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Supersymmetric Models and Collider Signatures

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Abstract.

We briefly review the SUGRA, GMSB and AMSB supersymmetry breaking models. We then discuss the phenomenological differences between them and consequent characteristic experimental signatures. This is followed by a review of the discovery potential for supersymmetry at the Tevatron, LHC and a future e^+e^- linear collider.

1. Introduction

In the past twenty years there has been a great deal of theoretical study of low energy supersymmetry and a number of experimental searches. However, these searches have found no evidence for supersymmetry. Within the next ten years a number of new collider experiments will probe higher energies and low energy supersymmetry will either be discovered experimentally or will no longer be relevant to the problem of electroweak symmetry breaking.

After briefly surveying the models which are used in experimental studies we will discuss the discovery potential and signatures for current and future experiments.

2. SUSY Models

We will consider the Minimal Supersymmetric Standard Model (MSSM). This is the supersymmetric extension of the the Standard Model (SM) which has minimal particle content, *i.e.* it contains two Higgs doublets rather than the one of the SM and the superpartners of the Standard Model fields. This model has one less parameter than the Standard Model, provided that supersymmetry (SUSY) is unbroken. There is an additional parameter μ which gives mixing between the two Higgs doublets but the couplings in the scalar potential are constrained by SUSY. However, as the superpartners have not been observed, SUSY must be broken in such a way as to not reintroduce the quadratic dependence of the Higgs mass on the cutoff scale. This is called soft SUSY

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quadratic dependence of the Higgs mass on the cutoff scale. This is called soft SUSY breaking and leads to a large number of additional parameters: soft SUSY breaking masses for the scalars and gauginos; soft SUSY breaking A terms, which couple two sfermions and a Higgs; and B terms, which couple two Higgs bosons. The trilinear A terms are only important for the third generation sfermions as they enter in terms proportional to the fermion masses. The Z boson mass is given in terms of the other parameters of the model.

In the MSSM R-parity related to baryon (B) and lepton number (L) by $R_P = (-1)^{3B+2S+L}$, is assumed to be conserved which means that SUSY particles can only be produced in pairs and the lightest SUSY particle (LSP) is stable. As the LSP is stable it must be neutral as charged stable matter is excluded by cosmological arguments. This implies that all SUSY events have two LSPs in them leading to missing transverse energy in SUSY events because the LSPs do not interact in the detector. R-parity need not be conserved and this leads to very different experimental signatures [1].

It is difficult to use the MSSM for detailed experimental studies due to the large number of free parameters it contains. Furthermore large ranges of the parameters are excluded and a real model will surely have far fewer fundamental parameters. Therefore models of SUSY breaking are used which are motivated by theoretical ideas. All have a common feature; SUSY is broken in some hidden sector and then transmitted to the MSSM fields. The models differ in how this transmission is accomplished:

SUGRA [2] In supergravity models all the scalar masses (M_0), the gaugino masses ($M_{1/2}$), the A and B parameters are assumed to be unified at the GUT scale ($\sim 10^15$ GeV). As the model predicts M_Z in terms of the other parameters it is possible to use $\tan\beta = v_1/v_2$, the ratio of the vacuum expectation values for the two Higgs doublets, and the known value of M_Z to fix B and $|\mu|$. This leaves five parameters M_0, $M_{1/2}$, A, $\mathrm{sgn}\,\mu$, $\tan\beta$ which completely determine the mass spectrum and decay patterns of the particles. The gluino mass ($m_{\tilde{g}}$) is strongly correlated with $M_{1/2}$ and the slepton mass with M_0. The LHC experiments have defined several SUGRA points which are often used in simulations [3] [4].

GMSB [5] The Gauge Mediated SUSY Breaking model aims to solve the problem of flavour changing neutral current problem which is generically present in SUGRA models by using gauge interactions rather than gravity to transmit the SUSY breaking. The messenger sector consists of some particles, X, which have SM interactions and are aware of SUSY breaking. The simplest choice is to have the messenger particles in complete $SU(5)$ **5** or **10** representations to preserve the grand unified (GUT) symmetry. The fundamental SUSY breaking scale F must be such that $\sqrt{F} \lesssim 10^{10}$ GeV or SUGRA breaking will dominate. The gaugino masses occur at one-loop while the squark and slepton masses occur at two-loop. The LSP is an almost massless gravitino so that the sparticles decay as in a SUGRA model followed by the decay of the next-to-lightest SUSY particle (NLSP) to the gravitino. The NLSP need not be neutral and its lifetime is model dependent. This

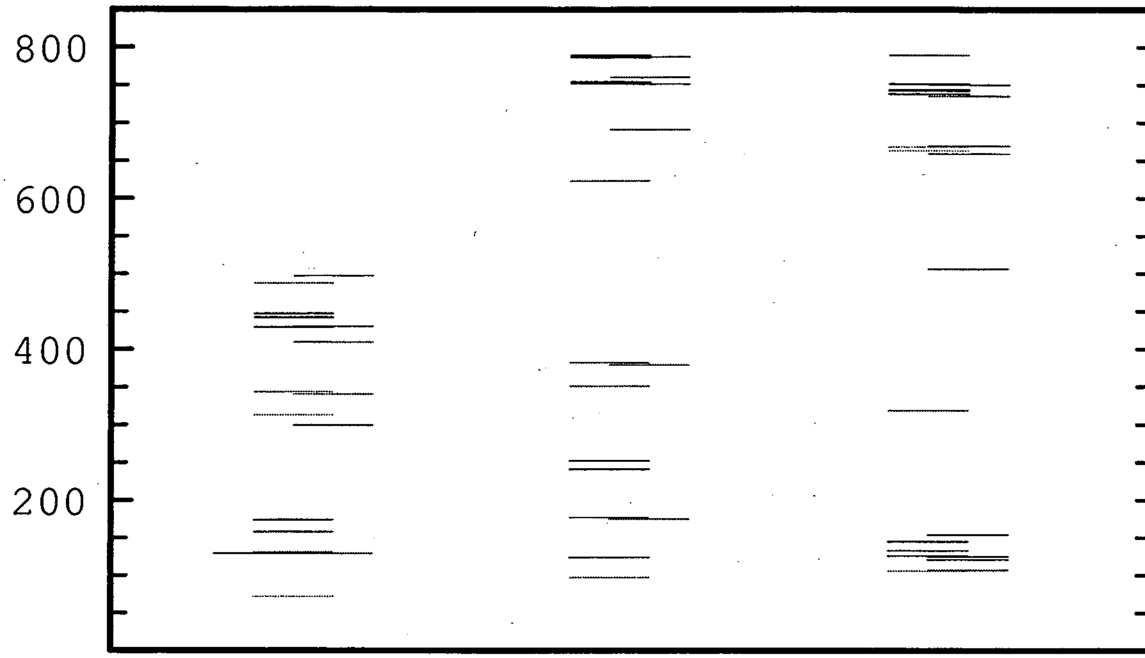


Figure 1. Examples of mass spectra in SUGRA, GMSB and AMSB models for $\tan\beta = 3$ and $\operatorname{sgn}\mu = +$. The other parameters are: $M_0 = 100\,\mathrm{GeV}$, $M_{1/2} = 200\,\mathrm{GeV}$ for the SUGRA model; $M = 100\,\mathrm{TeV}$, $N_5 = 1$, $\Lambda = 70\,\mathrm{TeV}$ for the GMSB model; $M_0 = 200\,\mathrm{GeV}$, $M_{3/2} = 35\,\mathrm{TeV}$ for the AMSB model. Plot taken from [8].

model has six parameters: $\Lambda = F/M$ the scale for the SUSY masses; $M > \Lambda$ the messenger mass scale; $N_5 \geq 1$ the number of $\mathbf{5}+\bar{\mathbf{5}}$ messenger fields; the ratio of the vacuum expectation values $\tan\beta$; $\operatorname{sgn}\mu$ the sign of the μ parameter; and $C_{\mathrm{grav}} \geq 1$ which controls the NLSP lifetime.

AMSB [6] The super-conformal anomaly is always present and predicts sparticle masses in terms of $M_{3/2}$, the gravitino mass The simplest version of this model predicts tachyonic sleptons and therefore some other SUSY breaking mechanism must be present in order to get a realistic spectrum. One way to do this is to add a universal scalar mass (mAMSB) or new very heavy fields (DAMSB). The (mAMSB) model has four parameters: M_0 the universal scalar mass; $M_{3/2}$ the gravitino mass; $\tan\beta$ the ratio of Higgs VEVs; and $\operatorname{sgn}\mu$. The DAMSB model has five parameters: M the mass of the new fields; n the number of new fields; $M_{3/2}$; $\tan\beta$; and $\operatorname{sgn}\mu$. The AMSB model has one important feature in that the LSP is mainly wino likely and almost degenerate with the lightest chargino, $\tilde{\chi}_1^+$, but this feature is lost in DAMSB.

All of these models are implimented in the ISAJET event generator [7].

The spectra of the SUSY particles in these models can be very similar, an example of each is shown in Fig. 1. The main differences in these models are the ratios of the squark to slepton masses and the differences between the electroweak gaugino and gluino masses. In the SUGRA model the scalar masses are universal at the GUT scale and therefore the differences in the masses come from the renormalization group evolution (RGE) to the electroweak scale. However in the GMSB models the masses at the SUSY breaking scale are proportional to the relevant gauge couplings and therefore the strongly interacting squarks are heavier than the sleptons, relative to the SUGRA model. In the AMSB model the sleptons are very light compared to the squarks unless the universal scalar mass is very large. Similarly for the gauginos the splitting of the gluino and electroweak gaugino masses in the SUGRA model comes from the RGE however in the GMSB model the gaugino masses are proportional to the gauge couplings at the SUSY breaking scale and therefore the strongly interacting gluino is heavier than the weakly interacting gauginos. In the AMSB model the soft breaking mass for the gluino is larger than the soft breaking masses for the electroweak gauginos at the GUT scale which gives a bigger splitting between the gluino and electroweak gauginos masses than in SUGRA models. The nature of the lightest neutralino is also different in the different models. In the SUGRA model it is usually mainly bino whereas in the AMSB model it is mainly wino and degenerate with the lightest chargino. In the As discussed above, the lightest neutralino in the GMSB model is the Gravitino and the NLSP, which can be neutral or charged, is most important for phenomenology.

Obviously once supersymmetry is discovered it will be important to make accurate measurements of SUSY particles masses and couplings in order to investigate the model of SUSY breaking. However at present, given we have seen no evidence for supersymmetry in experimental studies, the main interest is in simulating models which give qualitatively different experimental signatures so that we can be certain that all variants can be observed. For example the DAMSB model is very similar to a SUGRA model and has not therefore been subjected to many detailed studies, whereas in the mAMSB model which has an almost degenerate lightest neutralino and chargino the dominant chargino decay mode is $\tilde{\chi}^+_1 \to \pi^+\tilde{\chi}^0_1$ which is very different from SUGRA models and therefore of more interest.

There are a number of signatures which are characteristic of supersymmetry, regardless of the model of SUSY breaking: missing transverse energy; a high multiplicity of high transverse momentum jets; many isolated leptons; copious b-jet production; a large rate of Higgs production; isolated photons; and quasi-stable charged particles. It should be noted that not all of these signals are present in all models and that production of any heavy object will give some of these signals.

In order to simulate supersymmetry it is essential to have a consistent model. We cannot consider one sparticle in isolation because all the supersymmetric particles which are kinematically allowed will be produced. In hadron colliders production of the squarks and gluinos dominates provided the centre-of-mass energy is high enough. The production of those sparticles which only have electro-weak couplings may be dominated by the decays of squarks and not by direct production. The dominant backgrounds at the LHC are combinatorial from SUSY events after some simple cuts are applied.

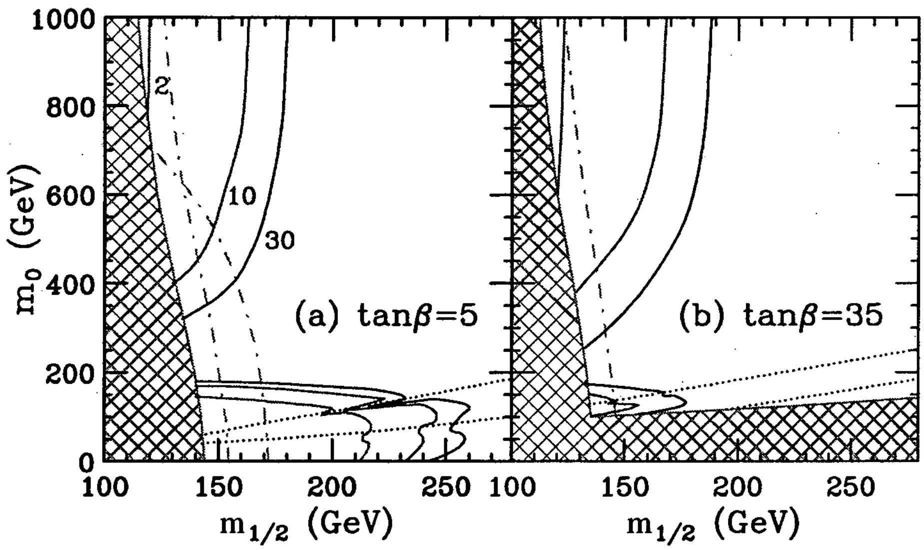


Figure 2. Tevatron reach in the Tri-lepton channel in the $M_0, M_{1/2}$ plane, for fixed values of $A_0 = 0$, $\mu > 0$ and **(a)** $\tan\beta = 5$ or **(b)** $\tan\beta = 35$. Results are shown for 2, 10 and 30 fb^{-1} integrated luminosity. The curves require the observation of at least 5 events and are 3σ exclusion contours. The cross-hatched region is excluded by current limits on the superpartner masses and the dot-dashed liners correspond to the projected LEP-II reach for the chargino and lightest Higgs masses. Figure taken from [9, 10].

The situation at the Tevatron where electroweak gaugino production may dominate and Standard Model processes are the most important source of background is very different. At a lepton collider where the full spectrum is unlikely to be accessible and the beam energy and polarization can be used to separate sparticles the situation is much simpler.

3. Tevatron

In Run I of the Tevatron neither CDF or D0 claimed the discovery of any signal for supersymmetry. A number of limits were obtained which we will not discuss here [12,13]. Run II of the Tevatron which has both an increase in the centre-of-mass energy to 2 TeV and one hundred times the luminosity will extend the mass range but the search reach is limited. Due to the centre-of-mass energy the production of squarks and gluinos may not dominate and the best channel for the discovery of SUSY may be gaugino production, *i.e.* production of $\tilde{\chi}^0_2\tilde{\chi}^+_1 \to \ell^+\ell^-\tilde{\chi}^0_1\ell^+\nu\tilde{\chi}^0_1$. Fig. 2 shows the search potential in this channel at Run II of the Tevatron for different integrated luminosities. The background to this process is dominated by gauge boson pair production followed by leptonic decays with WZ/γ being the dominant background process.

If this signal is observed structure in the $\ell^+\ell^-$ mass distribution will constrain the $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ masses, this will be discussed in more detail for the LHC in the next section.

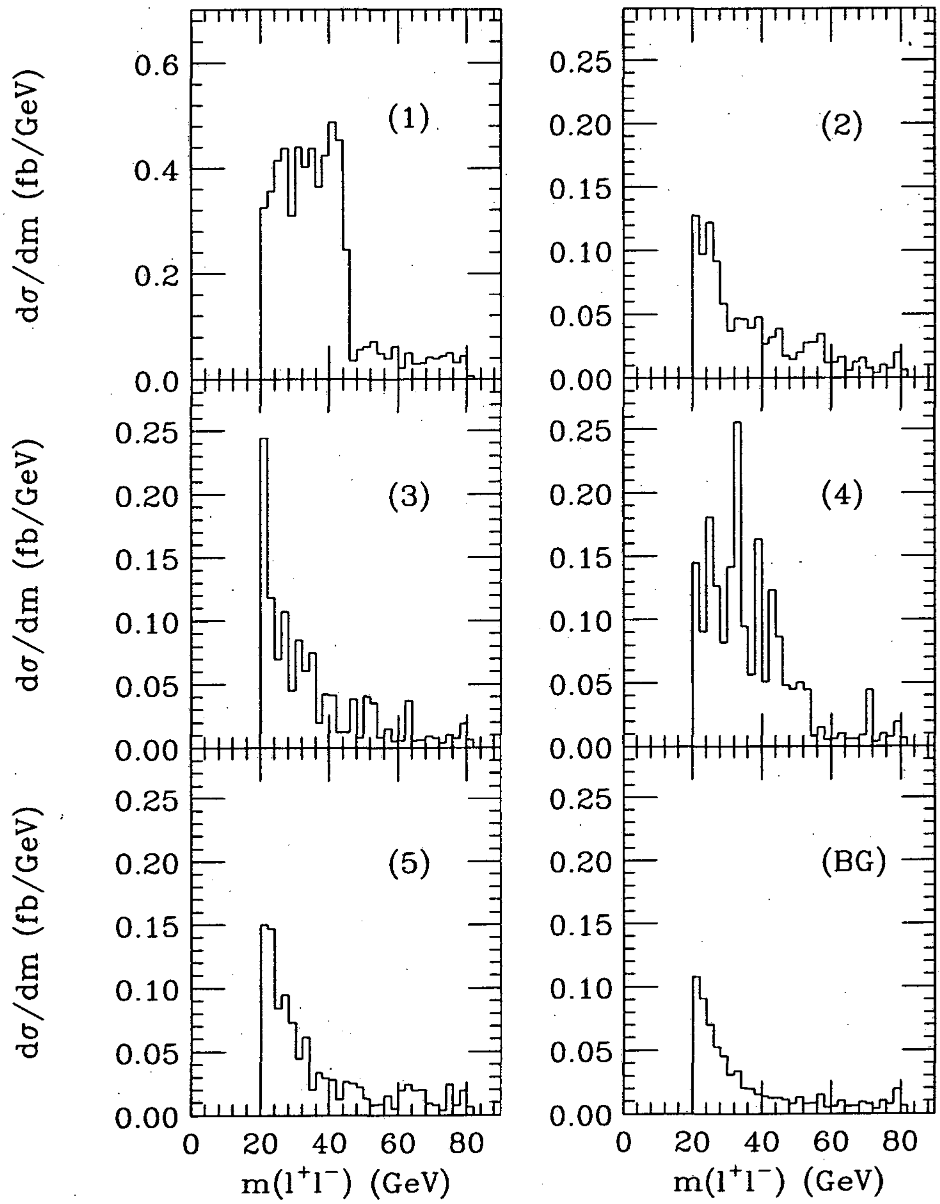


Figure 3. Opposite sign, same flavour dilepton mass reconstruction for five study points given below and the WZ and $t\bar{t}$ background. The background is included in all the histograms. It should be noted that since this plot was produced point 1 has been ruled out by searches at LEP. Point 1 has $M_0 = 100\,\text{GeV}$, $M_{1/2} = 200\,\text{GeV}$, $A_0 = 0\,\text{GeV}$, $\tan\beta = 3$, $\text{sgn}\,\mu = +$; point 2 has $M_0 = 140\,\text{GeV}$, $M_{1/2} = 175\,\text{GeV}$, $A_0 = 0\,\text{GeV}$, $\tan\beta = 35$, $\text{sgn}\,\mu = +$; point 3 has $M_0 = 200\,\text{GeV}$, $M_{1/2} = 140\,\text{GeV}$, $A_0 = -500\,\text{GeV}$, $\tan\beta = 35$, $\text{sgn}\,\mu = +$; point 4 has $M_0 = 250\,\text{GeV}$, $M_{1/2} = 150\,\text{GeV}$, $A_0 = -600\,\text{GeV}$; $\tan\beta = 3$, $\text{sgn}\,\mu = +$; point 5 has $M_0 = 150\,\text{GeV}$, $M_{1/2} = 300\,\text{GeV}$, $A_0 = 0\,\text{GeV}$, $\tan\beta = 30$, $\text{sgn}\,\mu = -$ and non-universal GUT-scale Higgs masses $M_{H_1,H_2} = 500\,\text{GeV}$. Plot taken from [9,11].

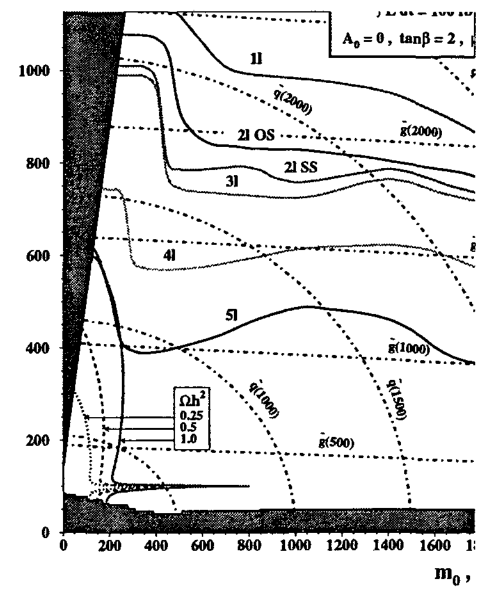


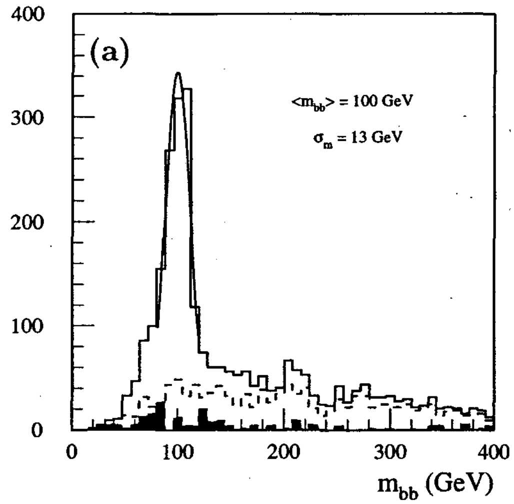
Figure 4. Discovery potential of the LHC for final states with at least two jets, $\not{E}_T > 100\,\mathrm{GeV}$ and at least one isolated lepton. An integrated luminosity of $100\,\mathrm{fb}^{-1}$ has been assumed. Plot taken from [14].

However as can be seen from Fig. 3 for those points which are still allowed by the LEP limits the endpoint of the distribution which gives information on the mass difference of the lightest two neutralinos will be difficult to measure.

It is possible to extend the search reach by using channels involving jets and missing transverse energy. If supersymmetry is discovered at the Tevatron it will determine the mass scale of some of the particles. The LHC will then make detailed measurements of the SUSY spectrum.

4. LHC

Many detailed studies of the search potential of the LHC have been performed by both the ATLAS [3] and CMS collaborations [4]. At the LHC the strongly interacting squarks and gluinos are predominantly produced unless they are very heavy giving large SUSY production cross sections. This allows hard cuts to be applied to the data in order to reduce the Standard Model background leaving combinatorial backgrounds from the SUSY events themselves as the dominant source of background. Most of the studies have assumed the full integrated luminosity of the LHC which enables hard cuts to be used. In practice the discovery of SUSY will probably take less time and use weaker cuts in which case the Standard Model background will be more important.



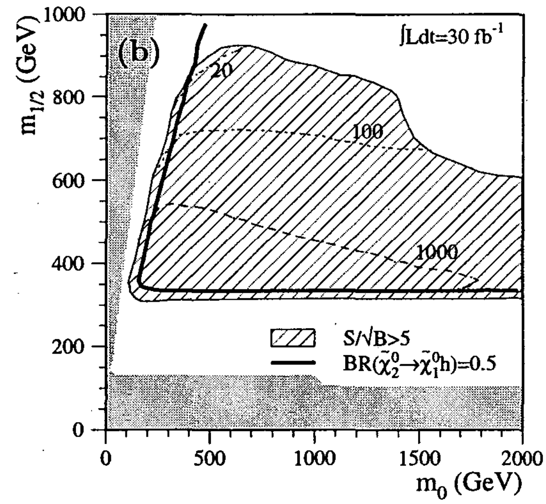


Figure 5. **(a)** The reconstructed $b\bar{b}$ mass distribution for events passing $h \rightarrow b\bar{b}$ selection cuts. The distributions are for the SM background (shaded), the total SUSY+SM background (dashed) and the summed signal+background for SUGRA point 1. **(b)** The 5σ discovery contour curves for $h \rightarrow b\bar{b}$ from SUSY cascade decays in the $M_0, M_{1/2}$ plane for $\tan\beta = 10$, $\mathrm{sgn}\,\mu = +$. The expected number of reconstructed $h \rightarrow b\bar{b}$ events are also shown. The dark shaded regions are theoretical or experimentally excluded. Both (a) and (b) assume $30\,\mathrm{fb}^{-1}$ integrated luminosity and are taken from [3].

The LHC studies can be broadly grouped into two categories: the first attempts to find some signal indicative of SUSY and find an excess in order to discover supersymmetry by exploiting inclusive signatures; the second then tries to make use of more information from the SUSY events in order to measures masses and other parameters of the model.

There is a very large range of accessible masses in inclusive signals, *i.e.* jets, leptons and missing transverse energy ($\not{E}_T$). Fig. 4 shows the mass reach in SUGRA models for the CMS experiment [14]. This covers all the interesting theoretical range, *i.e.* $M_{\tilde{g}} \lesssim 2.5\,\mathrm{TeV}$. It is useful to define global variables for SUSY searches. For example if we consider events with at least four jets and missing transverse energy the variable

$$M_{\mathrm{eff}} = p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + \not{E}_T, \tag{1}$$

where $p_{T,i}$ is the transverse momentum of the ith jet, is very useful. The peak in the M_{eff} distribution correlates well with the SUSY mass scale where $M_{\mathrm{SUSY}} = \min(M_{\tilde{u}}, M_{\tilde{g}})$. This can determine the squark/gluino masses to about 15% [15].

There have been many studies of techniques to reconstruct sparticle masses and properties. Here we will illustrate the techniques by choosing examples from case studies. In general both the squarks and gluino are produced. The depending on the relative masses one decays into the other as these decays occur via the strong interaction. The weak gauginos are then produced in the decays of the lighter strongly interacting

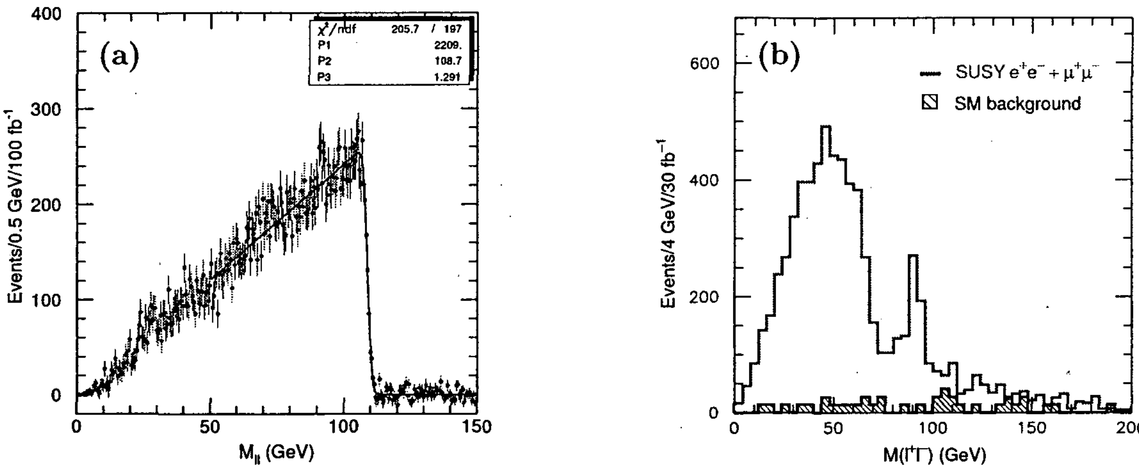


Figure 6. (a) Dilepton $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\ell^+\ell^-$ signal at SUGRA point 5 for $100\,\mathrm{fb}^{-1}$ including backgrounds after flavour subtraction, *i.e.* the plot shows $\mathrm{e}^+\mathrm{e}^- + \mu^+\mu^- - \mathrm{e}^{\pm}\mu^{\mp}$. (b) Dilepton $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$ distribution for SUGRA point 4 (solid) and SM background (shaded) with $30\,\mathrm{fb}^{-1}$. Both plots are taken from [3].

particles, for example $\tilde{\mathrm{q}}_L \to \tilde{\chi}_2^0\mathrm{q}$. In most models a significant number of second-to-lightest neutralinos are produced. These neutralinos then either decay via $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mathrm{h}$ or $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$, possibly via either an intermediate slepton $\tilde{\chi}_2^0 \to \tilde{\ell}^+\ell^- \to \tilde{\chi}_1^0\ell^+\ell^-$ or Z boson $\tilde{\chi}_2^0 \to \mathrm{Z}^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\ell^+\ell^-$. The Higgs decay mode tends to dominate if it is kinematically accessible. Most studies have used these decays as a starting point for mass measurements. Many other SUSY particles can then be identified by adding more jets or leptons to reconstruct other particles in the decay chain.

If the decay of the $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mathrm{h}$ exists then approximately 20 % of SUSY events contain $\mathrm{h} \to \mathrm{b}\bar{\mathrm{b}}$. In these models the Higgs would be discovered in SUSY events at the LHC rather than by the traditional Standard Model-like Higgs searches. The mass of $\mathrm{b}\bar{\mathrm{b}}$ pairs is shown in Fig. 5(a) after the following cuts: $\not{E}_T > 300\,\mathrm{GeV}$; more than two jets with $p_T > 100\,\mathrm{GeV}$ and more than one with $|\eta| < 2$; no isolated leptons to suppress the $\mathrm{t}\bar{\mathrm{t}}$ background; only two b-jets with $p_{T,\mathrm{b}} > 55\,\mathrm{GeV}$ and $|\eta| < 2$; $\Delta R_{\mathrm{b}\bar{\mathrm{b}}} < 1.0$ again to suppress the $\mathrm{t}\bar{\mathrm{t}}$ background. This gives a clear peak in the $\mathrm{b}\bar{\mathrm{b}}$ mass distribution at the Higgs mass. The SM background is very small and the dominant background is from other SUSY decays. This method works over a large region of parameter space in SUGRA Models, Fig. 5(b).

In the regions of parameter space where the decay mode $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mathrm{h}$ is not kinematically accessible, the reconstruction of the leptonic decay mode is necessary in order to constrain the $\tilde{\chi}_2^0$ mass. The important decay modes are either via a real slepton, Fig. 6(a), or via virtual sleptons and gauge bosons Fig. 6(b). In Fig. 6b there is also a peak at the Z mass due to the production of Z bosons in other SUSY decays.

The leptons produced in neutralino decays can be combined with the other decay products of the heavier SUSY particles in order to reconstruct them. For example the

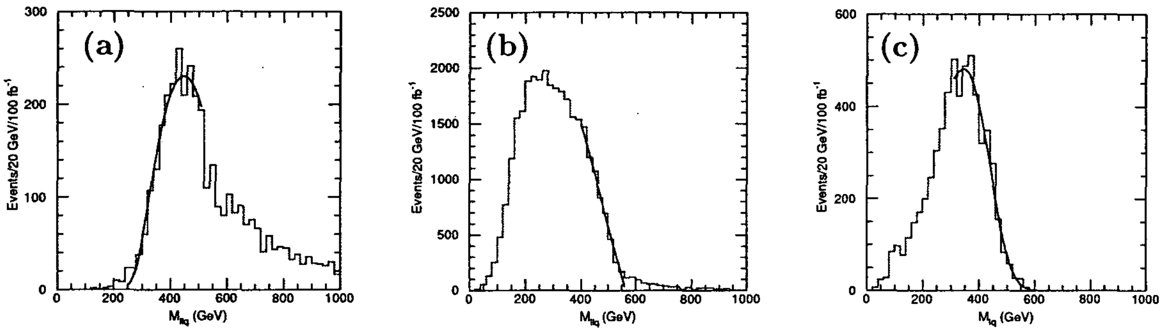


Figure 7. (a) Distribution of the larger $\ell^+\ell^-$q mass for $M_{\ell\ell} > M_{\ell\ell}^{\max}/\sqrt{2}$. (b) The smaller of the two $\ell^+\ell^-$q masses for the signal. (c) The $\ell^\pm$q mass distribution for combinations with $M_{\ell^+\ell^-\mathrm{q}} < 600\,\mathrm{GeV}$. Plots taken from [3].

$\tilde{\chi}^0_2$ is often produced in left squark decays, $\tilde{\mathrm{q}}_L \to \mathrm{q}\tilde{\chi}^0_2 \to \mathrm{q}\tilde{\ell}\ell \to \mathrm{q}\ell^+\ell^-\tilde{\chi}^0_1$. In order to identify this decay chain the following cuts are applied: two isolated leptons with transverse momentum, $p_T > 10\,\mathrm{GeV}$; more than four jets one with $p_T > 100\,\mathrm{GeV}$ and the rest with $p_T > 50\,\mathrm{GeV}$; missing transverse energy $\not{E}_T > \max(100.0, 0.2M_{\mathrm{eff}})$. The mass of the q$\ell\ell$ has a maximum at

$$M_{\ell\ell\mathrm{q}}^{\max} = \left[\frac{\left(M^2_{\tilde{\mathrm{q}}_L} - M^2_{\tilde{\chi}^0_2}\right)\left(M^2_{\tilde{\chi}^2_0} - M^2_{\tilde{\chi}^0_1}\right)}{M^2_{\tilde{\chi}^0_2}}\right]^{\frac{1}{2}}, \tag{2}$$

where $M^2_{\tilde{\mathrm{q}}_L}$ is the squark mass and $M_{\tilde{\chi}^0_{1,2}}$ are the lightest and next-to-lightest neutralino masses respectively. This distribution is shown in Fig. 7(a). The minimum of this distribution, Fig. 7(b), and the ℓq distribution, Fig. 7(c), also provide useful information. This system has four constraints, *i.e.* the upper edges in ℓq, $\ell\ell$ and $\ell\ell$q distributions, and the lower edge in the $\ell\ell$q distribution, and four unknowns, *i.e.* $M_{\tilde{\chi}^0_1}$, $M_{\tilde{\chi}^0_2}$, $M^2_{\tilde{\mathrm{q}}_L}$ and $M^2_{\tilde{\ell}_R}$ which can therefore be reconstructed. The errors on the $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\mathrm{q}}_L$ and $\tilde{\ell}_R$ masses are 12 %, 6 %, 3 % and 9 %, respectively. The mass of the unobserved LSP is determined, Fig. 8. The errors on the particle masses are strongly correlated and a precise determination of one mass would reduce the errors on the rest [16].

In GMSB models a similar type of analysis is possible. For example, consider a case where the NLSP is the lightest neutralino which then decays to a gravitino and a photon, *i.e.* $\tilde{\chi}^0_1 \to \gamma\tilde{\mathrm{G}}$. As in SUGRA models the $\tilde{\chi}^0_2$ can decay leptonically to give the lightest neutralino. This gives the decay chain, $\tilde{\chi}^0_2 \to \ell^+\ell^-\tilde{\chi}^0_1 \to \ell^+\ell^-\gamma\tilde{\mathrm{G}}$. If we require $M_{\mathrm{eff}} > 400\,\mathrm{GeV}$; $\not{E}_T > 0.1M_{\mathrm{eff}}$; at least two leptons and two photons where photons and electrons have $p_T > 20\,\mathrm{GeV}$ and muons $p_T > 5\,\mathrm{GeV}$. Here information can be obtained from the $\ell^+\ell^-$, $\ell^+\ell^-\gamma$ and $\ell^\pm\gamma$ mass distributions. There are two structures in the $\ell^\pm\gamma$ distribution and therefore these distributions provide four constraints which are sufficient to measure the $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$ and $\tilde{\ell}_R$ masses in this model.

In AMSB models the signatures are very similar to SUGRA models except that the $\tilde{\chi}^+_1$ may not be observable due to the small mass difference between the lightest chargino

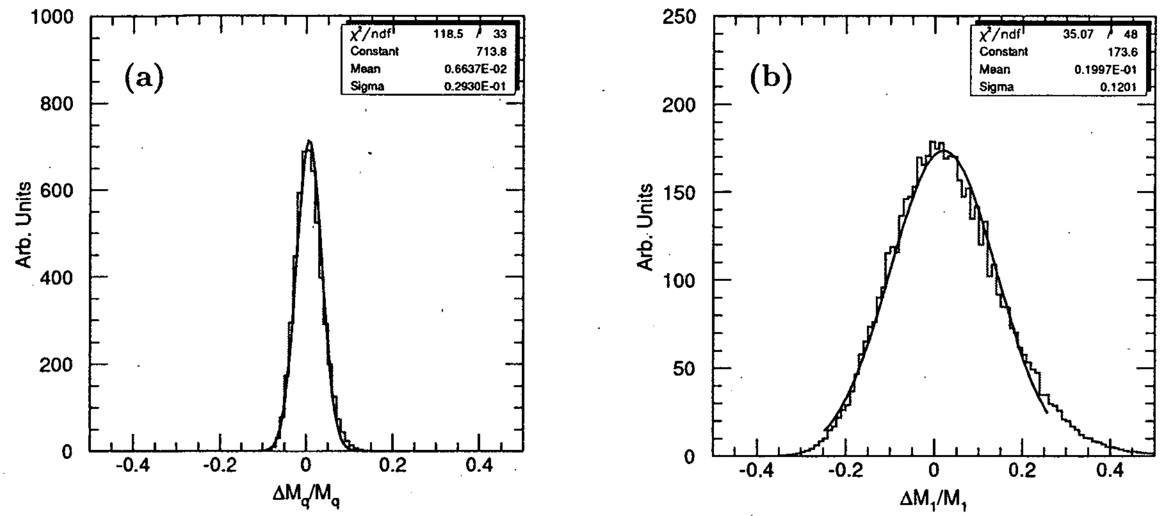


Figure 8. **(a)** Distribution of the fractional difference between the reconstructed and true squark mass. **(b)** Distribution of the fractional difference between the reconstructed and true $\tilde{\chi}^0_1$ mass. Both plots were taken from [3].

and the LSP.

The signatures of SUSY in models with R-parity violation are very different because the LSP can decay inside the detector which means there may be no missing transverse energy. The LSP will decay to give either leptons [3, 17], leptons and jets [3] or just jets [3, 18]. In these models the LSP mass can be found by reconstructing all its decay products which often allows the LSP mass to be measured with greater precision than is possible in SUGRA models.

5. Lepton Colliders

Any future linear collider will start operation after the LHC and therefore the study of supersymmetry at such a machine will be in the context of what we already know from the LHC. A collider with centre-of-mass energy of less than 1 TeV will probably concentrate on the sparticles which only interact weakly, *i.e.* the electroweak gauginos and sleptons. A higher energy collider may also be able to produce the squarks, however at any lepton collider production of gluinos is difficult, unless they are lighter than the squarks in which case they are produced in squark decays.

An e^+e^- machine has a number of advantages over a hadron collider: the energy of the beam provides a kinematic constraint; polarization of the electrons and possibly positrons provides a powerful tool and the signal to background ratio is of order one before cuts are applied. The great power of such a facility is the ability to make precise measurements of the masses and couplings of sparticles which may already have been observed at the LHC. All the examples we will consider are taken from [8]. Similar studies can also be found in [19]

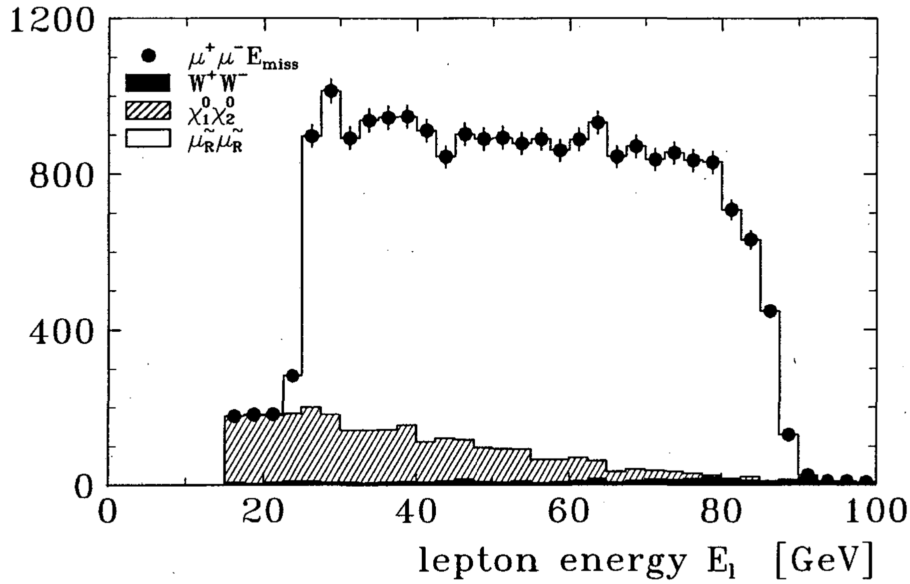


Figure 9. The energy spectrum E_μ of the muons produced in the process $e^+e^- \to \tilde{\mu}_R\tilde{\mu}_R \to \mu^-\tilde{\chi}_1^0\mu^+\tilde{\chi}_1^0$ at $\sqrt{s} = 320\,\text{GeV}$ for an integrated luminosity of $160\,\text{fb}^{-1}$. Plot taken from [8]

If we consider, for example, the production of smuons, $e^+e^- \to \tilde{\mu}^+\tilde{\nu}^- \to \tilde{\chi}_1^0\mu^+\tilde{\chi}_1^0\mu^-$, the events will have a $\mu^+\mu^-$ pair and missing energy. The energy spectrum of the muons is shown Fig. 9. This spectrum is flat apart from beamstrahlung, initial-state radiation and resolution effects at the high edge. The end points of this distribution can be related to the masses of the smuon and lightest neutralino. Using this process both the $\tilde{\chi}_1^0$ and $\tilde{\mu}$ masses can be determined to $\sim 0.5\,\%$. If the polarization of the beams is changed the amount of left and right slepton in the mass eigenstate can also be determined. In the case shown in Fig. 9 the machine is below threshold for the other SUSY particles, apart from $\tilde{\chi}_1^0\tilde{\chi}_2^0$, and therefore the SUSY background is small. The Standard Model background is even smaller after event selection.

The heavier gauginos can also be produced, *e.g.* $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \ell^+\ell^-\ell^+\ell^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ at sufficiently high center of mass energy. The dilepton masses and energies for this process are shown in Fig. 10. The masses of both the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ can be determined from the di-lepton energy spectrum with typical errors of about 0.2%. The di-lepton mass spectrum gives additional information on the mass difference between the two leptons and this difference can typical be measured with a precision of better than 50 MeV.

These mass measurements will be more accurate than those achievable by the LHC, if the lepton collider has sufficient energy to produced the particles. Furthermore it should be possible to determine the mixings in the gaugino sector which is difficult at the LHC. Note that, as discussed above, the extraction of masses at the LHC may result in strongly correlated errors. Measurements from a linear collider of some masses could therefore be used to improve the errors on the LHC results for the heavier particles, *e.g.* the squarks, which the lepton collider may not be able to produce.

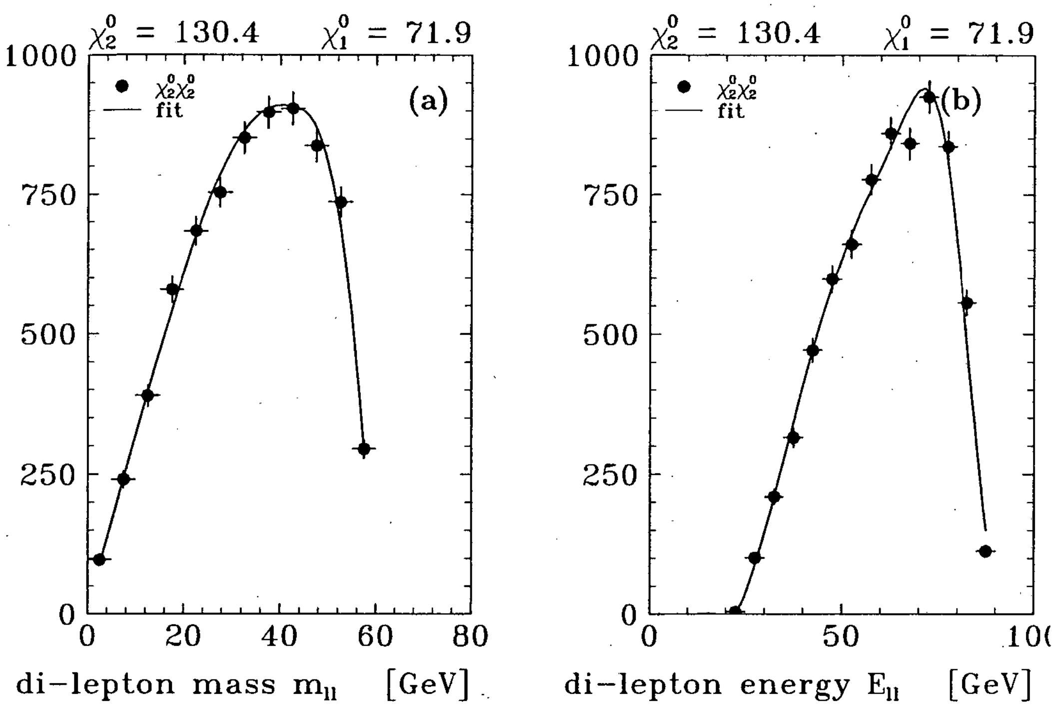


Figure 10. **(a)** The di-lepton mass and **(b)** di-lepton energy spectrum for $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0\ell^+\ell^-\tilde{\chi}_1^0$ at $\sqrt{s}$ = 320 GeV for an integrated luminosity of 160 fb^{-1}. Plot taken from [8]

6. Conclusions

The upgraded Tevatron has some search potential for supersymmetry however, given the current limits, the event rates will be low. The most promising signal is from tri-leptons produced following the production of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, but the search range is limited.

The production rate of SUSY particles at the LHC is very large unless the squarks and gluinos are very heavy. Looking for signals of direct production of gauginos and sleptons is difficult but not impossible (jet vetoes have to be used). It is very difficult to observe the heavier gauginos unless they are strongly mixed because otherwise they are mainly Higgsino and therefore do not couple to the squarks and so cannot be produced in their decay.

A future e^+e^- collider would be a very powerful tool for precise measurements of masses and couplings provided that the energy is high enough. A few precise measurements made with such a machine could, in combination with the LHC measurements, greatly constrain the underlying model.

We are approaching the end of an era. Low energy supersymmetry has been studied for the last twenty years, without any experimental verification. However the within the next eight years or so, the searches will reach high enough mass scales so that it will either be discovered or cease to be relevant to the problem of electro-weak symmetry breaking.

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