^+e^-$ decays. QCD calculations are essentially complete[21] for Z^0 + jet, and are nearing completion[22] for Z^0 + two jets. We expect that the photino–gluino or photino–squark topology should be quite distinctive, and that only $\sim$ 100 events should suffice for discovery.

Let us now turn back to the large cross sections. In addition to the gluino pair final state, the squark pair and squark–gluino final states are produced copiously. I show in Fig. 10 the total cross sections for the reaction

$$\bar{p}p \rightarrow \tilde{u}\tilde{q}^* + \text{anything} \qquad (31)$$

at $\sqrt{s}$ = 0.63 TeV, 1.8 TeV, and 2 TeV. What are the detection requirements for squarks and gluinos in these final states? The signal, as we have already seen, consists of 1 to 3 jets on each side of the beam axis, and missing energy. The sources of background depend upon the superparticle masses and the c.m. energy of the initiating hadrons.

For superpartners with masses in the interval

$$10\ \text{GeV}/c^2 \lesssim M \lesssim 100\ \text{GeV}/c^2\ , \qquad (32)$$

three kinds of background must be considered for experiments at the $S\bar{p}pS$ and the Tevatron. Monojets occur in the inclusive production of

$$W \;\rightarrow\; \tau\nu \qquad (33)$$
$$\hookrightarrow \text{hadrons}$$

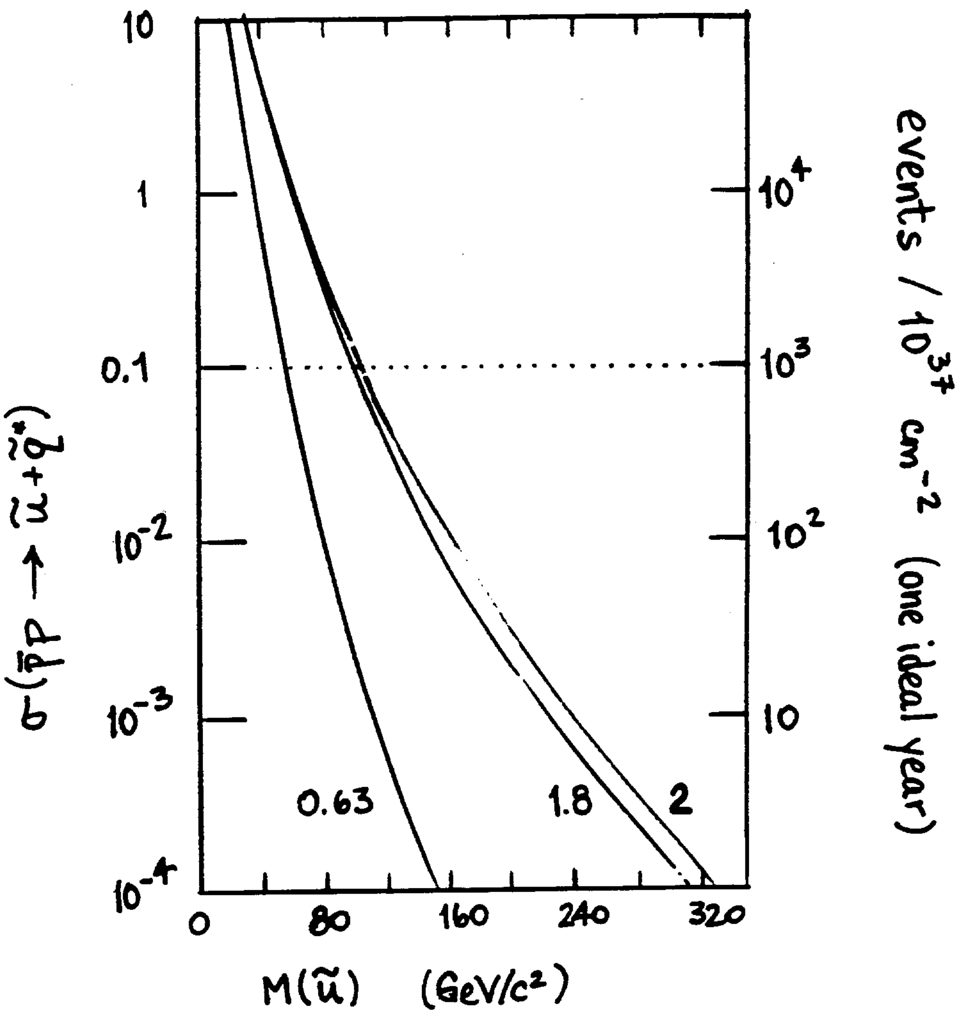

Figure 10: Total cross sections for the reaction $\bar{p}p \to \tilde{u}\tilde{q}^* +$ anything at $\sqrt{s} =$ 630 GeV, 1.8 TeV, and 2 TeV (from Ref. 20).

and

$$\begin{array}{l} Z^0 + g \\ \hookrightarrow \nu\bar{\nu} \end{array} \tag{34}$$

for which the reaction rates and event characteristics are both calculable and measurable. The multijet signals are simulated by the inclusive production of

$$W + \text{jets or } Z + \text{jets}, \tag{35}$$

followed by missing–energy decays of W or Z. Heavy–quark decays within ordinary QCD jets, such as

$$b \to c\ell^- \nu \tag{36}$$

can give rise to a sizeable missing transverse momentum. A lepton veto (is this practical within jets?) can provide important discrimination, and a cut on transverse momentum with respect to the jet axis is certainly useful. An important measurement[23] is the heavy–quark yield in energetic jets, for which the predictions of perturbative QCD should be reliable.[24]

Because of these backgrounds, we expect[17] that $\sim 10^3$ events will be required to establish a signal in this regime, or in the territory accessible to the SSC. The expected discovery limits for a variety of superpartners are shown in Table 5. Although these give a reasonable idea of how high the limits can be pushed, we must ask whether the $\bar{p}p$ colliders can close gaps in the limits on very light gluinos and squarks: how low in mass can we push, and still find a characteristic signature?

When we speak of cross section estimates for the production of superpartners, it is important to remark that calculations based on the perturbatively acquired squark or gluino content of the proton[25] are likely to lead to overestimates near

Table 5: Expected discovery limits for superpartners at $S\bar{p}pS$ and Tevatron Colliders, based on associated production of scalar quarks and gauginos. All superpartner masses are set equal.

Superpartner	Mass limit (GeV/c^2) $\sqrt{s} = 540$ [630]GeV, $\int dt\mathcal{L}$ $(\text{cm})^{-2}$: 10^{36}	10^{37}	10^{38}	$\sqrt{s} = 2$ TeV: 10^{36}	10^{37}	10^{38}
Gluino or squark (1000 events)	40 [45]	55 [60]	70 [75]	85	130	165
Photino (100 events)	35 [35]	55 [60]	85 [90]	45	90	160
Zino (1000 events)	17	30	50	22	50	95
Wino (1000 events)	20	35	55	32	60	110

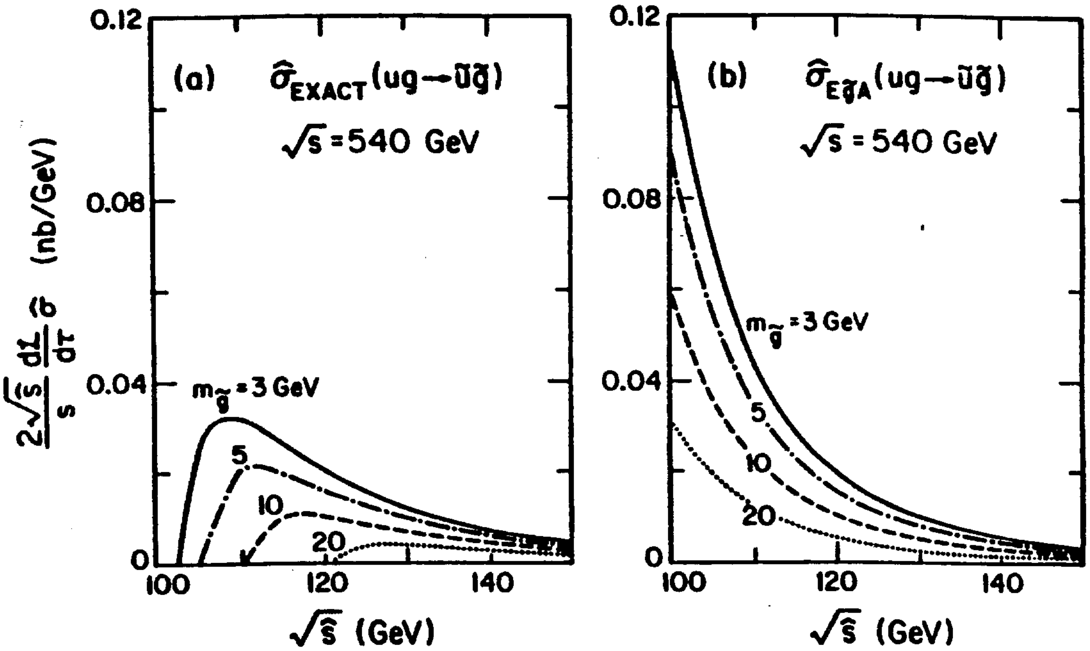

Figure 11: Comparison of (a) exact (Born term) and (b) effective gluino approximations for the product of the subprocess cross section $\hat{\sigma}(ug \to \tilde{u}\tilde{g})$ and the luminosity function for 100 GeV/c^2 up–squarks. Solid, dash–dotted, dashed, and dotted curves represent gluino masses of 3, 5, 10, and 20 GeV/c^2, respectively. The area under each curve represents the total $\tilde{u}\tilde{g}$ production cross section summed over two chiralities. (From Barger, et al., Ref. 26).

threshold. This is because kinematics are often poorly approximated, and because the leading logarithmic term in the Altarelli-Parisi evolution is not, in this regime, large compared to the finite term.[26] Indeed, the Born–term calculations discussed above correctly represent the evolution in this regime. A numerical example is shown in Fig. 11 for squark-gluino production at $\sqrt{s} = 540$ GeV.

During the past year, there has been a great deal of progress in elaborating what the standard model predicts, and what supersymmetry implies. In addition to the work on W + jets and Z + jets cited above,[21,22] several areas are significant:

- The incorporation of initial–state radiation into standard model Monte Carlo programs[27];
- The calculation of QCD amplitudes for multiparton final states[28];
- The development of Monte Carlo simulations for supersymmetry, with plausible experimental cuts included.[29]

Although the job is not complete, it is well begun.

4 Supersymmetry at the SSC

The outlines of the search for supersymmetry at the SSC are given in *EHLQ*.[1] Progress since Snowmass '84 was summarized recently at the Oregon workshop by Dawson.[30] Cross sections for the production of superpartners should be quite ample for a luminosity of 10^{32} cm^{-2}sec^{-1} or more, and a c.m. energy of 40 TeV. As examples, I show in Figs. 12–14 the integrated cross sections for the production of superpartners with rapidities $|y_i| < 1.5$, for the reactions

$$pp \to \tilde{g}\tilde{g} + \text{anything}, \tag{37}$$

$$pp \to \tilde{g}\tilde{q} + \text{anything}, \tag{38}$$

and

$$pp \to \tilde{g}\tilde{\gamma} + \text{anything}, \tag{39}$$

respectively.

On the basis of these and other cross section calculations and a rudimentary assessment of the requirements for detection, we have estimated the discovery limits for various energies and luminosities. These estimates are shown in

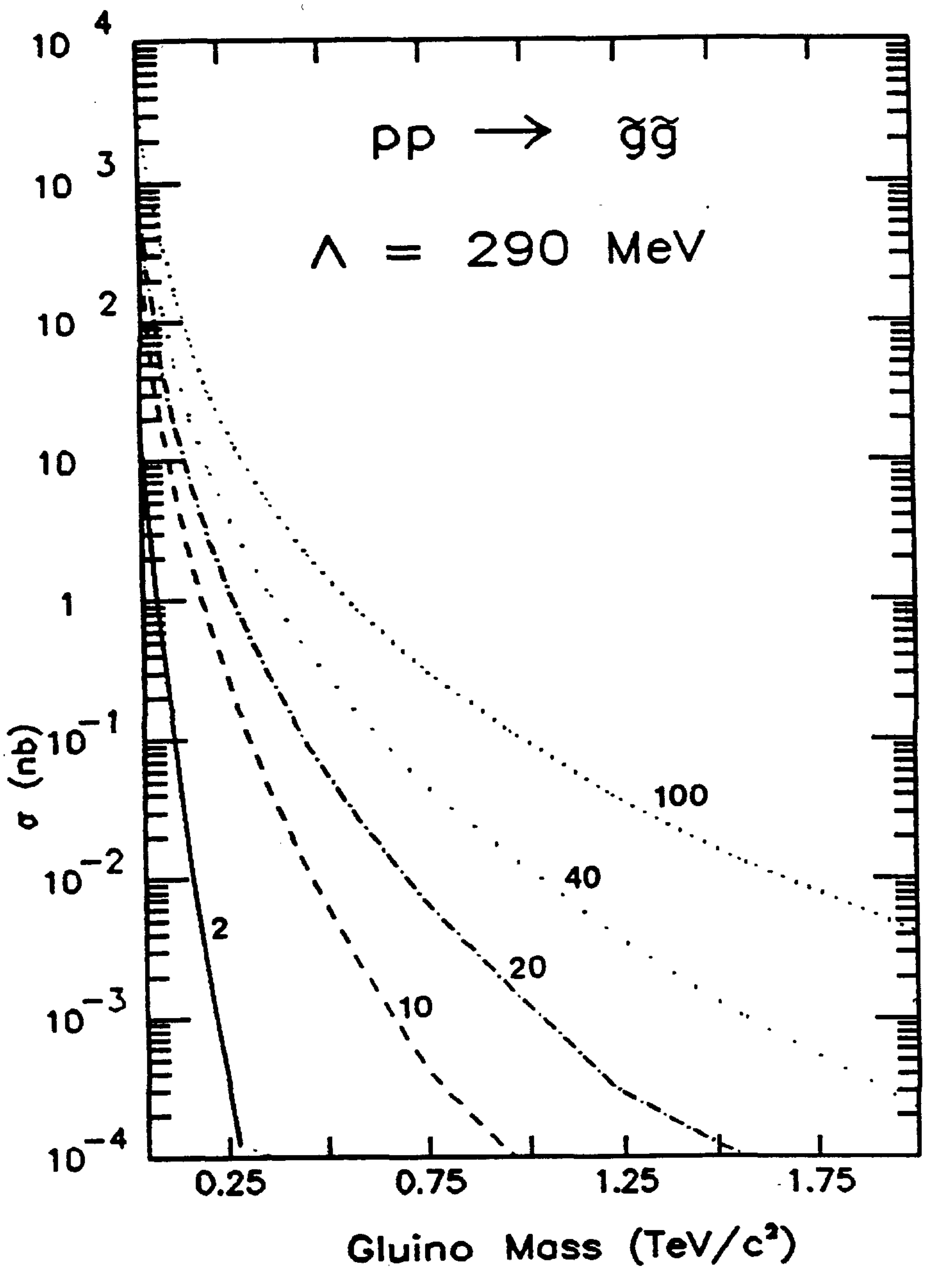

Figure 12: Cross sections for the reaction $pp \to \tilde{g}\tilde{g}$ + anything as a function of gluino mass, for collider energies $\sqrt{s} = 2, 10, 20, 40$, and 100 TeV, according to the *EHLQ* parton distributions (Set 2). Both gluinos are restricted to the interval $|y_i| < 1.5$. For this illustration, the squark mass is set equal to the gluino mass. [From Ref. 1.]

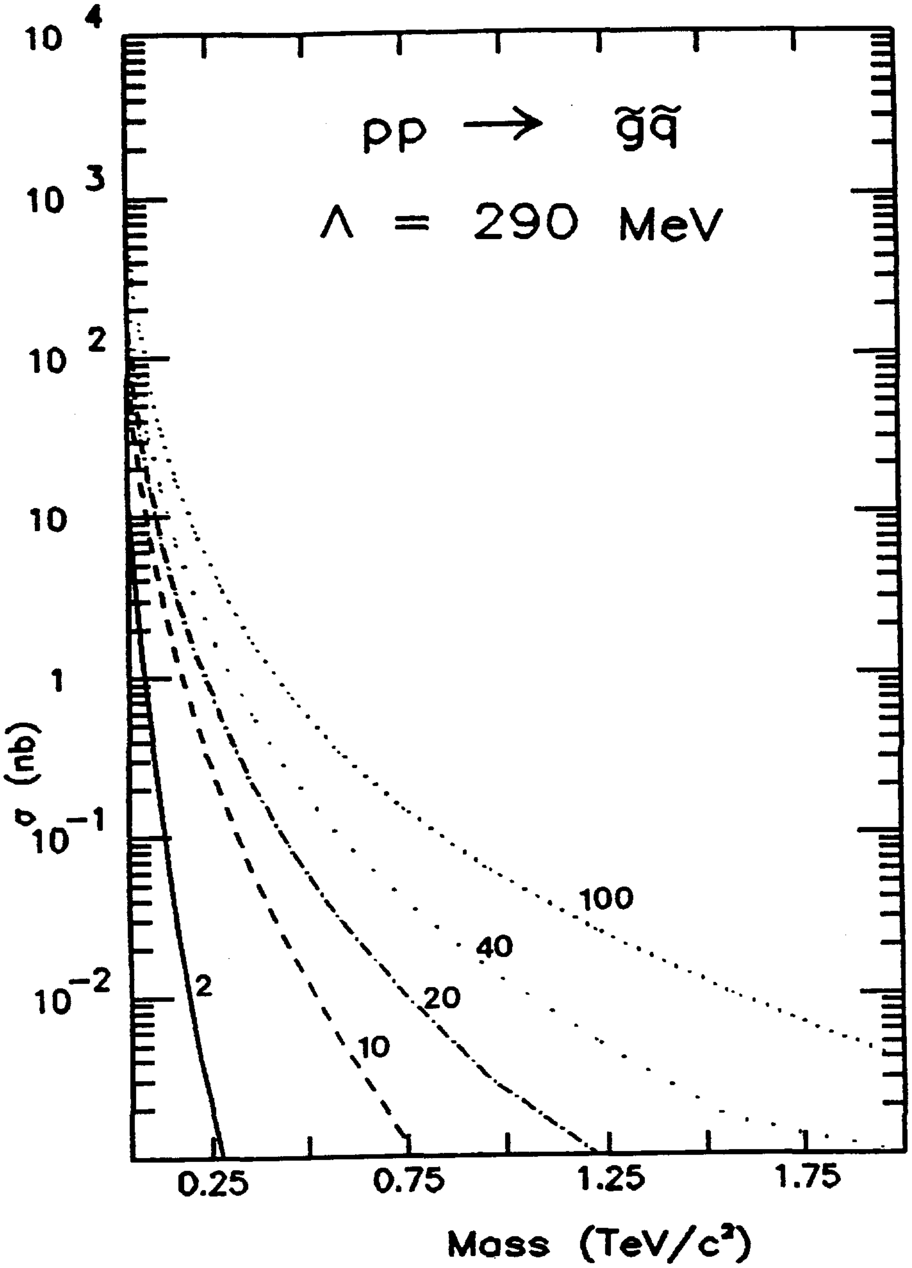

Figure 13: Cross sections for the reaction $pp \to \tilde{g}(\tilde{q}_u$ or $\tilde{q}_d$ or $\tilde{q}_u^*$ or $\tilde{q}_d^*) +$ anything as a function of the superparticle mass for collider energies $\sqrt{s} = 2$, 10, 20, 40, and 100 TeV, according to the *EHLQ parton distributions* (Set 2). We have assumed equal masses for the squarks and gluino, and have included the partners of both left–handed and right–handed quarks. Both squark and gluino are restricted to the rapidity interval $|y_i| < 1.5$. [From Ref. 1.]

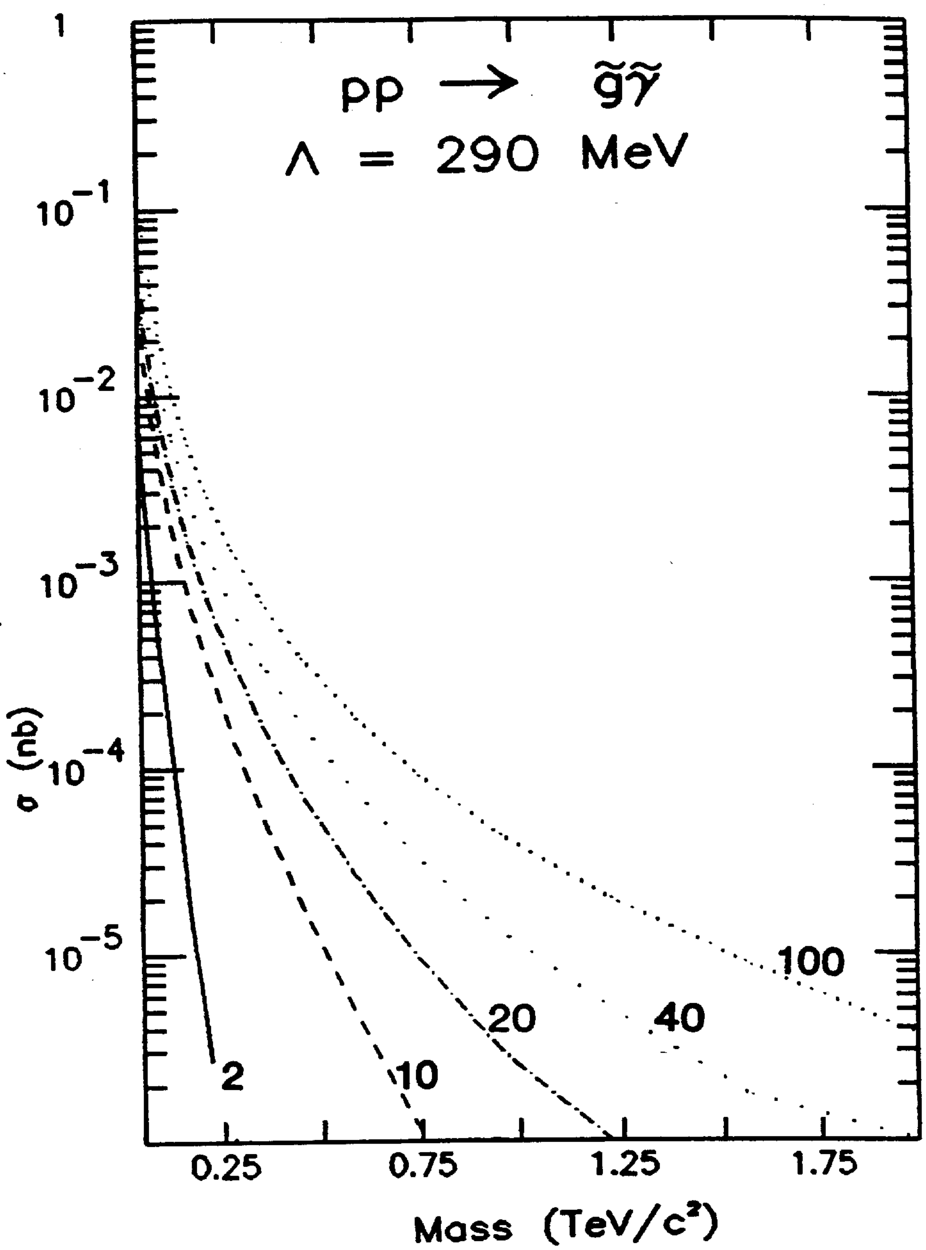

Figure 14: Cross sections for the reaction $pp \rightarrow \tilde{g}\tilde{\gamma}$ + anything as a function of the photino mass, for collider energies $\sqrt{s}$ = 2, 10, 20, 40, and 100 TeV, according to the *EHLQ* parton distributions (Set 2). Both gluino and photino are restricted to the rapidity interval $|y_i| < 1.5$. For this illustration, all squark and gaugino masses are taken to be equal. [From Ref. 1.]

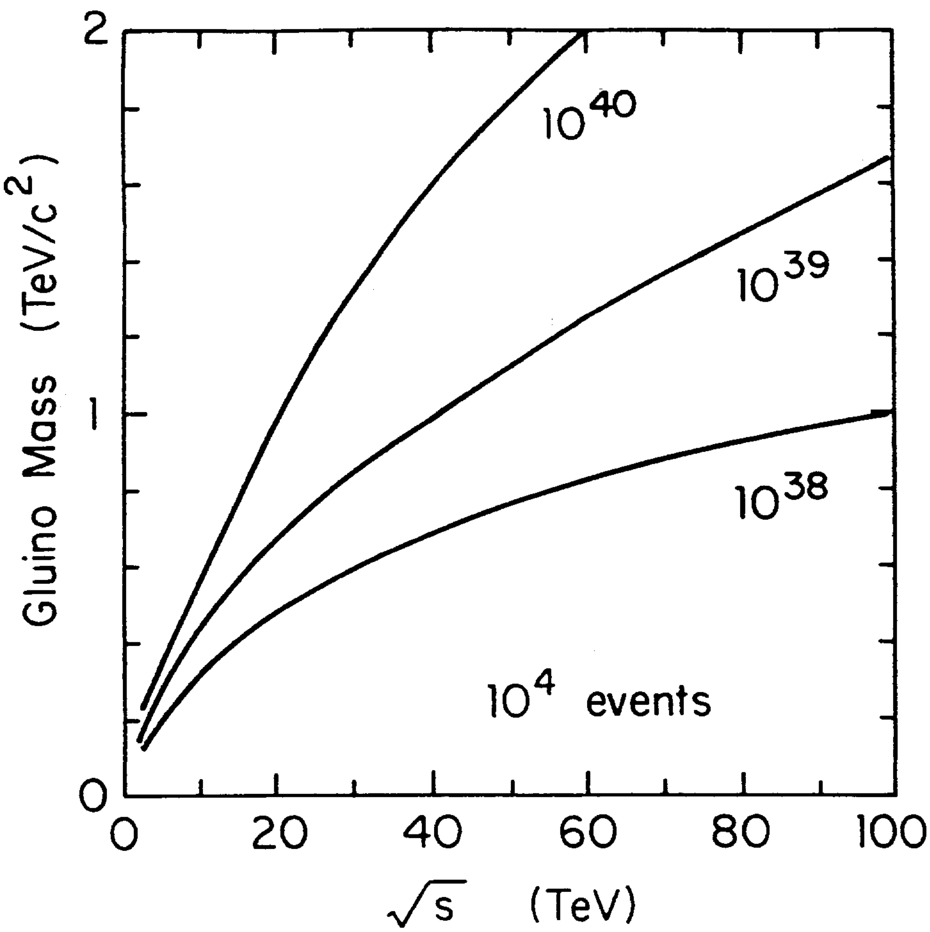

Figure 15: "Discovery limits" for gluinos in pp and $\bar{p}p$ collisions. Contours show the largest mass for which 10^4 gluino pairs are produced with $|y_i| < 1.5$, for specified energy and luminosity (in cm^{-2}). The *EHLQ* parton distributions of Set 2 were used. [From Ref. 1.]

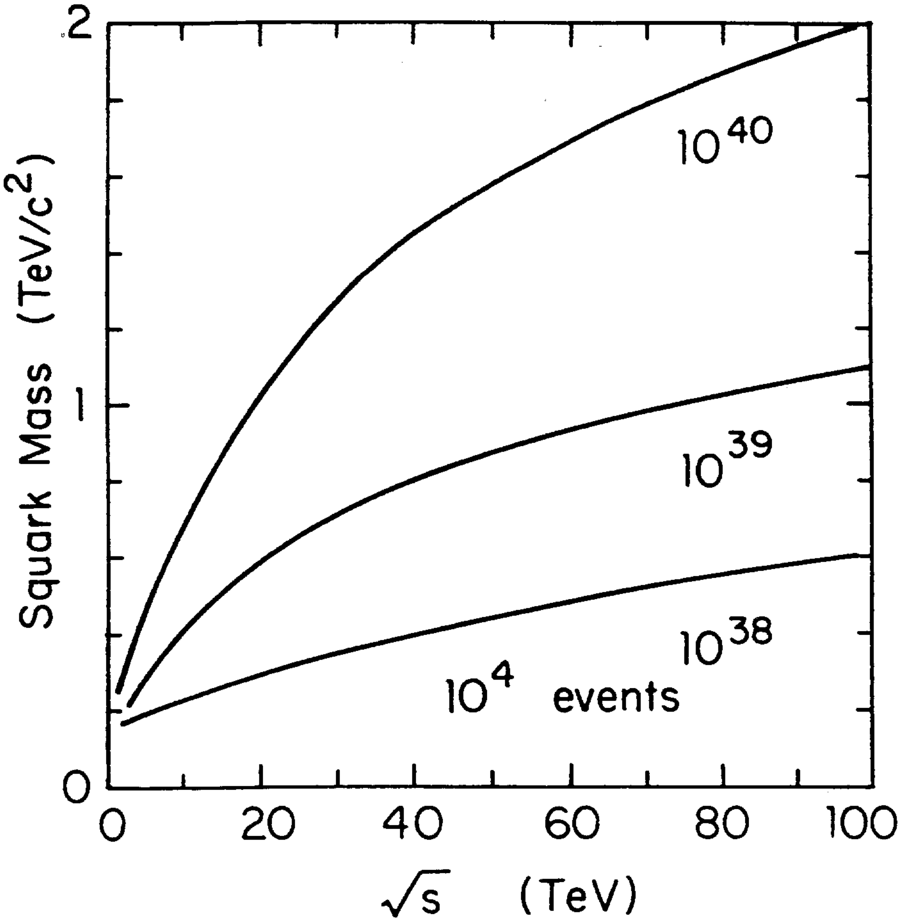

Figure 16: "Discovery limits" for squarks in pp and $\bar{p}p$ collisions. Contours show the largest mass for which 10^4 squark pairs are produced with $|y_i| < 1.5$, for specified energy and luminosity (in cm^{-2}). The *EHLQ* parton distributions of Set 2 were used. [From Ref. 1.]

Figs. 15–20 for gluinos, squarks, photinos, zinos, winos, and sleptons. We infer from these estimates that a 40–TeV $p^{\pm}p$ collider with integrated luminosity exceeding 10^{39} cm^{-2} should be adequate to establish the presence or absence of the superpartners predicted by models of low–energy supersymmetry.

5 Conclusions

We have examined a general class of supersymmetric theories in which the effective low–energy theory relevant at 1 TeV or below is the supersymmetric extension of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. The search for supersymmetry is complicated by the absence of reliable predictions for the masses of superpartners. Low–energy supersymmetry is surprisingly unconstrained by experiment, in spite of increasing efforts over the past eighteen months. For example, gluinos and photinos as light as ~ 1 GeV/c^2 are allowed for some ranges of parameters, in all scenarios. Interesting limits can be placed on *stable* squarks and sleptons. For *unstable* scalar quarks, stringent limits exist only if the photino is massless.

A complete catalogue of total and differential cross sections exists for the production of superpartners in $p^{\pm}p$ and e^+e^- collisions. Detailed simulations, including detector characteristics, are required; important work along these lines is in progress, but continued iteration with experimental reality will be needed. At the $S\bar{p}pS$ and Tevatron Colliders, rates are ample for superpartner masses up to about 100 GeV/c^2, but good signatures beyond the traditional "missing E_T" tag must be devised. The SSC will permit the study of squarks and gluinos up to masses of 1 Tev/c^2 and beyond.

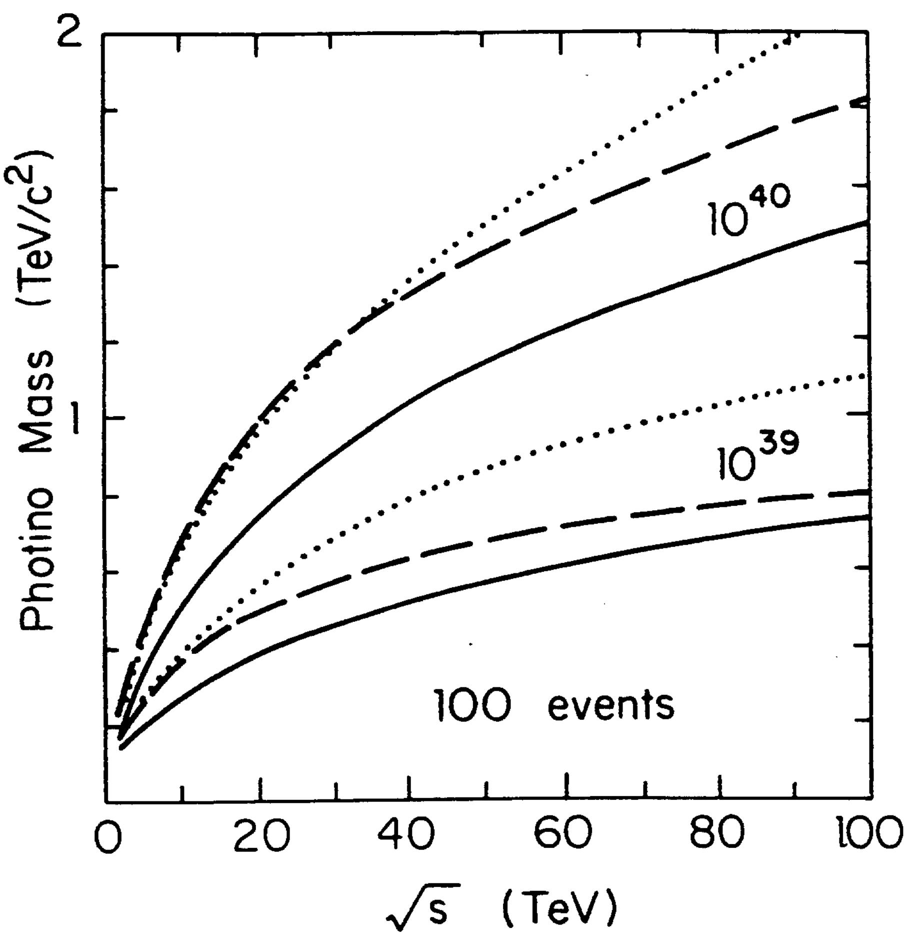

Figure 17: "Discovery limits" for photinos produced in association with gluinos in pp (solid lines) or $\bar{p}p$ (dashed lines) collisions, or in association with squarks (dotted lines). Contours show the largest mass for which 100 photinos are produced with $|y_i| < 1.5$, for specified energy and luminosity (in cm^{-2}). The *EHLQ* parton distributions of Set 2 were used. [From Ref. 1.]

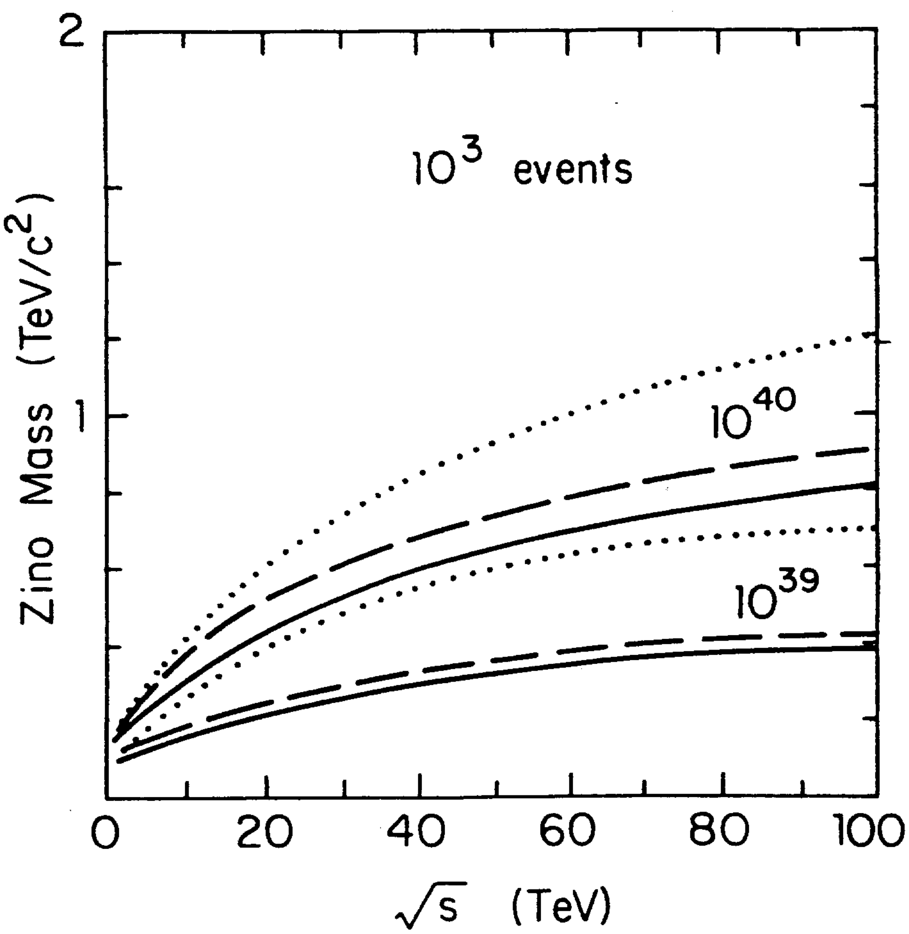

Figure 18: "Discovery limits" for zinos produced in association with gluinos in pp (solid lines) or $\bar{p}p$ (dashed lines) collisions, or in association with squarks (dotted lines). Contours show the largest mass for which 10^3 zinos are produced with $|y_i| < 1.5$, for specified energy and luminosity (in cm^{-2}). The *EHLQ* parton distributions of Set 2 were used. [From Ref. 1.]

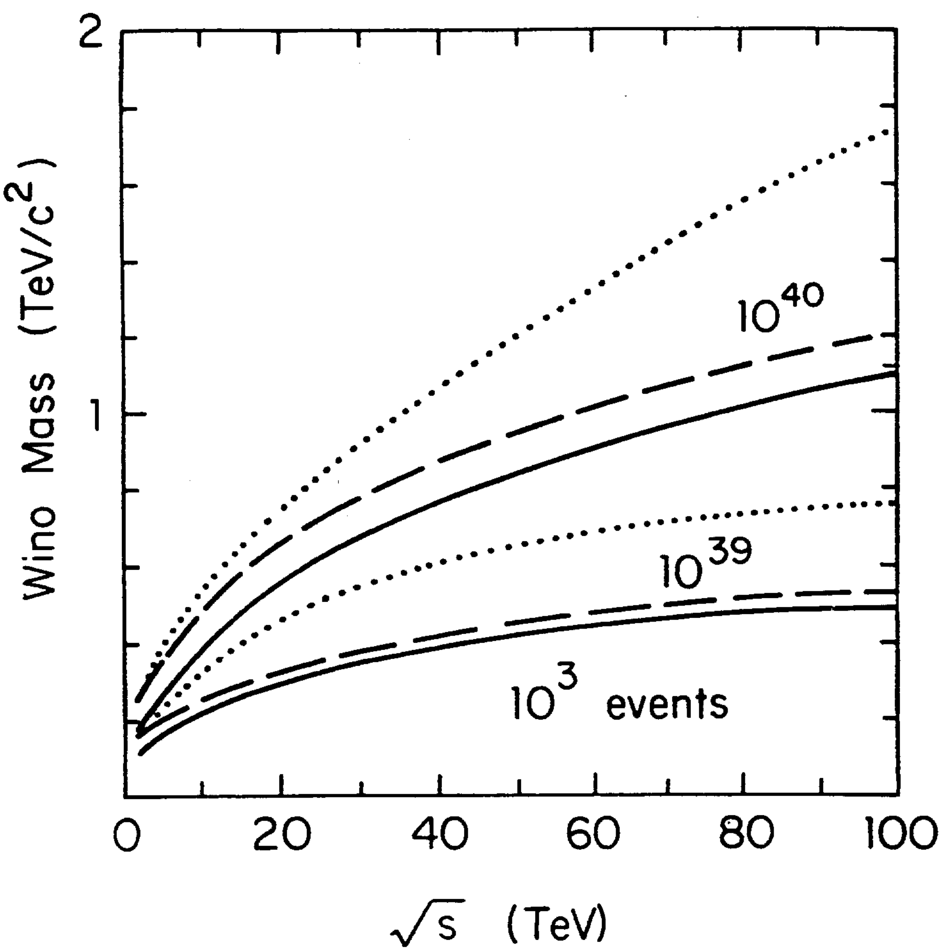

Figure 19: "Discovery limits" for winos produced in association with gluinos in pp (solid lines) or $\bar{p}p$ (dashed lines) collisions, or in association with squarks (dotted lines). Contours show the largest mass for which 10^3 winos are produced with $|y_i| < 1.5$, for specified energy and luminosity (in cm^{-2}). The *EHLQ* parton distributions of Set 2 were used. [From Ref. 1.]

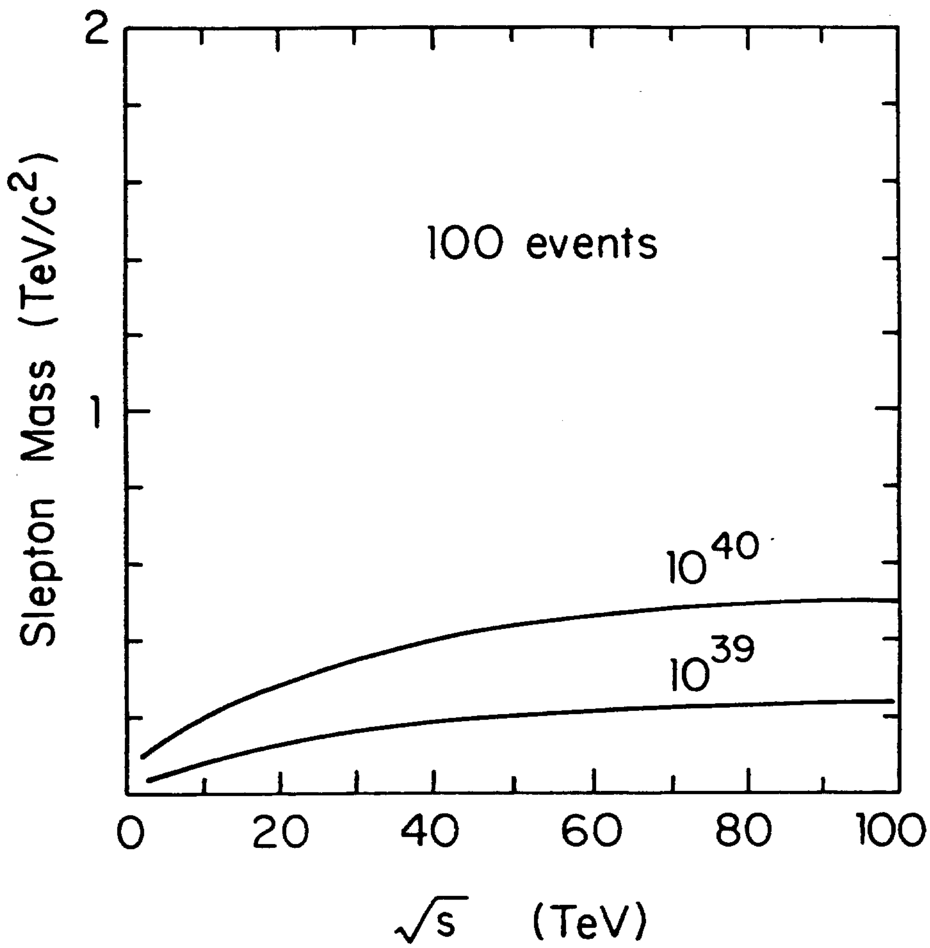

Figure 20: "Discovery limits" for sleptons in pp (solid lines) or $\bar{p}p$ (dashed lines) collisions. Contours show the largest mass for which 100 slepton pairs are produced with $|y_i| < 1.5$, for specified energy and luminosity (in cm^{-2}). The *EHLQ* parton distributions of Set 2 were used. [From Ref. 1.]

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