Chapter 6

Supersymmetric Physics

6.1 Introduction

The recent observation of the top quark by the CDF and DØ Collaborations [1, 2] provides the last quark in the Standard Model (SM). Future experiments at the highest energy accelerators should plan to search for signs of physics beyond the Standard Model as well as continue testing the Standard Model. A very well motivated candidate for physics beyond the Standard Model is supersymmetry (SUSY).

Supersymmetry [3] is needed to connect the Standard Model with an ultimate perturbative unification of the fundamental interactions. Recent measurements of the gauge couplings at LEP [4] show that the Standard Model, when extrapolated to very high energies, fails to provide such unification, whereas a supersymmetrized Standard Model works very well [5]. SUSY also solves the fine tuning problem associated with the Higgs mass and provides a natural candidate for cold dark matter. Thus, a direct search for SUSY phenomena at high energy particle accelerators is crucially important. Recent indirect indications provide optimism that superpartners may be accessible at Fermilab.

Previous studies [6] have examined the potential of various planned or proposed accelerators for the discovery of supersymmetry. All of these studies assume one interaction per beam crossing. In this report, we specifically examine the SUSY discovery potential at an upgraded Tevatron. Multiple interaction effects are taken into account. Experimental issues specific to the Tevatron are also discussed.

We first describe briefly phenomenological arguments for the existence of SUSY particles in the mass range between 100 GeV/c^2 and a few TeV/c^2. We show that a large fraction of the predicted mass range is accessible at the Tevatron through the search for the lower mass particles in the model. The capabilities for discovering SUSY particles at a luminosity-upgraded Tevatron (TeV33) are summarized for 2 fb^{-1}, 10 fb^{-1} and 100 fb^{-1}.

6.2 Motivations for SUSY

The Standard Model has been enormously successful in explaining a wide variety of physics. Its principles appear to be valid over a remarkable range, from cosmological phenomena in the very early universe, to all microscopic phenomena up to the electroweak energy of about 100 GeV. At present, aside from a few two or three standard deviation effects, the Standard Model is in agreement with all current experimental data. In spite of this, there are a number of "structural" defects in the Standard Model, related mainly to the Higgs phenomenon. The Standard Model gives no explanation for the breaking of $SU(2) \times U(1)$, but merely accommodates it by giving the square of the Higgs mass (m_H^2) an unphysical negative value. Further, the Higgs boson, being a spin zero particle, possesses a quadratic self mass divergence. It leads to large quantum corrections ($\mathcal{O}(M_X^2/M_W^2)$) if one assumed the Standard Model held up from the electroweak scale M_W to ultra-high energy scale M_X (*e.g.*, the GUT or Planck scales). This correction requires major fine tuning to specify parameters of the theory to 23 decimal places.

Supersymmetry can protect the electroweak scale from the large corrections in the Higgs sector [3]. SUSY treats Bose and Fermi degrees of freedom on an equal footing. For every Bose helicity state, there is a corresponding Fermi state. The Bose and Fermi states make equal and opposite contributions to the Higgs self energy, thus canceling the quadratic divergence. SUSY is likely the only symmetry that can solve this problem. Further, when combined with supergravity grand unification [7], the Higgs mechanism can be derived since the breaking of supersymmetry at the GUT scale leads to electroweak breaking at the Z scale. Currently, no other theory possesses a working natural explanation of the Higgs mechanism. In the Standard Model the Higgs mechanism is assumed. To maintain supersymmetry, however, one must assume the existence of the SUSY partners of the Standard Model particles (*i.e.*, the squarks, sleptons, gluino, etc.), 32 new particles as listed in Table 6.1. To prevent the fine tuning problem from re-arising, their masses must lie in the general range of

$$M_{SUSY} \simeq 100 \text{ GeV/c}^2 \text{ to } 1 \text{ TeV/c}^2.$$

Since the current CDF/DØ sensitivity for gluinos and squarks is about 170 GeV/c^2, one sees that the lack of present evidence for these particles is not surprising, but that they should be within reach of the next round of accelerator experiments.

The first (indirect) experimental indication for the existence of the new SUSY particles was shown with the 1990 precision LEP measurements of the Standard Model couplings, α_1, α_2, and α_3 [5]. When extrapolated to higher energies by the renormalization group equations, these three running couplings within the Standard Model with one Higgs doublet do not meet at a point. On the other hand, in the supersymmetrized Standard Model the couplings do meet at a GUT scale M_G of about 10^{16} GeV/c^2 within the experimental uncertainties. This requires that:

- the SUSY mass spectrum is consistent with the range between about 100 GeV/c^2 to a few TeV/c^2, just as was required to resolve the fine tuning problem;
- there exists two (and only two) Higgs doublets.

Table 6.1: List of supersymmetric partners and Higgs bosons. Here, $\tilde{t}_i, \tilde{b}_i$, and $\tilde{\tau}_i$ $(i = 1, 2)$ are mixtures of the corresponding left- and right- chiral scalar fields, charginos are mixtures of charged higgsino and wino, and neutralinos are mixtures of two neutral higgsinos, bino and the neutral wino.

Particle Name	Spin	Physical States
squarks	0	$\tilde{d}_L$, $\tilde{u}_L$, $\tilde{s}_L$, $\tilde{c}_L$, $\tilde{b}_1$, $\tilde{t}_1$, $\tilde{d}_R$, $\tilde{u}_R$, $\tilde{s}_R$, $\tilde{c}_R$, $\tilde{b}_2$, $\tilde{t}_2$
sleptons	0	$\tilde{e}_L$, $\tilde{\nu}_{eL}$, $\tilde{\mu}_L$, $\tilde{\nu}_{\mu L}$, $\tilde{\tau}_1$, $\tilde{\nu}_{\tau L}$, $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_2$
charginos	$\frac{1}{2}$	$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$
neutralinos	$\frac{1}{2}$	$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$
gluino	$\frac{1}{2}$	$\tilde{g}$
Higgs bosons	0	h, H, A, $H^{\pm}$

The supersymmetrized Standard Model with two Higgs doublets plus grand unification is thus consistent with the low energy LEP measurements.

With two Higgs doublets, there are five physical Higgs states (3 neutral and 2 charged Higgs bosons): h, H^0, A^0, $H^{\pm}$. Supersymmetry predicts one of them to be a relatively light Higgs boson. The lightest Higgs boson (h) should be lighter than the Z^0 at tree level. However, a large top-quark Yukawa coupling induces a correction to the prediction at the one-loop level. The upper bound is pushed up to

$$M_h \simeq 130 \text{ GeV/c}^2.$$

This limit is beyond the reach of LEP-II, but may be possible to detect via the $h \to b\bar{b}$ mode (see "Light Higgs Physics" chapter) at TeV33.

The above description of supersymmetry has been refined over the past four years with improved data and more accurate theory, and has withstood the test of time. One has the outline of a minimal model to describe physics beyond the Standard Model and yet be consistent with all the LEP data supporting the Standard Model: *a supersymmetrized Standard Model with two Higgs doublets, with this spectrum holding up to M_G.*

The minimal model does not predict the many new mass parameters associated with the new supersymmetric particles. However, in the minimal supergravity models, all SUSY effects are determined by only 4 additional parameters and one sign. These may be taken to be the following: m_0 (a common scalar mass - related to squark masses), $m_{1/2}$ (a common gaugino mass - related to gluino mass), A_0 (a common trilinear interaction amongst the scalars), $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$ (H_2 gives mass to up-quarks and H_1 to down-quarks and leptons), and the sign of μ (the Higgsino mixing parameter). The universality of m_0 automatically suppresses unwanted flavor changing neutral currents [1] (FCNC). Further, and most important, this makes *supersymmetry the most highly predictive proposal of physics beyond the Standard Model.*

[1] Non-universal models can be constructed, but they cannot deviate greatly from the universal ones in the FCNC channels. The existence of the superparticles below 1 TeV generally leads to large FCNC, especially in K^0-$\bar{K}^0$ oscillations. To avoid this requires the squark masses to be highly degenerate.

Models with R-parity conservation yield a natural candidate ($\tilde{\chi}_1^0$), the lightest neutralino, for the cold dark matter that astronomers now believe constitute the majority of matter in our galaxy and the universe. Remarkably, the relic abundance of these neutralinos left over from the Big Bang, is consistent with the amount required by cosmological theory of the inflationary scenario[8] over a wide range of the SUSY parameters.

If the representations used to break the GUT group are not too large, the low energy predictions are mostly independent of the GUT physics. Thus the theory does not need any commitment to a specific (and little understood) GUT dynamics.

The above discussion describes a supersymmetric theory that is relatively model independent, is highly theoretically motivated, calculationally straight forward, and depends on only a few parameters to describe a large amount of phenomena. The relatively few parameters in the theory, makes the theory highly predictive, and one may further limit the parameter space by the existing bounds on the SUSY parameters from LEP and the Tevatron, and most recently from the CLEO measurement of the $b \to s + \gamma$ decay. The recent measurement of the top mass by CDF and DØ also aids in restricting the parameter space (since the top is apparently quite close to its Landau pole value), and an accurate value of M_{top}, which might be expected from a Tevatron upgrade, would significantly help in making more precise SUSY particle predictions, within the assumed framework.

6.3 The SUSY Particle Spectrum

There are a minimum of 32 new particles in the SUSY+Higgs sector. In the most general model, these masses and their couplings are arbitrary parameters not constrained by the model. The large number of arbitrary parameters in the general SUSY model make experimental predictions difficult and unattractive. Even assuming a GUT hypothesis (SUSY-GUT), the number of arbitrary parameters remain large. As mentioned before, much progress has been made recently in developing a minimal model with few parameters. The models we studied in this report are mostly these minimal supergravity models (MSGM or Constrained MSSM in some literature) with only 4 arbitrary parameters and an arbitrary sign.

The supersymmetric partners to the particles in the Standard Model and the five Higgs states in the MSSM are shown in Table 6.1. Note that the charginos ($\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$) are mixtures of charged higgsino and wino states. In the literature, they are sometimes labelled as $\tilde{W}_1$ and $\tilde{W}_2$. Similar nomenclature is also used for the neutralino states.

Requiring unification of the coupling constants at the GUT scale ("the GUT hypothesis") leads to the following relationships at any scale:

$$\begin{aligned} M_{\tilde{W}} &= \frac{\alpha_2}{\alpha_3} M_{\tilde{g}} \\ M_{\tilde{B}} &= \frac{5\alpha_1}{3\alpha_2} M_{\tilde{W}} \end{aligned}$$

Confirmation of these mass-relations, would provide crucial insight into unification.

The current limits on the masses of SUSY particles are summarized in Table 6.2. Some of these limits are model specific. Note that all the current experimental limits on SUSY states

Table 6.2: Current mass limits on supersymmetric partners (some are model dependent).

Sparticle	Mass Limit	Comments
$\tilde{g}$	173 GeV/c^2	DØ & CDF
$\tilde{q}$	229 GeV/c^2	DØ & CDF ($M_{\tilde{q}} = M_{\tilde{g}}$)
$\tilde{t}_1$	100 GeV/c^2	DØ ($\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$)
	48 GeV/c^2	LEP140 (purely right stop and $M_{\tilde{\chi}_1^0} = 30$ GeV/c^2)
$\tilde{\chi}_1^\pm$	65 GeV/c^2	LEP140 (higgsino-like $\tilde{\chi}_1^\pm$ and $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} > 10$ GeV/c^2)
$\tilde{\chi}_2^0$	69 GeV/c^2	LEP140 (higgsino-like $\tilde{\chi}_2^0$ and $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} > 10$ GeV/c^2)
$\tilde{\chi}_1^0$	20 GeV/c^2	LEP
$\tilde{\ell}$	45 GeV/c^2	LEP
$\tilde{e}$	53 GeV/c^2	LEP140 (gaugino-like $\tilde{\chi}_1^0$ and $M_{\tilde{\chi}_1^0} < 35$ GeV/c^2)
$\tilde{\nu}$	43 GeV/c^2	LEP
h	60 GeV/c^2	LEP

are below the expected mass spectrum of weak scale MSSM. Therefore, it is not surprising that none of the SUSY particles have been found yet. A luminosity upgraded Tevatron or new accelerators are needed to explore the mass regime where weak scale MSSM is expected.

At hadron colliders, sparticles can be produced via the following lowest order reactions:

- $q\bar{q},\ gg,\ qg \rightarrow \tilde{g}\tilde{g},\ \tilde{g}\tilde{q},\ \tilde{q}\tilde{q}$ (strong production)
- $q\bar{q},\ qg \rightarrow \tilde{g}\tilde{\chi}_i^0,\ \tilde{g}\tilde{\chi}_i^\pm,\ \tilde{q}\tilde{\chi}_i^0,\ \tilde{q}\tilde{\chi}_i^\pm$ (associated production)
- $q\bar{q} \rightarrow \tilde{\chi}_i^\pm\tilde{\chi}_j^\mp,\ \tilde{\chi}_i^\pm\tilde{\chi}_j^0,\ \tilde{\chi}_i^0\tilde{\chi}_j^0$ ($\tilde{\chi}$ pair production)
- $q\bar{q} \rightarrow \tilde{\ell}\tilde{\nu},\ \tilde{\ell}\tilde{\ell},\ \tilde{\nu}\tilde{\nu}$ (slepton pair production)

Figure 6.1 shows the cross section for sparticle pair production as a function of the gluino mass assuming a mass relation in SUSY-GUTs. Once produced, sparticles rapidly decay to other sparticles initiating a cascade which ends with the LSP ($\tilde{\chi}_1^0$).

The Higgs bosons of the MSSM can be produced via direct s-channel subprocesses:

- $q\bar{q},\ gg \rightarrow h,\ H,\ A,\ H^\pm H^\mp,$

They can also be produced in association with other heavy quarks and vector bosons, and in some cases, via vector boson fusion.

6.4 "SUSY Physics" Search Strategies at TeV33

Historically, collider experiments have concentrated on the search for squarks and gluinos. At the maximum center of mass energy of 2 TeV, Figure 6.1 shows that the squark/gluino

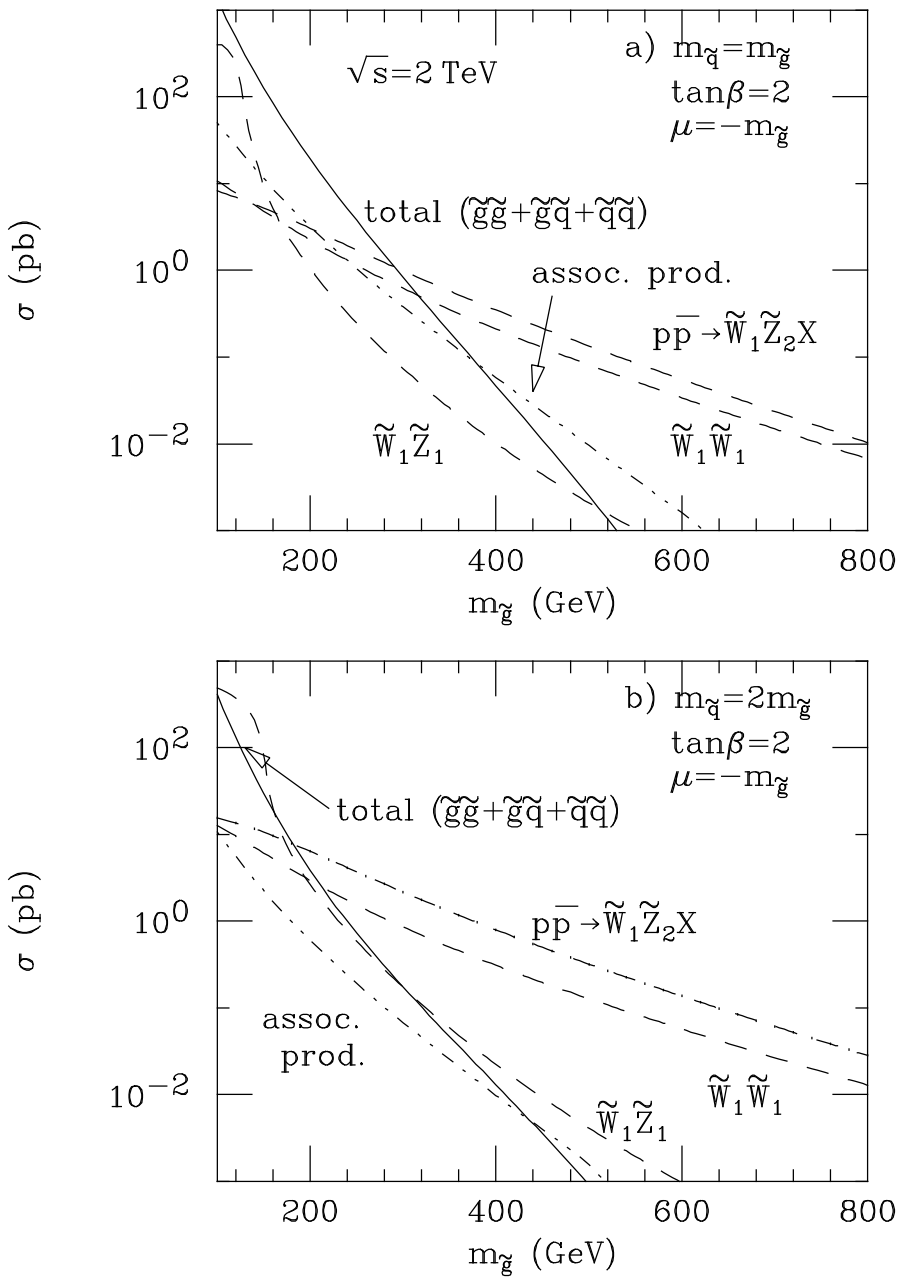


Figure 6.1: Cross section for sparticle pair-production as a function of the gluino mass for two specific parameter sets [6]; (a) $\tan\beta = 2$, $\mu = -M_{\tilde{g}}$, $M_{\tilde{q}} = M_{\tilde{g}}$, (b) $\tan\beta = 2$, $\mu = -M_{\tilde{g}}$, $M_{\tilde{q}} = 2\ M_{\tilde{g}}$.

Table 6.3: Search for Supersymmetric Partners (LSP = $\tilde{\chi}_1^0$)

Production	Key Decay Mode	Signature
$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$	$e.g., \tilde{g} \to qq\tilde{\chi}_1^0$, $\tilde{q} \to qqq\tilde{\chi}_1^0$ $(M_{\tilde{q}} > M_{\tilde{g}})$	$\not{E}_T$ + multijets
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\ell\nu$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$,	Trilepton + $\not{E}_T$
	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 qq$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$,	Dilepton + $\not{E}_T$ + jets
$\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to \tilde{\chi}_1^0 c$	$\not{E}_T$ + 2 acollinear jets
	$\tilde{t}_1 \to \tilde{\chi}_1^{\pm} b$, $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\ell^{\pm}\nu$, $\tilde{\chi}_1^{\mp} \to \tilde{\chi}_1^0 qq$	Single lepton + $\not{E}_T$ + b's
	$\tilde{t}_1 \to \tilde{\chi}_1^{\pm} b$, $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\ell^{\pm}\nu$, $\tilde{\chi}_1^{\mp} \to \tilde{\chi}_1^0\ell^{\mp}\nu$	Dilepton + $\not{E}_T$ + b's
$W/Z + h$	$h \to bb, \tau\bar{\tau}$	2 b's or 2 τ's

production cross section drops rapidly with higher gluino masses. The searches become kinematically limited. However, the lightest chargino and the second lightest neutralino are one-third to one-fourth as massive as the squark and gluinos. Their production cross sections become dominant for high gluino masses, thereby greatly enhancing the possibility of discovering supersymmetry at the Tevatron with large integrated luminosities.

Table 6.3 shows some of the channels which may be used to search for SUSY at the Tevatron. Clearly, we must maintain good parton identification capabilities with the Tevatron detectors in order to take full advantage of the high luminosities: good identification of leptons (e and μ), $\not{E}_T$ (ν and LSP), b-jets, and light quark/gluon jets.

Multiple interactions will be one of the major challenges faced at high luminosities. We will discuss some of the effects of multiple interactions on parton identification (specifically on lepton isolation, missing E_T resolution and b-tagging) in the next section. We will also explore the potential for SUSY discovery for specific channels in a high luminosity environment.

6.5 Physics Reaches at TeV33

6.5.1 Search for the Lightest Chargino using Trilepton Events

One of the most promising channels for the discovery of SUSY at a hadron collider is the trilepton final state [9] arising from chargino-neutralino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) pair production with subsequent leptonic decays ($\tilde{\chi}_1^{\pm} \to \ell\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell\bar{\ell}\tilde{\chi}_1^0$) in the framework of the Minimal Supersymmetric Standard Model.

Trilepton analysis at $\sqrt{s}$ = 1.8 TeV and 100 pb^{-1}

The current CDF and DØ analyses use inclusive electron and muon trigger samples at $p_T^{trig} \sim 10$ GeV/c when $\mathcal{L} < 1 \times 10^{31}$ cm^{-2}·sec^{-1}, and/or a lower p_T ($e.g., p_{T1}^{trig} > 8$ GeV/c, $p_{T2}^{trig} > 3$ GeV/c) dilepton trigger sample at higher luminosity, $\mathcal{L} > 1 \times 10^{31}$ cm^{-2}·sec^{-1}. The signal event must contain three isolated leptons. After some additional requirements, both

CDF and DØ found zero event candidates in Run 1A data. This is completely consistent with CDF/DØ estimate of the backgrounds (Drell-Yan, Z, $b\bar{b}$, $t\bar{t}$ and diboson). The current CDF and DØ limits[2] (from Run 1A) of the chargino mass are comparable to the LEP result [10].

The DØ analysis requires a cut on $\not\!\!E_T$ (> 10 GeV), while the CDF analysis does not require any $\not\!\!E_T$ cut. These analyses are optimized for a low mass chargino search at the level of 20 pb^{-1}. With 100 pb^{-1}, we need to reduce some backgrounds (Drell-Yan, Z and $b\bar{b}$) substantially by using a $\not\!\!E_T$ cut. With $\not\!\!E_T > 15$ GeV, the total background will be $\sigma_{BG} \sim$ 4 fb, while a large fraction of signal events will be accepted (*e.g.*, about 80% for 70-GeV/c^2 $\tilde{\chi}_1^{\pm}$). With this higher $\not\!\!E_T$ cut, the total number of background events is expected to be less than one at 100 pb^{-1}. The 95% confidence level (C.L.) upper limit curve at 100 pb^{-1} is extrapolated from the current Run 1A results. We find that chargino masses up to 70 GeV/c^2 can be probed with 100 pb^{-1}. Since this limit is model specific, we extract the maximum reach from Fig. 1 of Ref. [11] and find the reach could be as large as 90 GeV/c^2 in some region of parameter space, requiring 5 signal events for zero background.

Trilepton analysis at $\sqrt{s} = 2$ TeV and 2-100 fb^{-1}

The chargino search using the trilepton channel at a luminosity upgraded Tevatron (M.I. and TeV33) is studied by three groups [11, 12, 13]. Table 6.4 summarizes their analyses. Both Refs. [12] and [13] assumed a large acceptance for the leptons (e and μ), while coverage similar to the current CDF detector is assumed in Ref.[11].

The analyses in Refs. [11] and [13] are optimized for the search without $\not\!\!E_T$ cut. The main differences between the two analyses are (a) the geometric coverage of the leptons, (b) the transverse mass cut, and (c) DY/Z background estimate.

The acceptance for the signal and background events in Ref. [13] is typically larger by a factor of 2-3 than that in Ref. [11] due to the different geometric coverage for leptons assumed. The transverse mass cut efficiently reduces $t\bar{t}$ and WZ backgrounds. Cut 3 ($M_{\ell\ell} <$ 20 GeV/c^2 for any dilepton) reduces $t\bar{t}$ events (with $b \to \ell + X$). Table 6.5 summarizes the comparison of $t\bar{t}$, WZ and ZZ backgrounds. There are no obvious disagreements between two analyses if the lepton coverage is taken into account.

The main concern in Ref. [11] is the fake probability that dilepton events (DY and Z) are identified as trilepton events by picking up an additional lepton (real or misidentified lepton) because of the low lepton p_T. They assume 10^{-4} per event which is somewhat better than the current CDF and DØ analyses. Reference [13] assumes that it will be smaller with their analysis cuts. Their Cut 3 is optimized to achieve this. Another way to reduce the background is to apply a $\not\!\!E_T$ cut. We have revised the analysis in Ref. [11] by requiring $\not\!\!E_T >$ 20 GeV. The background cross section for DY/$Z + X$ is expected to be ~0.1 fb (from 2.19 fb), while about 80% of 120-GeV/c^2 chargino events are accepted. The total background becomes ~0.5 fb which is the same level as in Ref. [13]. Taking into account the difference in the geometric coverage and details of the selection cuts, there are no obvious disagreements for the estimate of the total background. We should achieve a total background estimate

[2] The limits are model-dependent. The CDF result, for example, was obtained by assuming that $M_{\tilde{\ell}}$ and $M_{\tilde{\nu}}$ are given by RGE equations and that $M_{\tilde{q}} = 1.2 \times M_{\tilde{g}}$. Therefore, there are large regions of parameter space where the current CDF and DØ data do not have sensitivity.

Table 6.4: Comparison of three trilepton analyses

Monte Carlo Generator → Cuts:	Ref. [11] ISAJET [14]	Ref. [13] PYTHIA [15]	Ref. [12] ISAJET [14]
(1) Kine/Geom			
$p_T(\ell_1)$	>10 GeV/c	>10 GeV/c	>20 GeV/c
$p_T(\ell_2)$	> 4 GeV/c (5 GeV/c for e)	> 5 GeV/c	>15 GeV/c
$p_T(\ell_3)$	> 4 GeV/c (5 GeV/c for e)	> 5 GeV/c	>10 GeV/c
$\|\eta(e)\|$	<2.4 (1.1 for e_1)	<2.5	<2.5
$\|\eta(\mu)\|$	<1.1 (0.6 for μ_1)	<2.5	<2.5
ISO($\Delta R = 0.4$)	<2 GeV	<2 GeV	$< E_T(\ell)/4$
(2) Z veto	75-105 GeV/c^2	76-106 GeV/c^2	81-101 GeV/c^2
(3) Other $M_{\ell\ell}$ veto	9-11 GeV/c^2 (Υ)	<20 GeV/c^2	N/A
	2.9-3.1 GeV/c^2 (J/ψ)	(ee, $\mu\mu$, and $e\mu$)	
(4) $\Delta\phi_{\ell_1\ell_2}$	$< 170°$	$< 143°$	N/A
(5) $M_T(\ell_1 \not{E}_T)$	N/A	<70 GeV/c^2	N/A
(6) $\not{E}_T$	N/A	N/A	>25 GeV
(7) $N_{jet}(E_T$ >15 GeV)	N/A	N/A	0
Background [fb]			
$t\bar{t}$	0.19	0.06	0.005
WZ *etc.*	0.21	0.38	0.2
ZZ *etc.*	0.04	0.09	N/A
DY/$Z + X$	2.19	0.14	N/A
Total BG	2.63	0.67	0.21

Table 6.5: Comparison of backgrounds (in fb) in two trilepton analyses. There is no obvious disagreement if one takes into account the difference of the $\eta(\ell)$ coverage.

Cuts	Ref. [11]	Ref. [13]
$t\bar{t}$	0.19	0.33 (Cuts 1-2)
WZ *etc.*	0.21	0.85 (Cuts 1-4)
ZZ *etc.*	0.04	0.12 (Cuts 1-4)

less than 1 fb with any of the 3 sets of cuts.

Figure 6.2 is taken from Ref. [13] as a representative plot. The cross section times branching fraction times detection efficiency is plotted as a function of the $\tilde{\chi}_1^\pm$ mass. Typical DØ or CDF detection efficiencies have been applied. Each point in the plot represents the prediction from a specific MSSM model (that is, from a specific choice of the MSSM parameters). We find that the minimum $\sigma \cdot BR \cdot \epsilon_{tot}$ for integrated luminosities of 2 fb^{-1}, 10 fb^{-1} and 100 fb^{-1} are 3.0 fb, 1.3 fb and 0.4 fb, respectively, by requiring the number of signal events for a 5σ significance above background. The maximum $\tilde{\chi}_1^\pm$ masses we can probe are 210 GeV/c^2, 235 GeV/c^2, and 265 GeV/c^2. Note that for a few models, $\tilde{\chi}_1^\pm$ might escape detection with much lower masses.

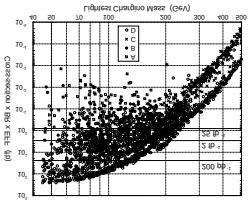
For 10 fb^{-1} and 100 fb^{-1} integrated luminosities (at TeV33), we have to consider the effect of multiple interactions in lepton selection. Based on our preliminary calculations, we expect that the trilepton signal and background efficiencies will be additionally reduced by $f_S = 72\%$ and $f_{BG} = 75\%$ with respect to the MC studies performed without multiple interactions. Thus, the significance will be modified by the factor D, given by

$$D = \frac{f_S}{\sqrt{f_{BG}}}.$$

The modified significance can be applied to Fig. 6.2. We find that the modified $\sigma \cdot BR \cdot \epsilon_{tot}$ for 10 fb^{-1} and 100 fb^{-1} are 1.6 fb and 0.48 fb, respectively. The corresponding maximum $\tilde{\chi}_1^\pm$ masses we can probe are 230 GeV/c^2 and 255 GeV/c^2. Thus we expect the mass limits are decreased by about 10 GeV/c^2. It should be noted that for certain ranges of parameters, charginos as light as the current LEP bound will be undetectable in this channel. Therefore, it will not be possible to infer an absolute model independent lower mass limit on the charginos if no signal is seen at the Tevatron. However, Fig. 6.2 shows that at these high luminosities, a majority of the low mass MSSM models can be reached at the Tevatron.

The analysis in Ref. [12] was optimized for high mass charginos where $\not{E}_T$ and lepton p_T are substantially larger. Thus, the fake lepton problem is negligible. The dominant background is WZ events. The total background is smaller than that in Ref. [13]. However, the signal acceptance is also smaller, so that both analyses have similar sensitivities. Figure 6.3(a) from Ref. [12] shows $\tilde{\chi}_1^\pm$ reach in the $m_{1/2}$-m_0 plane when $A_0 = 0$, $\tan\beta = 2$ and $\mu > 0$. The maximum chargino masses accessible are 180 GeV/c^2, 210 GeV/c^2 and 260 GeV/c^2 for integrated luminosities of 2 fb^{-1}, 10 fb^{-1} and 100 fb^{-1}, respectively (see Fig. 6.3(b)). A similar figure for $\mu < 0$ can be found in Ref. [12]. The maximum chargino masses accessible in this case are 170 GeV/c^2, 230 GeV/c^2 and 280 GeV/c^2 for integrated luminosities of 2 fb^{-1}, 10 fb^{-1} and 100 fb^{-1}, respectively. Once again, if we take into account the effect due to multiple interactions, we expect the mass limits are decreased by about 10 GeV/c^2. The corresponding maximum $\tilde{\chi}_1^\pm$ masses we can probe are 220 GeV/c^2 and 270 GeV/c^2 for integrated luminosities of 10 fb^{-1} and 100 fb^{-1}, respectively.

Figures 6.3(c) and (d) show the analysis results for $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to (\ell^\pm\nu\tilde{\chi}_1^0)(\ell^\mp\nu\tilde{\chi}_1^0) \to$ dilepton + $\not{E}_T$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to (q\bar{q}\tilde{\chi}_1^0)(\ell^\pm\ell^\mp\tilde{\chi}_1^0) \to$ dilepton + $\not{E}_T$ + jets. Though the discovery reach in these channels is mostly a subset of the region probed via trilepton events, they could provide an important independent confirmation of supersymmetry if it is discovered in the trilepton channel. In the $m_0 > 400$ GeV/c^2 region and for $\mu > 0$, the dilepton reach is actually


D
C
B
A
50 fb^{-1}
3 fb^{-1}
500 fb^{-1}
Lightest Chargino mass (GeV)
200
300
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better than the trilepton reach at high luminosities. Once supersymmetry is discovered, the dilepton + $\not\!\!E_T$ + jets channel can also be used to determine parameters of supersymmetric models by looking at the dilepton invariant mass which is bounded by $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$.

It should be noted that we have assumed an upgraded detector for Main Injector and TeV33 scenarios. The upgraded coverage for leptons is assumed to be $|\eta| < 2.5$. If one performed the analysis with a current CDF-like detector [11] with $\sigma_{BG} = 0.5$ fb, the reach for chargino mass would be ~150 GeV/c^2 at 2 fb^{-1}. This is about 30% lower than the 210 GeV/c^2 in Ref. [13].

In summary, a majority of the SUSY parameter space accessible in the trilepton mode can be reached at the Tevatron with high luminosities. Chargino masses up to 270 GeV/c^2 can be probed with 100 fb^{-1} of data. As shown in Figure 6.3(c), this range is equivalent to the search for 500-600 GeV/c^2 gluinos.

6.5.2 Search for Gluinos using Missing E_T + Multijet Events

We explore the potential for the traditional gluino and squark search in multi-jet events with large $\not\!\!E_T$. In the Run-1A analysis, both CDF and DØ found $\sigma_{BG} \sim 2$ pb and set the 95% C.L. limit on the gluino mass of 220-229 GeV/c^2 if $M_{\tilde{q}} = M_{\tilde{g}}$. The asymptotic limit is $M_{\tilde{g}} >$ 170 GeV/c^2, independent of squark mass. Both limits are determined for a specific choice of SUSY parameters.

$\not\!\!E_T$ + multijet analysis at $\sqrt{s} = 1.8$ TeV and 100 pb^{-1}

For 100 pb^{-1}, we need to reduce the background substantially. CDF used cuts of $\not\!\!E_T >$ 60 GeV and $N_{jet}(E_T > 15 \text{ GeV}) \geq 3$ in the Run-1A analysis. For this study, we revised the CDF analysis with cuts of $\not\!\!E_T > 80$ GeV and $N_{jet}(E_T > 20 \text{ GeV}) \geq 4$. The other cuts on lepton veto, fake $\not\!\!E_T$ due to mismeasured jets etc. remain the same. With the new cuts, our expectation of the background cross section is

$$\sigma_{BG} \;=\; 0.16 \text{ pb}.$$

The 1.64σ significance above background for 100 pb^{-1} is 0.07 pb (or 7 events). Therefore, we find the 95% C.L. limit on the gluino mass of 270 GeV/c^2 if $M_{\tilde{q}} \sim M_{\tilde{g}}$, for a specific choice of supersymmetry model.

$\not\!\!E_T$ + multijets analysis at $\sqrt{s} = 2$ TeV and 2-100 fb^{-1}

Table 6.6 shows a comparison of two analyses [16, 13]. The analysis in Ref. [16] (similar to the DØ analysis), estimates the background to be $\sigma_{BG} = 1.2$ pb. This is consistent with the current DØ (and CDF) result of 2 pb. The dominant background sources are $t\bar{t}$, W and Z events. These backgrounds will be reduced by requiring

$$E_T(j_1) + E_T(j_2) + \not\!\!E_T \;>\; 300 \text{ GeV},$$

as suggested by Ref. [13]. The total background is then expected to be

$$\sigma_{BG} \;=\; 40 \text{ fb}.$$

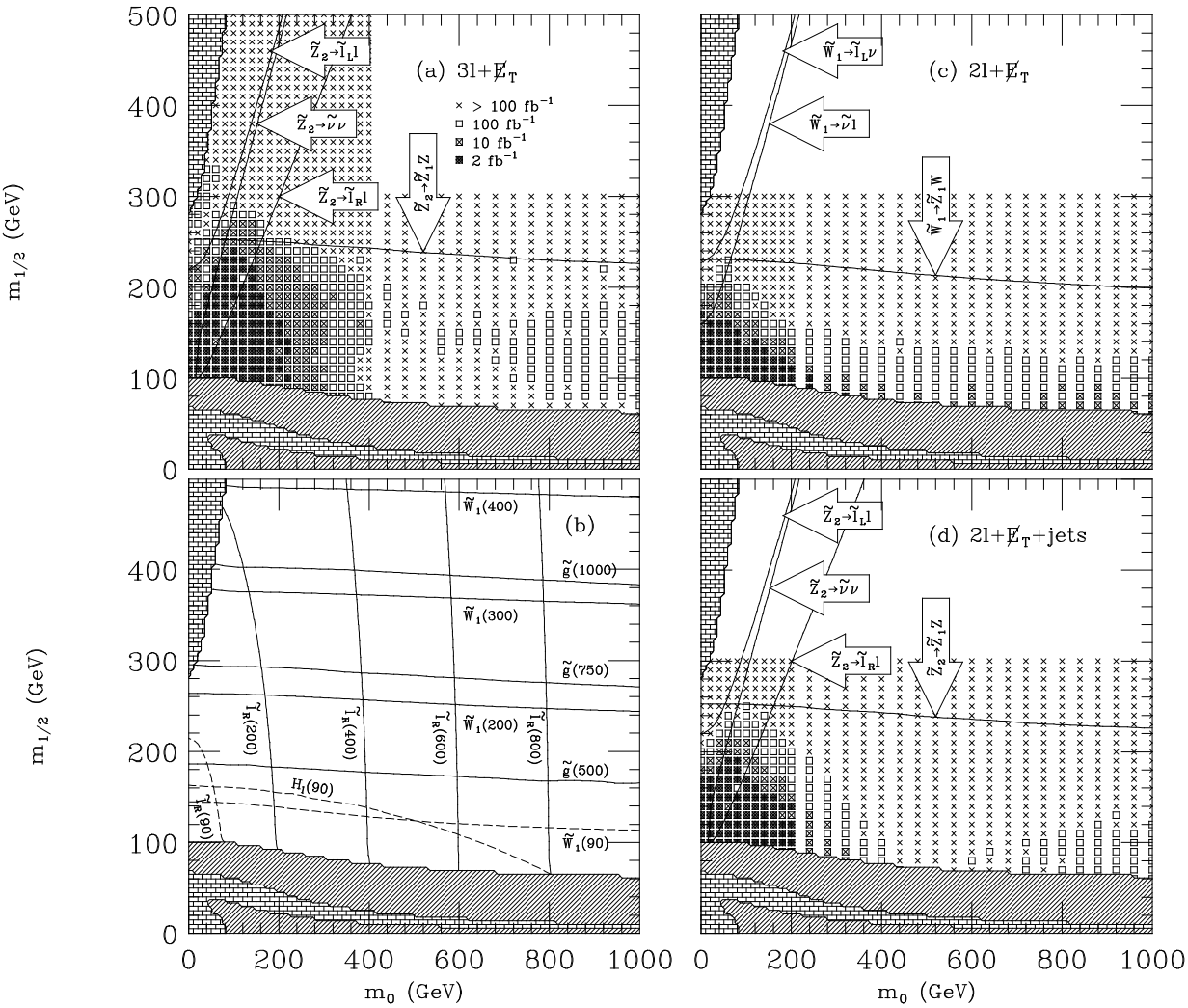

Figure 6.3: (a) Regions of the $m_{1/2}$ versus m_0 plane (with $A_0 = 0$, $\tan\beta = 2$, $\mu > 0$) where trilepton events should be detectable for integrated luminosities of 2 fb^{-1}, 10 fb^{-1} and 100 fb^{-1} in minimal supergravity models. The bricked region is excluded by theoretical constraints, while the gray shaded region is excluded by experiment [12]. (b) Contours for $M_{\tilde{g}}$, $M_{\tilde{\chi}_1^\pm}$, and $M_{\tilde{\ell}_R}$ for comparison with (a). (c) Regions of parameter space that can be probed in the opposite dilepton + $\not{E}_T$ events from $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ pair-production. (d) Regions of parameter space that can be probed in the opposite dilepton + jets events from $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair-production followed by decays to $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$.

Table 6.6: Comparison of two different $\not\!\!E_T$ + multijet analyses

Monte carlo generator → Cuts	Ref. [16] ISAJET [14]	Ref. [13] PYTHIA [15]
(1) $\not\!\!E_T$	>75 GeV	>75 GeV
(2) $\Delta\phi(j\not\!\!E_T)$	$> 30°$	$> 25.6°$
(3) $p_T(\ell)$ for the lepton veto	>15 GeV/c	>15 GeV/c
(4) $N_{jet}(E_T > 15$ GeV)	≥ 4	N/A
(5) S_T (Transverse Sphericity)	N/A	>0.2
(6) $E_T(j_1) + E_T(j_2) + \not\!\!E_T$	N/A	>300 GeV
Background [fb]		
$t\bar{t}$	145	24
W	710	11
Z	320	5
WW	0.4	N/A
ZZ	0.04	N/A
Total BG	1175	40

For TeV33 ($\int \mathcal{L}dt \geq 10$ fb^{-1}), there are two possible factors that may degrade the reach:

- $\not\!\!E_T$ – the $\not\!\!E_T$ resolution may be degraded in the high luminosity environment. We use a fairly high cut on $\not\!\!E_T$ (75 GeV), compared to 20 GeV in the trilepton analysis. We estimated an additional r.m.s. spread of 6 GeV in $\not\!\!E_T$ resolution due to events with an average of 10 multiple interactions. This led to a small effect for the signal events with $\not\!\!E_T > 20$ GeV. The effect on a 75 GeV cut is therefore assumed to be negligible. The effect on the QCD background is also assumed to be small.

- Jet identification – extra jets may be expected from additional events overlapped with the signal events. Currently, we are studying the probability of observing the jets ($E_T > 15$ GeV) from 9 additional events using Run 1 data. We assume this to be a small effect for this report.

We, therefore summarize the studies for $\not\!\!E_T$ + multijets channel without considering any degradation due to the multiple interactions.

Figure 6.4 shows $\sigma \times$ EFF versus $M_{\tilde{g}}$ for a variety of SUSY models. The maximum possible reach (5σ significance above the background) in the gluino mass is ~390 GeV/c^2 for 2 fb^{-1}. For luminosities of 10 fb^{-1} and 100 fb^{-1}, the maximum reach[3] is ≥400 GeV/c^2. Note that the reach in this direct search is considerably lower than the trilepton search for equivalent luminosities.

[3]The production cross section is falling steeply, so we only quote a minimum value for the maximum reach.

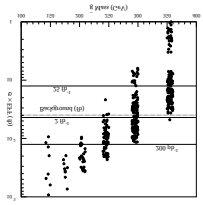

Figure 6.4: Gluino search in minimal supergravity models (or CMSSM): The $\sigma \times$ EFF is plotted for $\not{E}_T$ + jets signal versus the gluino mass [13]. The dotted line represents the background cross section of 40 fb. Three solid lines indicate the 10σ significance of the signal events above the background for integrated luminosities of 200 pb^{-1}, 2 fb^{-1} and 25 fb^{-1}.

Table 6.7: Cross section for $\tilde{t}_1\tilde{t}_1$ pair-production at 2 TeV, calculated with ISAJET (V7.06) and CTEQ2L parton distribution functions.

Mass (GeV/c^2)	σ (pb)
80	42
100	14
130	3.6
150	1.7

6.5.3 Light Top Squark Search

In the "$\not\!\!E_T$" strategy outlined above, we assumed that all the squarks are mass degenerate. Given the high value for the top mass recently reported by DØ and CDF, Yukawa interactions should drive the stop ($\tilde{t}_1$) mass to a value much lower than the other squarks. There are three alternate decay modes possible for the light stop if it is lighter than the Standard Model top quark: (1) the two-body decay into a chargino ($\tilde{\chi}_1^{\pm}$) plus a b quark if the chargino is lighter than the stop; or (2) the three body decays to (s)lepton, (s)neutrino plus a b quark if the sleptons and sneutrinos are light enough; or (3) the two body decay into a neutralino ($\tilde{\chi}_1^0$) plus a c quark. Only possibilities (1) and (3) would be detectable at the Tevatron. The search strategies for a light stop are outlined in Refs. [17, 13].

Typical $\tilde{t}_1\tilde{t}_1$ Cross-sections

The cross section for stop production calculated using CTEQ2L parton distribution functions is given in Table 6.7. The $\tilde{t}_1\tilde{t}_1$ events are generated with ISAJET (Version 7.06) and simulated using a CDF parameterized detector simulation [18]. This has the advantage of providing realistic lepton identification efficiencies, as well as jet and $\not\!\!E_T$ resolution. The stop cross section depends only on the stop mass, but the decay kinematics depend on the mass of the chargino and the LSP.

Single-lepton Channel

If we look for one chargino in the event to decay leptonically, the large background from W + multijets can be reduced to an acceptable level by identifying one jet as coming from a b quark by a secondary vertex tag.

The event selection criteria similar to Ref. [17] are:

- At least one lepton ($ISO < 4$ GeV) with $E_T > 12$ GeV and $|\eta| < 1$;
- $2 \leq N_{jet} \leq 4$ with $E_T > 15$ GeV in $|\eta| < 2$;
- $\not\!\!E_T > 25$ GeV;
- $M_T(\ell\not\!\!E_T) < 45$ GeV;

Table 6.8: Observed $\tilde{t}_1\tilde{t}_1$ cross section via single-lepton (e or μ) events as a function of stop mass. We assume the branching ratio of $\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ to be 11% for electron or muon channels. The b-tagging (per b jet) efficiency is taken to be a **conservative** number of $\epsilon_b =$ 20% being independent of $E_T(b)$ above 15 GeV.

Mass (GeV/c^2)	ϵ_{sel} (%)	ϵ_{tag} (%)	σ_{obs} (fb)
80	11	21	430
100	13	26	210
130	19	28	84
150	19	29	41

- At least one b-tagged jet in $|\eta(b)| < 2.4$;
- $|z_{vertex}| < 50$ cm.

The b-tagging (per b jet) efficiency is taken to be a **conservative** number of $\epsilon_b = 20\%$ being independent of $E_T(b)$ above 15 GeV.

The efficiency for these cuts together with the observed cross section as a function of stop mass is tabulated in Table 6.8. For simplicity, we assume the chargino mass to be 60 GeV/c^2, the LSP mass to be 30 GeV/c^2, and the branching ratio of $\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ to be 11% for electron or muon channels. The selection includes a lepton geometric and identification efficiency of about 60%. The inclusion of leptons with rapidity out to 2 will increase the efficiency by only about 15% for a stop mass of 100 GeV/c^2. The efficiency falls off for high stop mass due to the transverse mass cut. It should be noted that both analyses in Refs. [17, 13] use $\epsilon_b = 30\%$.

We expect a signal to background ratio of $\approx$1 at $M_{\tilde{t}_1} =$ 110-120 GeV/c^2 [17, 13]. With an integrated luminosity of 2 fb^{-1}, it should be possible to probe a top squark up to 130 GeV/c^2 (5σ) for $M_{\tilde{\chi}_1^{\pm}} \sim 2M_{\tilde{\chi}_1^0} \sim 60$ GeV/c^2. If the b-tagging (per b jet) efficiency is $\epsilon_b =$ 50% (independent of $E_T(b)$ above 15 GeV), the observed $\tilde{t}_1\tilde{t}_1$ cross section via single-lepton (e or μ) events increases by a factor of 2 and the limit of about 150 GeV/c^2 is found.

Since this limit is model specific, we extract the maximum reach from more general analysis ($\epsilon_b = 30\%$ being independent of $E_T(b)$ above 15 GeV) in Ref. [13] and finds the 5σ mass limits of 150, 175 and 210 GeV/c^2 for 2, 10 and 100 fb^{-1}.

Di-lepton Channel

If we require both charginos to decay leptonically, we expect the background to be significantly reduced at the price of the additional leptonic branching fraction (here taken to be 11%). The event selection requires two identified electrons with a geometric and identification efficiency of about a 40% per event. The selection criteria similar to Ref. [17] are as follows:

- At least one lepton with $E_T > 8$ GeV and $|\eta| < 1$;
- The second lepton with $E_T > 5$ GeV and $|\eta| < 2.4$;

Table 6.9: Observed $\tilde{t}_1\tilde{t}_1$ cross section via di-lepton (ee, $e\mu$, $\mu\mu$) events as a function of stop mass. We assume the branching ratio of $\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ to be 11% for electron or muon channels.

Mass (GeV/c^2)	ϵ_{sel} (%)	σ_{obs} (fb)
80	9	190
100	11	74
130	12	22
150	12	9.5

- $N_{jet} \geq 1$ with $E_T > 15$ GeV;
- $20° < \phi_{\ell\ell} < 160°$, where $\phi_{\ell\ell}$ is the opening angle between the lepton momenta in the plane transverse to the beam;
- B $(= p_T(\ell_1) + p_T(\ell_2) + \not{E}_T\ ) < 100$ GeV.

We separate the stop from standard model top events by defining a variable B [17] as the scalar sum of the lepton momenta and the missing transverse energy. The results including both electrons and muons are summarized in Table 6.9. In this study, we assume the chargino mass to be 60 GeV/c^2, the LSP mass to be 30 GeV/c^2. The cut on B parameter reduces the efficiency as the stop mass approaches that of the top quark. The observable cross section is reduced relative to the single lepton channel mostly due to the fact that the tagging efficiency is 2-3 times the branching fraction. However, this signal is expected to be cleaner than the single lepton decay mode. The signal to background ratio is expected to be $\approx$1 at $M_{\tilde{t}_1}$ = 130-150 GeV/c^2 [17, 13]. In an integrated luminosity of 2 fb^{-1}, it should be possible to explore a top squark mass up to $\sim$130 GeV/c^2 (5σ).

Since this limit is model specific, we extract the maximum reach from more general analysis ($\epsilon_b = 30\%$ being independent of $E_T(b)$ above 15 GeV) in Ref. [13] and finds the 5σ mass limits of 150, 170 and 200 GeV/c^2 for 2, 10 and 100 fb^{-1}.

$\not{E}_T$ + 2 acollinear jets

A recent analysis of Run 1a data by DØ [19] shows that for the case $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$, the Tevatron more than doubles the mass region excluded by LEP, as shown in Fig. 6.5. For this search, the signal is $\not{E}_T$ plus two acollinear jets. No significant signal is observed above background. The main cuts used are:

- $\not{E}_T\ > 40$ GeV
- $E_t(j_2) > 30$ GeV
- $\not{E}_T$ not back to back with jets
- no leptons (e or μ) in the event with $P_t > 10$ GeV/c

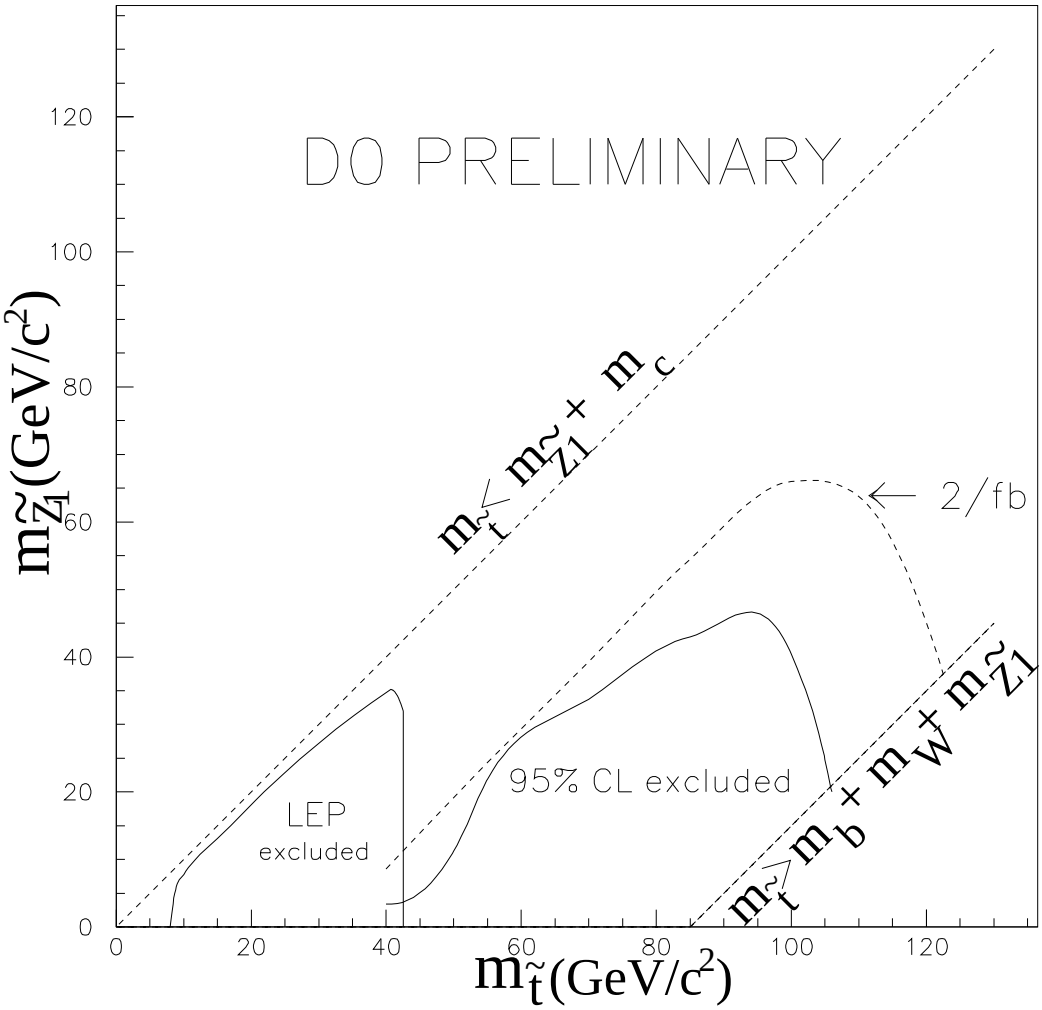

Figure 6.5: Current 95% CL DØ limit for the signal $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$ (solid line), and estimated future reach with the same cuts for an integrated luminosity of 2 fb^{-1} (dashed line).

The above analysis is repeated for an integrated luminosity of 2 fb^{-1} with the same event selection procedure as the original analysis. Assuming no additional signal events are found, the region to be excluded is shown in Fig. 6.5. This technique can be used for top squark masses as high as 150 GeV/c^2. However, the analysis is not able to improve the reach for integrated luminosities of 10 and 100 fb^{-1}, because the backgrounds are dominant. Additional reach may be obtained by reoptimizing the event selection for higher mass objects (*e.g.*, higher $\not{E}_T$ cut). If the top squark exists at masses below the top quark, and the $\tilde{t}_1 \to \tilde{\chi}_1^0 c$ signal is kinematically favored, it will most likely be discovered at TeV33.

6.5.4 Summary

The Standard Model (SM) of particle physics is in remarkably excellent agreement with existing data. In spite of this fact, there are strong theoretical arguments to suggest that the SM will break down in the TeV domain. Thus high energy physics is currently in the unique position of having a theory that works at a level of high precision, but must in fact be modified at an energy scale not far above existing accelerators. There are of course many reasons for building a new high energy accelerator. However, in view of the present status of high energy physics, a primary purpose must be to discover new physics.

Any model of new physics must face the difficult task of accommodating the high precision tests of the SM, and yet significantly modifying it at an energy scale not much beyond the Z boson. Further, the solution that supersymmetry (SUSY) gives to the hierarchy problem requires that there be a large array of new SUSY particles lying approximately between 100 GeV and 1 TeV. In spite of this, supersymmetry succeeds in perturbing the successes of the SM negligibly due to the fact that it implies the rapid decoupling of these particles from the SM particles. Further, experimental searches for the SUSY particles have examined only a very small part of the expected mass range of 100 GeV - 1 TeV, and so it is not surprising that the new SUSY particles have not yet been discovered. It is thus of importance for new accelerators to try to increase the mass reach if supersymmetry is to be tested.

The SUSY model the TeV33 SUSY group analysed was based on the particle spectrum of the MSSM (a SUSY partner for each SM particle with two Higgs doublets) combined with grand unification (based on supergravity) and R parity. (Supergravity is the gauge theory of global supersymmetry (MSSM) just as Yang-Mills theory is the gauge theory of global (constant) phase invariance.) This model is the most attractive from both the theoretical and experimental considerations. The supergravity induced interactions allow one to deduce the soft breaking of supersymmetry at the GUT scale (which only can be done by hand for the low energy MSSM), and from this one obtains an explanation of the origin of electroweak symmetry breaking at the Z scale by radiative effects. In addition, low energy predictions are almost all independent of the grand unification group, and hence of the unknown GUT physics. Several experimental successes have led to the acceptance of the model. It predicted the existence of grand unification more than a decade before the precision LEP data allowed its verification. Further, unification occurs if SUSY masses are precisely in the range needed to resolve the gauge hierarchy problem mentioned above. The model is also consistent with the low energy SM tests, as well as current bounds on proton decay. Finally, we mention that the condition of R parity invariance leads to a stable lightest supersymmetric particle (LSP)

Table 6.10: Preliminary results on the maximum mass reach for SUSY particles at TeV33. The reach is defined such that the number of signal events is either 5 events or a 5σ significance above background. The effect due to multiple interactions is considered only for 10 fb^{-1} and 100 fb^{-1}. The $(*)$ indicates the 95% C.L. limit with specific model in CDF or DØ analysis. The gluino mass limit for 100 pb^{-1} is extrapolated from the current CDF/DØ analysis for their particular SUSY model and with $M_{\tilde{q}} = M_{\tilde{g}}$.

Sparticle	Tevatron 20 pb^{-1}	Tevatron 100 pb^{-1}	Main Injector 2 fb^{-1}	TeV33 10/100 fb^{-1}
$\tilde{\chi}_1^{\pm}$	47 GeV/c$^2(*)$	70 GeV/c$^2(*)$	210 GeV/c^2	230/270 GeV/c^2
$\tilde{g}$	229 GeV/c$^2(*)$	270 GeV/c$^2(*)$	390 GeV/c^2	$\sim$400/>400 GeV/c^2
$\tilde{t}_1(\rightarrow \tilde{\chi}_1^{\pm} b)$	n/a	n/a	150 GeV/c^2	175/210 GeV/c^2
$\tilde{t}_1(\rightarrow \tilde{\chi}_1^0 c)$	100 GeV/c$^2(*)$	n/a	150 GeV/c$^2(*)$	n/a

which gives the right amount of dark matter over a large fraction of the parameter space. (This prediction is non-trivial as the relic dark matter density depends on such disparate quantities as the electroweak coupling constant, the LSP mass, the gravitational constant and the Hubble constant.)

If one adds additional light Higgs doublets to the particle spectrum, agreement with grand unification (or proton decay bounds) is lost, while a Higgs singlet would generally destabilize the gauge hierarchy. While the assumption of four generations (though not more) is still consistent with grand unification, it would ruin the prediction of M_b/M_τ for groups such as SU(5) or SO(10). Thus, the chosen model is fairly constrained, and it is therefore worthwhile to use it as the prototype for accelerator tests.

The SUSY mass limits at Tevatron, Main Injector and TeV33 are summarized in Table 6.10. This table shows the strong possibility of discovering SUSY at the Tevatron over a large region of parameter space. The theory predicts the existence of a light chargino ($\tilde{\chi}_1^{\pm}$) and two light neutralinos ($\tilde{\chi}_{1,2}^0$). These are generally lighter than the gluino and hence most accessible to observation at TeV33. We also have significant potential for dicovering the top squark, especially if the top proves to be heavy.

The SUSY mass limits at TeV33 (25 fb^{-1}) are also compared to the limits expected at LEP-II and NLC in Table 6.11. While LEP-II can find or exclude the light chargino ($\tilde{\chi}_1^{\pm}$) and light top-squark ($\tilde{t}_1$) masses up to nearly its kinematical limit ($\sqrt{s}/2$), searches at TeV33 improve a reach 2-3 times that of LEP-II. If LEP-II found a 90-GeV chargino, we should study 270-360 GeV gluino at TeV33. A preliminary study on determination of gluino mass shows the 300-GeV gluino mass could be measured within about 20 GeV [21]. TeV33 is also competitive to NLC in the gluino/squark searches. Thus, the SUSY searches at TeV33 is complementary to those at LEP-II and NLC. It should be noted that the light Higgs (h) search is also an important concomitant search, since SUSY predicts it to be lighter than 130 GeV/c^2.

The CERN Large Hadron Collider (LHC) will be a machine capable of a thorough search

Table 6.11: Summary of SUSY mass limits (5σ) at various colliders. "Exhaustive limit" means the least mass limit. Searches at LHC are not shown here. However, the limits are largely improved, *e.g.*, 1300-2000 TeV/c^2 for gluino depending on the choice of the parameter space.

Collider	LEP-II [6]	TeV33		NLC [6]
$\sqrt{s}$	190 GeV	2 TeV		500 GeV
$\int \mathcal{L}dt$	500 pb^{-1}	25 fb^{-1}		20 fb^{-1}
	Max. limit	Exhaustive limit	Max. limit	Max. limit
$\tilde{\chi}_1^{\pm}$	90 GeV	65 GeV [20]	250 GeV	248 GeV
$\tilde{g}/\tilde{q}$	85 GeV (100 pb^{-1})	300 GeV	over 400 GeV	~250 GeV
$\tilde{t}_1$ ($\rightarrow c\chi_1^0$)	83 GeV	48 GeV [20]	120 GeV (2 fb^{-1})	~250 GeV
$\tilde{t}_1$ ($\rightarrow b\chi_1^{\pm}$)	N/A	100 GeV	180 GeV	~250 GeV

for SUSY particles below the TeV scale [6]. If Fermilab can deliver an integrated luminosity of order 20-25 fb^{-1} (not 100 fb^{-1}) with reasonably upgraded CDF and DØ detectors before the LHC turns on, we can have the first physics result within ~1 year after LHC turns on. If the gluino (chargino) is $\leq$ 400 (250) GeV, TeV33 (25 fb^{-1}) still has a chance to discover the SUSY particles during the LHC era.

In conclusion, the Tevatron may not be able to exclude SUSY theories if the searches prove inconclusive. However, TeV33 provides an excellent opportunity for the discovery of SUSY, as shown in this report.

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