DEVELOPMENTS IN SUPERSYMMETRY
PHENOMENOLOGY

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We survey strategies generally employed for SUSY discovery at colliders and then discuss how these may have to be altered for SUSY searches at the Tevatron if \( \tan \beta \) is large. We also discuss the reach of the Tevatron and the LHC in gauge-mediated SUSY breaking scenarios, assuming that the NLSP decays into photons. Finally, we briefly recapitulate measurements (which serve to guide us to the underlying theory) that might be possible at future colliders if supersymmetry is discovered.

Weak scale supersymmetry is now a mature subject, and much theoretical and experimental effort has been expended in the development of strategies for sparticle searches at colliders. As yet no direct signal has been found in experiments at LEP2 and at the Tevatron. The absence of any signal has been translated into lower limits on sparticle masses. This translation is always done within the framework of a model, frequently taken to be the mSUGRA model, or sometimes, the MSSM supplemented with ad hoc assumptions about squark/slepton masses and gaugino masses, together with the conservation of \( R \)-parity. Some searches are less sensitive to these assumptions than others: for example, it is not unreasonable for charged slepton searches at LEP to assume that other charged sparticles are heavier (since they would otherwise have been found), and that the slepton directly decays to the lightest SUSY particle (LSP) which is frequently the neutralino \( \tilde{Z}_1 \). For other searches, such as those for squarks and gluinos at the Tevatron or LHC, cascade decays are very important, and the signals depend on properties of all sparticles lighter than these.

Analyses from LEP2 have resulted in bounds \( m_{\tilde{W}_1} \gtrsim 87 - 91 \text{ GeV}, \)
\( m_{\tilde{t}_R} \gtrsim 85 \text{ GeV} \) and \( m_{\tilde{\mu}_R} \gtrsim 75 \text{ GeV} \), the exact value depending on \( m_{\tilde{Z}_1} \). At the Tevatron, the D0 and CDF collaborations have reported negative results for their searches for gluinos and squarks in the \( E_T \) as well as dilepton channels (the CDF collaboration has searched in the same sign (SS) dilepton channel).

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characteristic of the production of Majorana gluinos), resulting in a lower mass bound of \( m_{\tilde{g}} \gtrsim 180 \) GeV (\( \gtrsim 250 \) GeV if \( m_{\tilde{q}} \approx m_{\tilde{g}} \)). These limits, which are reviewed in Ref.\(^2\), vary somewhat with the model, and may be considerably weaker for some ranges of mSUGRA parameters. It is significant that the bounds via the dilepton channels are already competitive with those from the \( E_T \) channel. With a data sample of several fb\(^{-1}\) that will be accumulated at the Main Injector (MI) or its luminosity upgrades, the reach via multi-lepton channels may exceed that via the canonical \( E_T \) search. Within any framework, such as mSUGRA, where electroweak gauginos are expected to be considerably lighter than the coloured gluinos, essentially background-free clean trilepton events (that are free from hadronic activity other than that due to QCD radiation) from \( \tilde{W}_1 \tilde{Z}_2 \) production potentially offer the greatest reach for supersymmetry at the Tevatron: for values of parameters where leptonic decays of \( \tilde{W}_1 \) and \( \tilde{Z}_2 \) are strongly enhanced, experiments in the MI era may probe \( m_{\tilde{1}/2} \) values as large as 225 GeV, corresponding to gluinos as heavy as 600 GeV. It should, however, be kept in mind that there are other regions of parameter space where the branching fraction for the decay \( \tilde{Z}_2 \rightarrow \ell \bar{\ell} \tilde{Z}_1 \) is strongly suppressed, so that there may be no detectable trilepton signal even for charginos below the LEP bound. Thus, while the clean trilepton channel may lead to a spectacular discovery of SUSY, non-observation of any signal will not result in unambiguous lower bounds of \( m_{\tilde{W}_1} \) or \( m_{\tilde{Z}_2} \).

Our discussion up to now has been limited to small values of the parameter \( \tan \beta \) for which bottom and \( \tau \) Yukawa couplings may be neglected. For larger values of \( \tan \beta \), these Yukawa interactions have two important effects. First, they lead to a reduction of \( m_{\tilde{b}_1} \) and \( m_{\tilde{\tau}_1} \) relative to the masses of corresponding first and second generation sfermions. Second, when Yukawa couplings are sizeable, contributions to chargino and neutralino decay mediated by Higgs scalars as well as those due to Higgsino components of neutralinos and charginos can considerably modify chargino and especially neutralino decay patterns. Both these effects enhance decays of neutralinos, charginos and even gluinos to third generation particles as illustrated in Fig. 1. We see that Yukawa coupling effects show up as non-universal leptonic branching fractions of \( \tilde{W}_1 \) and \( \tilde{Z}_2 \) for \( \tan \beta \) as small as 5-10. For still larger values of \( \tan \beta \), the decays to tau (bottom) increasingly dominate chargino and neutralino (gluino) decays, and for extremely large values of \( \tan \beta \) two body decays to third generation sfermions may become accessible.

These modifications due to Yukawa couplings have been incorporated in the simulation program ISAJET.\(^4\) The most important effect of these is that they reduce the cross sections for clean or jetty isolated multilepton events which we have just seen potentially provide the greatest SUSY reach at the
Figure 1: The dependence of various branching fractions on $\tan \beta$. In (a) and (b), we take the parameters $(m_0, m_{1/2}, A_0) = (150, 150, 0)$ GeV while (c) uses $(m_0, m_{1/2}, A_0) = (700, 250, 0)$ GeV. In all frames, $\mu > 0$ and $m_t = 170$ GeV.

luminosity upgrades of the Tevatron. In order to assess the prospects for detecting supersymmetry signals with tagged $b$-jets or tau leptons, we have performed an ISAJET simulation where in addition to the usually searched for (a) $E_T + \text{jets}$, (b) multijets + $n$ lepton ($e$ or $\mu$), $n = 1 - 3$ (SS and opposite sign (OS) for $n = 2$), (c) clean OS dileptons and (d) clean trilepton channels, we have also examined the detectability of SUSY at the Tevatron via (e) multijet + tagged $b/\tau$, (f) multijet + OS and SS dilepton or trilepton channels where at least one of the leptons is identified as $\tau$, and finally, (g) clean OS dilepton and trilepton channels where one of the leptons is identified as tau. In our simulation, we assume that jets with $E_T > 15$ GeV with just 1 or 3 charged prongs within $10^\circ$ of the axis and no other charged prongs within $30^\circ$ and with invariant mass smaller than $m_\tau$ are hadronically decaying taus. We also identify central $b$ jets with an efficiency of 50%. The result of our computation is summarized in Fig. 2 where we have scanned the $m_0 - m_{1/2}$ plane for several values of $\tan \beta$ to see if there is an observable signal in any of these channels. We have taken $A_0 = 0$. The grey (hollow) squares denote points where there is a 5σ signal above background with a minimum of 5 expected signal events, assuming an integrated luminosity of 2 $fb^{-1}$ $(25 fb^{-1})$ at a $\sqrt{s} = 2$ TeV $p\bar{p}$ collider. The bricked (shaded) regions of the plane are excluded by theoretical (experimental) constraints. Several comments are in order.

- The $E_T$, $E_T + b$, clean $3\ell$ and clean $3\ell$ with an identified tau channels establish the entire plot, though for some points a signal may also be observable in other channels. The region where the signal should be observable falls sharply with increasing values of $\tan \beta$. Indeed for the
largest values of $\tan \beta$ we see that there are no regions beyond LEP bounds where there will be an experimental signature at the MI.

- We have used rather hard cuts for the clean lepton channels which allow secondary $e$ and $\mu$ from decays of taus to pass with a very low efficiency. A subsequent study by the Wisconsin Group has shown that by using softer cuts for the clean trilepton sample, there would be additional ranges of parameters where a signal is just observable above physics backgrounds even if $\tan \beta$ is large. Potentially worrisome non-physics backgrounds where a soft jet is mis-identified as one of the leptons, or a heavy quark fakes an isolated lepton, are thought to be under control.

- Although the cross section for events with hadronically decaying taus is large, such taus are identified with very low efficiency in our simulation because we require the visible hadronic decay products to have $E_T > 15$ GeV. We urge our experimental colleagues to examine strategies to reliably identify hadronically decaying taus with smaller visible $E_T$, since this could significantly extend the region of the mSUGRA plane where there would be an observable signal if $\tan \beta$ happens to be large. This is desirable even in light of the soft lepton signal mentioned
above, since observation of a tau excess would indicate a source of lepton non-universality (though not necessarily large tan β).

Within the mSUGRA framework, $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}$ production are the dominant SUSY processes at the LHC if gluinos and squarks are lighter than 1-2 TeV. Once produced, the gluinos and squarks cascade decay to charginos and neutralinos, until the cascade terminates in the stable LSP. Sparticle production is thus signalled by multijet + multilepton + $E_T$ events. There may also be clean multilepton events from $\tilde{W}_1$ and $\tilde{Z}_2$ production, but these yield a smaller reach. Several studies have shown that within this framework, experiments at the LHC should be able to probe gluinos and squarks even if they are as heavy as 2 TeV. Although these studies have been performed for low tan $\beta$, unlike for the Tevatron, the LHC reach is more or less independent of tan $\beta$. The reason is that for a large range of mSUGRA parameters, $m_{\tilde{Z}_1} \simeq \frac{1}{3} m_{\tilde{W}_1}$, $\tilde{W}_1$, and $m_{\tilde{Z}_2} \simeq \frac{1}{6} m_{\tilde{g}}$, so that charginos and neutralinos have two body decays to real $W$, $Z$ and Higgs bosons if gluinos are heavy; their branching fractions to third generation fermions are thus determined by the decays of the bosons, and so are insensitive to tan $\beta$, except for small values of $m_0$ where decays to $\tilde{\tau}_1$ may be accessible but not decays to other sleptons. Our analysis bears out that for large tan $\beta$ the region of the $m_0 - m_{1/2}$ plane that can be explored at the LHC is qualitatively similar to that in our previous studies, except for low values of $m_0$ where the reach in $m_{1/2}$ is reduced from over 1 TeV to about 850 GeV. For parameter ranges where chargino and neutralino decays to stau are accessible or where three body decays dominate, we may expect significant lepton non-universality in SUSY events. We are currently exploring whether a detailed study of the tau rate and polarization could provide an independent indication that tan $\beta$ is large.

Supersymmetry should be readily discoverable at future $e^+e^-$ colliders, provided these have sufficient energy to pair produce charged sparticles or visibly decaying sneutrinos. The projected reach of Linear Colliders is compared to that of the LHC and Tevatron upgrades in Fig. 3, where the bricked and hatched regions have the same meaning as before. For the purposes of reach and for this purpose alone, a Linear Collider with a centre of mass energy between 1 and 1.5 TeV would have an mSUGRA reach comparable to the LHC.

Sparticle masses can be precisely (1-2% for $\tilde{l}, \tilde{\nu}, \tilde{W}_1$ and ~5% for $\tilde{t}_1$) measured at Linear Colliders, even if these cascade decay to the LSP. If SUSY is discovered, it should be possible to set up an essentially model-independent program at the NLC to measure sparticle properties. Such measurements provide us with guide posts that may help us unravel the dynamics of SUSY.
The availability of a polarized electron beam as well as variable but precisely tuned beam energy are crucial for these measurements. Some mass measurements, particularly of mass differences from a determination of kinematic endpoints, are also possible at the LHC. Indeed, it has been shown that it should be possible to use LHC measurements to test for consistency of (and hence falsify!) well-defined models, such as mSUGRA or gauge-mediated SUSY breaking models, with relatively few parameters. Various case studies show that it should also be possible to determine the mSUGRA parameters $m_{1/2}$ and $m_0$ from the data. It is, however, presently unclear how to directly go from LHC data to the underlying model. This is important since it is quite possible that none of the models that we have thought about will turn out to be right. In fairness though, such studies have only just begun, and much work remains to be done along this direction.

We have become accustomed to various assumptions about symmetries of physics at very high energy, that leads to the mSUGRA model (with its universal parameters) as the effective theory below the Planck scale. It is important to keep in mind that these assumptions may prove to be invalid. Testing these assumptions should be an integral part of any supersymmetry program, and our discussion shows that this should be possible at future $pp$ and lepton supercolliders.

Many SUSY searches (especially at hadron colliders) rely on $E_T$ from the undetected LSPs to discriminate the SUSY signal from Standard Model backgrounds. In models where $R$-parity is not conserved, the LSP (frequently the lightest neutralino) decays into ordinary particles, and the $E_T$ is considerably reduced. Assuming a minimal particle content, at least one of lepton or baryon
numbers is not conserved in $R$-parity violating models. In the former case, the LSP decays into leptons (possibly together with jets), so that even though $E_T$ is reduced, SUSY events result in increased cross sections for isolated multi-lepton topologies which have small backgrounds. In the most favourable case where the LSP decays only via $\tilde{Z}_1 \to \ell\ell\nu$ ($\ell, \ell' = e, \mu$), it should be possible to explore parameter ranges corresponding to $m_{\tilde{g}} = 800$ GeV even at the MI. The (almost) worst case scenario, however, is when the LSP decays entirely hadronically via $\tilde{Z}_1 \to qqq$ (or $\bar{q}q\bar{q}$): not only is the $E_T$ reduced, but leptons from chargino and neutralino decays find it harder to remain isolated. There may then be no observable signal at the MI if gluinos are heavier than about 200 GeV. Assuming, however, that LSP decay is the only significant effect of $R$ violating interactions, it has been shown that experiments at the LHC should still be able to probe gluino and squarks with masses up to 1 TeV even in this unfavourable case.

Models where gauge interactions, and not gravity, serve to mediate SUSY breaking effects to Standard Model particles and their superpartners have recently received a lot of attention. In these scenarios, the SUSY breaking scale $\sqrt{F}$ can be (but is not necessarily) as low as $O(100)$ TeV, so that the gravitino mass $m_{\tilde{G}} \sim F/M_P$ can be as small as $O(1 \text{ eV})$. The coupling of the longitudinal components of such superlight gravitinos to 100 GeV sparticles, while small compared to gauge couplings, is not negligible since it may cause the next lightest SUSY particle (NLSP) to decay into the gravitino within the experimental apparatus. The decay patterns of other sparticles are still governed by their (much larger) gauge and Yukawa couplings, and are essentially unaffected.

Collider signatures from such models depend very much on what the NLSP is, and also on its lifetime. If the NLSP is a neutralino, it can decay into a photon (and possibly also a $Z$ or Higgs boson) and a gravitino. If it decays outside the detector, the expected topologies are qualitatively similar to those within the mSUGRA model, though the relative cross sections may be different on account of differences in the mass spectra. If the NLSP decays inside the detector, SUSY events contain up to two isolated photons in addition to jets and leptons. The unstable NLSP need not be neutral. In many models, it is a charged slepton (frequently stau), in which case charginos and neutralinos (which may be secondary products of squark and gluino decays) decay into the stau/slepton ($\tilde{e}_R, \tilde{\mu}_R$) NLSP which then decays into tau/($e$ or $\mu$) and a gravitino. SUSY events then contain an abundance of taus/leptons. The NLSP may be quite long lived, so that its decay products emerge from a secondary vertex whose displacement could provide an additional handle on the signal: in particular, it could yield a measure of the SUSY breaking scale. A very long-
lived charged NLSP that makes it through the detector would be signalled\cite{16} by highly ionizing tracks.

We have simulated signals from gauge mediated models with a neutralino NLSP that decays promptly into photons using ISAJET. In the simplest of these models, Tevatron experiments would already be sensitive\cite{17} to values of the parameter $\Lambda$ (which fixes the sparticle mass scale) smaller than 50-60 TeV (corresponding to $m_{\tilde{\chi}} = 450$ GeV) via the multijet + isolated photons channel, while the corresponding reach of the MI would be as high as $m_{\tilde{\chi}} = 800$ GeV. The LHC should, via a search for inclusive $\gamma\gamma + jets + E_T$ events, be able to explore $\Lambda \leq 400$ TeV; this corresponds to $m_{\tilde{\chi}} \sim 2.8$ TeV, for which chargino and neutralino production is the dominant SUSY process. Finally we note that the $E_T$ spectrum of the photon in these events scales with the NLSP mass, and may yield information about the underlying parameters of the model. A study of this issue as well as of the reach of the LHC when the NLSP is a slepton is currently in progress.

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