SEARCHING FOR SUPERSYMMETRY: 
A MINIREVIEW

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ABSTRACT

After a lightning review of current bounds on the masses of supersymmetric particles, we describe strategies that may be helpful for extracting signals from the production of squarks, gluinos or top squarks, and from associated chargino-neutralino production at the Tevatron. We then briefly review SUSY signals at hadron and $e^+e^-$ supercolliders. We discuss how various SUSY signals may be correlated within the supergravity framework and indicate the sense in which $e^+e^-$ and hadron colliders may be complementary.

1 Current Status of Supersymmetry

Aesthetic issues aside, the interest in low energy SUSY phenomenology was originally driven by the recognition that SUSY can stabilize the gauge hierarchy provided sparticles are lighter than $O(1\,\text{TeV})$. More recently, the realization that the measured values of gauge couplings at LEP are in agreement with the minimal supersymmetric SU(5) model but \textit{incompatible} with minimal non-supersymmetric GUTs has led several groups to reexamine the expectations for sparticle masses and mixing patterns within the theoretically appealing supergravity (SUGRA) framework, the phenomenology of which we will return to in the last section. Experimental constraints from flavour changing neutral currents can readily be accommodated and, assuming $R$-parity is unbroken, SUSY models include a viable candidate for dark matter.

There is no direct evidence for sparticles in high energy collisions. This is not (yet) a cause for despair since, if we recall the original motivation for low

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energy SUSY, we would typically expect sparticle masses of 100-1000 GeV. Since SUSY theories are of the decoupling type in that virtual effects of sparticles decouple as $m_{SUSY} \to \infty$, the non-observation of any significant deviations from the Standard Model (SM) in precision experiments at LEP is compatible with (though not an argument for) low energy SUSY. The most straightforward limits on masses of sparticles with gauge couplings to the $Z$ come from a measurement of its total width; these limits on the mass of the slepton, the squark and the chargino ($\tilde{W}_1$), which are independent of how sparticles decay, are a few GeV below the kinematic bound $M_Z/2$. Exclusive searches and the measurement of the invisible and leptonic widths of the $Z$ yield (sparticle decay-dependent) lower limits even closer to $M_Z/2$. Since neutralinos ($\tilde{Z}_i$) couple to the $Z$ only via their Higgsino components, the bounds on their masses are sensitive to model parameters which determine the mixing patterns. The search for squarks and gluinos, because of their strong interactions, is best performed at hadron colliders. The non-observation of an excess of $E_T$ events at the Tevatron has enabled the D0 collaboration to infer lower limits of 150-160 GeV on their masses, improving on the earlier limit of $\sim 100$ GeV obtained by CDF; if $m_{\tilde{q}} = m_{\tilde{g}}$, the mass bound improves to 218 GeV. These bounds, which assume ten flavours of degenerate squarks, have some sensitivity to the model parameters which determine the cascade decay patterns of the $\tilde{q}$ and $\tilde{g}$. Within the minimal supersymmetric model (MSSM), which is the commonly used framework for experimental analyses, the Tevatron and LEP bounds together imply a lower bound just above 20 GeV on the mass of the $\tilde{Z}_1$ which, because $\tilde{Z}_1$ is assumed to be the (stable) lightest SUSY particle (LSP), may have some cosmological significance.

2 SUSY Search in the 1990’s

The LEP collider is expected to enter its second phase of operation around the end of next year when its energy will be upgraded to 175-200 GeV. Given a data sample of $O(100 \, pb^{-1})$, the clean environment of $e^+e^-$ collisions will readily enable experimentalists to search for charginos, sleptons, squarks and even Higgs bosons with masses up to 85-90 GeV ($b$-tagging capability may be necessary if $m_H \simeq M_Z$). The corresponding mass reach for neutralinos is sensitive to (model-dependent) mixing angles.

The D0 and CDF experiments are collectively expected to accumulate an integrated luminosity in excess of 100 $pb^{-1}$ by the end of the current Tevatron
run. In addition to extending the $E_T$ search region, the large increase in the data sample should enable them to (i) perform gluino and squark searches via multilepton events from their cascade decays, (ii) search for $\tilde{W}_1\tilde{Z}_2$ production via isolated trilepton events free of jet activity, and (iii) search for the lighter $t$-squark, $\tilde{t}_1$. Experimental analyses will be greatly facilitated by the recent incorporation\cite{4} of SUSY processes into ISAJET. We note that the Tevatron is unlikely to be able to detect sleptons beyond the range of LEP\cite{5}.

**Multilepton Signals from Gluinos and Squarks.** The conventional $E_T$ search for $\tilde{g}$ and $\tilde{q}$ is background limited. Even with an integrated luminosity of $1 \text{ fb}^{-1}$ that should be available with the Main Injector upgrade of the Tevatron, we anticipate a maximum reach of $\sim 270 \text{ GeV}$ ($\sim 350 \text{ GeV}$) if $m_{\tilde{q}} >> m_{\tilde{g}}$ ($m_{\tilde{q}} \simeq m_{\tilde{g}}$) in this channel\cite{6}. Heavy gluinos and squarks can also decay via the chargino and $\tilde{Z}_2$ modes which, unless suppressed by phase space, frequently dominate the decays of $\tilde{q}_L$ and $\tilde{g}$. The subsequent leptonic decays of the $\tilde{W}_1$ and $\tilde{Z}_2$ yield events with hard jets accompanied by 1-3 isolated, hard leptons and $E_T$. While there are substantial backgrounds to 1$\ell$ and $\ell^+\ell^-$ event topologies, the physics backgrounds in the $\ell^+\ell^\pm\ell^\mp$ and 3$\ell$ channels are essentially negligible, so that these search channels are essentially rate limited. These channels, which at the Main Injector have a reach\cite{7} of 230-300 GeV depending on $m_{\tilde{q}}$ and $m_{\tilde{g}}$, provide complementary ways of searching for gluinos and squarks at the Tevatron, and because they are free of SM backgrounds, may even prove superior if gluinos and squarks are very heavy.

**Search for Isolated Trilepton Events.** Associated $\tilde{W}_1\tilde{Z}_2$ production which occurs by $s$-channel $W^*$ and $t$-channel $\tilde{q}$ exchanges, followed by the leptonic decays of $\tilde{W}_1$ and $\tilde{Z}_2$ results in isolated trilepton plus $E_T$ events, with hadronic activity only from QCD radiation. SM backgrounds to the $3\ell + n_{\text{jet}} \leq 1$ signal are negligible, assuming that $WZ$ events can be vetoed with high efficiency by requiring $m_{\ell\ell} \neq M_Z$ within experimental resolution; a conclusive observation of a handful of such events would, therefore, be a signal for new physics. The branching fraction for leptonic decays of $\tilde{Z}_2$, and sometimes also of $\tilde{W}_1$, and hence, this signal, is enhanced if $m_\ell << m_{\tilde{q}}$ and the $\tilde{Z}_2\tilde{Z}_1Z$ is dynamically suppressed; this situation frequently occurs in SUGRA type models, if $m_{\tilde{q}} \simeq m_{\tilde{g}}$. Preliminary analyses by the CDF and D0 experiments\cite{8} (for large values of the Higgsino mass parameter, $\mu$) are already competitive with bounds from LEP. The experiments will soon explore\cite{4,5} parameter ranges not accessible at LEP and, under favourable circumstances, may be competitive with LEP II. Within the MSSM frame-
work, this reach translates to $m_{\tilde{g}} = 250 - 400$ GeV depending on $m_{\tilde{q}}, \mu$ and $\tan \beta$, the ratio of the two Higgs vacuum expectation values.

**Searching for Top Squarks at the Tevatron.** The large Yukawa interactions of the top family which mix $\tilde{t}_L$ and $\tilde{t}_R$ serve to reduce the mass of $\tilde{t}_1$, the lighter of the two mass eigenstates. In fact, it is theoretically possible that $\tilde{t}_1$ is essentially massless with other squarks and gluinos all too heavy to be produced at the Tevatron. The Tevatron lower limits on $m_{\tilde{q}}$, are derived assuming ten degenerate squark flavours, and so are not applicable to $\tilde{t}_1$. Currently, the best limit, $m_{\tilde{t}_1} \lesssim M_Z/2$, comes from LEP experiments; this bound can be evaded if the stop mixing angle and $m_{\tilde{t}_1} - m_{\tilde{Z}_1}$ are both fine-tuned, a possibility we do not entertain here.

The signals from top squark production depend on its decay patterns. For $m_{\tilde{t}_1} < 125$ GeV, the range of interest at the Tevatron, $\tilde{t}_1$ decays via the loop-mediated mode, $\tilde{t}_1 \rightarrow c \tilde{Z}_1$ when the tree level decay $\tilde{t}_1 \rightarrow b \tilde{W}_1$ is kinematically forbidden\[10\]. Stop pair production is then signalled by $E_T$ events from its direct decays to the LSP. With a data sample of 100 $pb^{-1}$, Tevatron experiments should be able\[11\] to probe stop masses up to 80-100 GeV, significantly beyond the present bounds. On the other hand, the tree level chargino mode dominates stop decays whenever it is kinematically allowed. The subsequent leptonic decay of one (or both) of the charginos lead to single lepton (dilepton) + $b$-jet(s)+$E_T$ events, very similar to those expected from $t\bar{t}$ pair production. Top production is thus a formidable background to the stop signal\[12\]. Also, for $m_t = 175$ GeV, $m_{\tilde{t}_1} = 100$ GeV and $m_{\tilde{W}_1} = 70$ GeV, stop events would contribute about 33% (20%) of the CDF top signal\[13\] in the 1$\ell$ (dilepton) channel. Special cuts need to be devised to separate stop from top events. Since stops accessible at the Tevatron are considerably lighter than $m_t$, and because the chargino, unlike $W$, decays via three body modes into a massive LSP, stop events are generally softer than top events. It has been shown\[14\] that by requiring $m_T(\ell E_T) < 45$ GeV ($p_T(\ell^+) + p_T(\ell^-) + E_T < 100$ GeV), in addition to other canonical cuts, stops with masses up to about 100 GeV should be detectable in the 1$\ell$ (dilepton) channel by the end of the current Tevatron run; for the single lepton channel sufficient $b$-tagging capability is also required.

### 3 Supersymmetry at Supercolliders

Direct searches at the Main Injector and LEP II will probe sparticle masses between 80-300 GeV; even assuming MSSM mass patterns, the chargino
search, by inference, will probe gluino masses up to about 400 GeV. Since the SUSY mass scale could easily be 1 TeV, it will, unless sparticles have already been discovered, be up to supercolliders such as the LHC at CERN or an $e^+e^-$ Linear Collider (*LC) to explore the remainder of the parameter space.

In the $E_T$ channel, the LHC can search\[14\] for gluinos and squarks with masses between 300 GeV to larger than 1 TeV. It is instructive to note that several multilepton signals must simultaneously be present\[15\] if any $E_T$ signal is to be attributed to squark and gluino production, though the various relative rates could be sensitive to the entire sparticle spectrum. The rate for like-sign dilepton plus $E_T$ events is enormous for $m_{\tilde{g}} \leq 300$ GeV; this ensures there is no window between the Tevatron and the LHC where gluino of the MSSM may escape detection\[14\]. Gluinos and squarks may also be a source of high $p_T$ $Z + E_T$ events at the LHC. The LHC can also search for “hadron-free” trilepton events from $\tilde{W}_1\tilde{Z}_2$ production. Backgrounds from top quark production can be very effectively suppressed\[16\] by requiring that the two hardest leptons have the same sign of charge. The signal becomes unobservable when the two-body decays $\tilde{Z}_2 \rightarrow (Z \text{ or } H) + \tilde{\ell}_1$ become accessible. The dilepton mass distribution in $\ell^+\ell^-\ell'$ events can be used to reliably measure $m_{\tilde{Z}_2} - m_{\tilde{\ell}_1}$. Selectrons and smuons with masses up to 250 GeV (300 GeV if it is possible to veto central jets with an efficiency of 99%) should also be detectable\[17\]. Finally, we note that with an integrated luminosity of 100 $fb^{-1}$ the $\gamma\gamma$ decays of scalar stoponium has been argued to allow for the detection of $\tilde{t}_1$ with a mass up to 250 GeV, assuming $\tilde{t}_1 \rightarrow b\tilde{W}_1$ (and, perhaps, also $\tilde{t}_1 \rightarrow bW\tilde{Z}_1$) is kinematically forbidden\[17\].

Charged sparticles (and sneutrinos, if $m_{\tilde{\nu}} > m_{\tilde{W}_1}$) should be readily detectable at the *LC. Unfortunately, most detailed $e^+e^-$ studies to date do not incorporate the cascade decays (which will be incorporated into ISAJET 7.11) of sparticles. The real power of these machines, however, lies in the ability to do precision experiments which can then be used to probe\[18\] unified models of interactions discussed in the next section. *LC is also the optimal facility to study the Higgs sector of SUSY\[19\].

4 Supergravity Phenomenology

Supergravity GUT models, via specific assumptions about the symmetries of interactions responsible for SUSY breaking, provide an economical framework for phenomenology by relating the many SUSY breaking parameters of the
MSSM. These relations hold at some ultra-high unification scale $M_X$ where these symmetries are manifest and the physics is simple. Complex sparticle mass and mixing patterns (recently incorporated into ISAJET 7.10), along with the correct breaking of electroweak symmetry emerge when these parameters are renormalized down to the weak scale as required for phenomenology. The model is completely specified by just four SUSY parameters which may be taken to be the common values of SUSY-breaking gaugino and scalar masses and trilinear scalar couplings, all specified at $M_X$, together with the Higgs sector parameter $\tan \beta$. In particular, $\mu$ and the pseudoscalar Higgs boson mass are determined. It is remarkable that even the simplest SUGRA GUTs are consistent with experimental constraints as well as cosmology[20].

Since the phenomenology is determined in terms of just four SUSY parameters, various SUSY cross sections become correlated. Different experimental analyses from $e^+e^-$ and hadron colliders can thus be consistently combined into a single framework[21], since various searches frequently probe different parts of the parameter space they often complement one another. It should, however, be remembered that this framework depends on assumptions about physics at the unification scale. For experimental analyses we, therefore, suggest using SUGRA models to obtain default values of MSSM input parameters, and then, to test the sensitivity of the predictions on the assumed SUGRA relations. Observation of sparticles would not only be a spectacular new discovery, but a measurement of their properties, particularly at linear colliders (where, it has been argued[18], it is possible to do precision measurements of sparticle parameters), would test various SUGRA assumptions, and so, serve as a telescope to the unification scale.

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