SUPERSYMMETRY REACH OF TEVATRON UPGRADES:
A COMPARATIVE STUDY

Howard Baer\textsuperscript{1}, Chih-hao Chen\textsuperscript{2}, Frank Paige\textsuperscript{3} and Xerxes Tata\textsuperscript{4}
\textsuperscript{1}\textit{Department of Physics, Florida State University, Tallahassee, FL 32306, USA}
\textsuperscript{2}\textit{Davis Institute of High Energy Physics, University of California, Davis, CA 95616, USA}
\textsuperscript{3}\textit{Brookhaven National Laboratory, Upton, NY 11973, USA}
\textsuperscript{4}\textit{Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA}
(March 26, 2022)

Abstract

We use ISAJET to perform a detailed comparison of the supersymmetry reach of the current Tevatron (100 pb\textsuperscript{-1}) with that of the Main Injector (2 fb\textsuperscript{-1}) and the proposed TeV33 upgrade designed to yield an integrated luminosity of 25 fb\textsuperscript{-1}. Our analysis is performed within the framework of the minimal supergravity model with gauge coupling unification and radiative electroweak symmetry breaking. For each of these three luminosity options, we delineate the regions of parameter space where jets plus missing energy plus 0, 1, 2 (opposite sign and same-sign dileptons), and 3 isolated lepton signals from the cascade decays of sparticles should be visible above standard model backgrounds. We compare these with the parameter regions where signals in the clean isolated dilepton and trilepton channels (from chargino/neutralino and slepton production) should be observable.
I. INTRODUCTION

The CDF and D0 experiments have each accumulated an integrated luminosity of about 100 pb$^{-1}$ in Run I of the Fermilab Tevatron. An analysis of these data, which include elementary particle collisions at the highest energies accessible today, has already led to the discovery of the top quark [1], and could reveal deviations from the expectations of the Standard Model (SM) of particle physics. These could take the form of new degrees of freedom (supersymmetry, technicolor, new gauge bosons, ...) or new effective interactions (quark compositeness, ...). At the very least, if no such deviation is observed, these data would serve to put phenomenological bounds on various extensions of the SM. Around 1999, the Main Injector (MI) is expected to begin operation: this should result in an order of magnitude increase in the size of the data sample. Tevatron experiments should then be sensitive to new physics processes with cross sections that are ten (three) times smaller than those accessible from an analysis of Run I data in rate-limited (background-limited) channels.

Rather general arguments based on the instability of the SM’s electroweak-breaking sector to high mass scales suggest that it should break down at an energy scale $\Lambda < \sim 1$ TeV, which is the raison d’être for supercolliders such as the Large Hadron Collider (LHC) at CERN, or an $e^+e^-$ collider operating at a center of mass energy of $\sim 1$ TeV. If $\Lambda$ is well below its upper bound, deviations from the SM may also manifest themselves at the Tevatron, if sufficient integrated luminosity can be accumulated. Recently, the demise of the Superconducting Super collider (SSC) has led several authors [2] to propose that a luminosity upgrade beyond the Main Injector, designed to provide a data sample of $10 – 25$ fb$^{-1}$, could have a significantly improved reach for new physics well before the LHC commences operation. We will refer to this proposed upgrade as TeV33. We make no attempt here to assess the credibility of the TeV33 goals, either for the accelerator or for the existing or upgraded detectors.

The purpose of this paper is to make a quantitative comparison between the capabilities of the current Tevatron, the MI upgrade, and the proposed TeV33 for the discovery of supersymmetry [3,4]. We focus on supersymmetry for several reasons. Supersymmetry (SUSY) provides the only known weakly coupled (and hence perturbatively calculable) framework that can naturally stabilize the Higgs sector of the SM. Since supersymmetry is a decoupling theory, SUSY models reduce to the SM if sparticles are heavy: thus, SUSY models are at least as consistent as the SM when confronted with the precision data from LEP. SUSY models include a natural candidate for dark matter, and they can be consistently and simply embedded in a grand unified framework. A completely different reason for focusing on supersymmetry for the purpose of comparing the capabilities of different experimental facilities stems from the fact that SUSY models contain several new particles with a variety of quantum numbers: colored scalars and fermions, as well as corresponding colorless particles. A supersymmetry skeptic could simply view our studies as providing a “theoretical laboratory” to compare the capabilities of various projected experimental facilities.

Several studies of the SUSY reach of TeV33 already exist [5–7], and results have been summarized in Ref. [4,2]. These studies do not all focus on the same SUSY reactions, differ significantly in the details of the computation of backgrounds (crucial in determining the reach), and present the final results in forms not amenable to direct comparison [8]. In
view of the importance of this issue, we felt that a systematic study in which all signals are simultaneously studied using a common simulation would be useful in making an assessment of the increased capability of TeV33 over the already approved MI upgrade. Moreover, we present for the first time a comparison of the reach in various multilepton channels for the three luminosity options at the Tevatron.

For definiteness, we work within the minimal supergravity framework, with assumptions (including grand unification and radiative electroweak symmetry breaking) detailed in our earlier studies [9,6] of SUSY signals at the Tevatron. The masses and couplings of all sparticles are then determined by just SUSY four parameters,

- $m_0$, the common scalar mass at the unification scale,
- $m_{\tilde{\chi}}$, the common gaugino mass at the unification scale,
- $A_0$, the common soft SUSY breaking trilinear scalar coupling, and
- $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs fields,

together with the sign of the Higgsino mass term $\mu$. Our results also depend on $m_t$; we shall take $m_t = 170$ GeV. The physical masses and couplings relevant to phenomenology are then obtained [9,6] using the renormalization group equations. We emphasize that we use this framework for expediency. Indeed the assumptions underlying this framework may ultimately prove to be incorrect. This is largely irrelevant for our purpose, which is only to compare the SUSY reach of the different Tevatron upgrades.

To orient the reader with the masses of various sparticles within this framework, we show, in Fig. 1, contours of the gluino (solid lines), squark (dashed lines) and lighter chargino (dotted lines) masses in the $m_0-m_{\tilde{\chi}}$ plane. We fix $A_0 = 0$ and illustrate the masses for

- a) $\tan \beta = 2, \mu < 0$,
- b) $\tan \beta = 2, \mu > 0$,
- c) $\tan \beta = 10, \mu < 0$, and
- d) $\tan \beta = 10, \mu > 0$.

The gluino mass contours are not exactly horizontal because of the difference between the pole and running gluino masses [10]. The bricked regions are excluded by theoretical constraints detailed in Ref. [8] while the hatched region is excluded from the non-observation of any SUSY signal at the Tevatron [11], or LEP [12], and includes the recent mass limit [13] $m_{\tilde{W}_1} > 65$ GeV from LEP1.5.

The cascade decays of gluinos and squarks can lead to a variety of multijet plus multilepton event topologies. Contributions from associated production processes, while included, are known to be small. In addition, electroweak production of charginos and neutralinos can lead to hadronically quiet multilepton signals via which to search for supersymmetry. In this paper, we use ISAJET 7.16 [14] to map out the supersymmetry reach in various channels at a 2 TeV $p\bar{p}$ collider, assuming an integrated luminosity of

- 100 pb$^{-1}$, roughly corresponding to what might be achieved from an analysis of the data from the current run;
- 2 fb$^{-1}$, corresponding to the approved MI upgrade; and
- 25 fb$^{-1}$, corresponding to what might be possible at the proposed TeV33 upgrade.
We assume identical detectors for each of these options. We neglect event pile-up effects, which have been shown to be small at least for the clean trilepton channel from $\tilde{W} \tilde{Z}$ production. We also neglect any experimental difficulties associated with operating at the high luminosities implied by TeV33. Our purpose here is mainly to evaluate which regions of SUGRA parameter space can be explored via various discovery channels, and how these change depending on different Tevatron luminosity options.

The remainder of this paper is organized as follows. In the next section, we briefly describe the event simulation that we use for the computation of various signals and backgrounds. In Sec. III, we focus on various multijet plus multilepton signals from the production and cascade decays of gluinos and squarks as well as from chargino and neutralino production, and map out the reach for supersymmetry in several of these channels for the three luminosity options introduced above. We present our results in the $m_0 - m_{1/2}$ plane for cases (a–d) introduced above. Variation with $A_0$ is briefly addressed. Sec. IV is devoted to the study of the corresponding reach via electroweak production of charginos and neutralinos. We compare the total SUSY reach for the three Tevatron options and briefly discuss how these compare to the reach for other facilities such as the LHC or an $e^+e^-$ linear collider operating at 500-1000 GeV in Sec. V.

II. EVENT SIMULATION

The implementation of the SUGRA framework into ISAJET has been described elsewhere and will not be repeated here. We generate all the lowest order $2 \rightarrow 2$ SUSY subprocesses in our simulation of $n$ lepton plus $m$ jet signals with $m \geq 2$ (except for unimportant $s$-channel Higgs boson mediated subprocesses). However, for the simulation of the clean multilepton signals, we have generated only slepton and chargino/neutralino events, since gluino and squark decays will very seldom yield final states without central jet activity.

To model the experimental conditions at the Tevatron, we use the toy calorimeter simulation package ISAPLT. We simulate calorimetry covering $-4 < \eta < 4$ with cell size $\Delta\eta \times \Delta\phi = 0.1 \times 0.0875$. We take the hadronic (electromagnetic) energy resolution to be $70\% / \sqrt{E}$ ($15\% / \sqrt{E}$). Jets are defined as hadronic clusters with $E_T > 15$ GeV within a cone with $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7$. We require that $|\eta_j| \leq 3$. Muons and electrons are classified as isolated if they have $p_T > 7$ GeV and $|\eta(\ell)| < 2.5$ and if the visible activity within a cone of $R = 0.3$ about the lepton direction is less than $E_T(\text{cone}) = 5$ GeV. In our analysis, we neglect multiple scattering effects and non-physics backgrounds from photon or jet misidentification, and we make no attempt to explicitly simulate any particular detector.

III. REACH IN MULTILEPTON PLUS MULTIJET CHANNELS

The multijet plus $E_T$ signal from gluino and squark production has been regarded as the most promising signature for supersymmetry at hadron colliders, provided that they are kinematically accessible. From a non-observation of any excess of $E_T$ events above SM expectations, the CDF and D0 experiments have already obtained the lower limits in the vicinity of 100-200 GeV on the masses of gluinos and squarks. These bounds have been derived within the framework of the minimal supersymmetric model, assuming ten
degenerate squark flavors. It has also been shown [15–18] that depending on \( m_{\tilde{q}} \) and \( m_{\tilde{g}} \), other signatures with multilepton plus jets in the final state may also be observable with a data sample of \( \mathcal{O}(100) \) pb\(^{-1}\).

If gluinos and squarks are relatively heavy, electroweak production of charginos (\( \tilde{W}_1 \)) and neutralinos (\( \tilde{Z}_2 \)) (which are expected to have masses \( \sim \frac{1}{2} m_{\tilde{g}} \) in models with a common gaugino mass at the unification scale) may offer the best hope for SUSY detection at the Tevatron [6]. With the integrated luminosity that has been accumulated in Run I of the Tevatron, these signals should be on the verge of observability [19–22]. For an integrated luminosity in excess of \( \mathcal{O}(1 \text{ fb}^{-1}) \) that should be available once the MI commences operation, the reach via the clean trilepton signal from the process \( pp \rightarrow \tilde{W}_1 \tilde{Z}_2 \rightarrow \ell \nu \tilde{Z}_1 + \ell' \ell' \tilde{Z}_1 \) may exceed that from gluino and squark reactions [5–7] for a wide range of parameters. We will defer the discussion of these reactions to the next section, and focus our attention on the multijet plus multilepton signatures for now.

We require,

- jet multiplicity \( n_{\text{jet}} \geq 2 \),
- transverse sphericity \( S_T > 0.2 \),
- \( \slashed{E}_T > 40 \text{ GeV} \).

As in our analysis of signals at the LHC [23], we require an analysis cut,

- \( E_T(j_1), E_T(j_2) > E^c_T \text{ and } \slashed{E}_T > E^c_T \),

where the parameter \( E^c_T \) is appropriately adjusted as described below. We further classify the events by their isolated lepton content as follows:

- (A) \( \slashed{E}_T \) events, with no isolated leptons. For this sample, we require that the missing energy not point along a jet, \( \Delta \phi(\slashed{E}_T, \slashed{E}_T^{j}) > 30^\circ \);
- (B) 1\( \ell \) events with exactly one isolated lepton with \( E_T(\ell) > 10 \text{ GeV} \). To reduce the background from \( W \) production, we also require \( M_T(\ell, \slashed{E}_T) > 100 \text{ GeV} \);
- (C) Opposite sign (OS) dilepton events with exactly two unlike sign isolated leptons, where we require \( E_T(\ell_1) > 10 \text{ GeV} \);
- (D) Same sign (SS) dilepton events with exactly two same sign isolated leptons, again with \( E_T(\ell_1) > 10 \text{ GeV} \);
- (E) 3\( \ell \) events, with exactly three isolated leptons with \( E_T(\ell_1) > 10 \text{ GeV} \). We veto events with \( |M(\ell^+\ell^-) - M_Z| < 8 \text{ GeV} \).

SUSY events are frequently rich in central \( b \) jets which can come from direct decays of gluinos and \( b \)-squarks; from the decay \( \tilde{Z}_2 \rightarrow \bar{b}b \tilde{Z}_1 \), which can have an enhanced branching fraction [24]; or from the production of Higgs bosons in SUSY events. We have therefore studied the prospects for the detectability of tagged \( b \) signatures in the sample of \( \slashed{E}_T \) and 1\( \ell \) SUSY samples. In our analysis, we take the efficiency of tagging a \( b \)-jet with \( E_T > 15 \text{ GeV} \) and \( |\eta_b| < 2 \) is 50%, and assume that the probability of mistagging other jets as a \( b \)-jet is 2%. We find that the signals for \( b \)-tagged 1\( \ell \) events occur at unobservably small rates over most of the parameter space, so that for the most part, we will confine our attention to just
• (F) $B + \text{jets} + E_T$ events, where we veto any leptons, and require at least one tagged $B$-hadron.

We have used ISAJET to compute these signals and the corresponding SM backgrounds which mainly come from,

• $W$ or $Z$ production, in association with jets (additional leptons could arise from radiation),

• $t \bar{t}$ production,

• $WW$, $WZ$ and $ZZ$ pair production, where jets come from QCD radiation, and

• QCD jet production, with $E_T$ due to mismeasurement of the jets.

Some care must be exercised in the generation of the backgrounds. It is highly more likely that events with a hard initial scattering will pass the hard cuts that we have imposed to separate the SUSY signal from the background (especially for large values of $E_T^c$). Since the cross section falls rapidly with the hard scattering $p_T$, it is necessary to generate the backgrounds in various $p_T$ bins to ensure that the relevant portions of the phase space are properly sampled. If this is not done, most of the events generated by the Monte Carlo procedure will be too soft to pass the hard cuts, leading to an underestimate of the backgrounds. To avoid this we follow the procedure detailed in Ref. [23], and generate background events in hard scattering $p_T$ in geometrically increasing bins between 25-400 GeV.

The $E_T^c$ dependence of the various backgrounds is shown in Fig. 2 for (a) $E_T$ events, (b) $1\ell$ events, (c) $OS$ dilepton events, (d) $SS$ dilepton events, (e) $3\ell$ events, and (f) $b + \text{jets} + E_T$ events. We use CTEQ2L structure functions [25] throughout our analysis. The long-dashed line shows the background from $t\bar{t}$ production, while the QCD background is shown by the long-dashed-dotted line. The long-dashed double-dotted (triple-dotted) line shows the backgrounds from $W + \text{jets}$ ($Z + \text{jets}$). Backgrounds from vector boson pair production are shown by the short-dashed (dotted) lines and are negligible, since the cross section for producing vector boson pairs together with at least two jets is rather small. The sum of all the backgrounds is shown as the solid line. We see from Fig. 2 that for all but the $E_T^c$ signal (and, to a lesser extent, the jets+$B+E_T$ signal), $t\bar{t}$ and $W$+jets backgrounds dominate over most of the range of $E_T^c$. For the $E_T^c$ signal, the background from $Z \rightarrow \nu\bar{\nu}$ plus jet events is also significant [26] and, in fact, dominates for very large values of $E_T^c$. Backgrounds from QCD and vector boson pair production are negligible in this case.

We have shown in our previous analyses [23] of SUSY signals at the LHC that the reach can be optimized by adjusting the value of $E_T^c$ in the analyses. Events from relatively light gluinos and squarks tend to be softer but have larger cross sections than SUSY events when gluinos and squarks are quite heavy. While a modest value of $E_T^c$ is probably optimal for the former case, the signal to background ratio as well as the statistical significance of the signal can be significantly improved by using larger values of $E_T^c$ when attempting to extract a signal for very heavy sparticles. This should also be true of experiments at the Tevatron. As the size of the data sample increases, generally speaking, we may expect that we would obtain the maximum reach by increasing the value of $E_T^c$. The analysis should, however, not be done for a single choice of this cut parameter that is optimized for the maximal reach.
because this would result in a very low efficiency for signal detection if sparticles happened to be relatively light. The optimal choice of \( E_T \) is also channel-dependent and somewhat sensitive to where we are in the parameter space.

To underscore this, we have shown in Fig. 3 are total signal cross sections as a function of \( E_T \) for the same event topologies (a)-(f) as in Fig. 2, but for several cases of input SUGRA parameters. In our illustration, we have fixed \( m_{\tilde{\chi}} = 120 \text{ GeV} \) so that \( m_{\tilde{g}} \) is roughly at 350-380 GeV. In the first three cases, we choose \( \tan \beta = 2, A_0 = 0, \mu < 0, \) and take

- (1) \( m_0 = 100 \text{ GeV} \) (solid)
- (2) \( m_0 = 200 \text{ GeV} \) (dashed)
- (3) \( m_0 = 800 \text{ GeV} \) (dotted)

Increasing \( m_0 \) mainly increases the mean squark mass: in case 1, the decays \( \tilde{g} \rightarrow q\bar{q} \) are kinematically accessible, and of course, the production of squarks is substantial; in case 2, squarks of the first two generation are just heavier than the gluino, so that the dominant gluino decay is via \( \tilde{g} \rightarrow b\bar{b} \); in case 3, all squarks are very heavy, and the gluino decays via three body modes. We have checked that flipping the sign of \( \mu \) does not qualitatively change the results. In the remaining two cases 4 and 5, we fix \( m_0 = 200 \text{ GeV} \) with \( \mu > 0, \) and choose

- (4) \( A_0 = -400 \text{ GeV} \) (dot-dashed)
- (5) \( A_0 = -430 \text{ GeV} \) (dot-dot-dashed)

These have been chosen so that the decay \( \tilde{g} \rightarrow t\tilde{t}_1 \) is kinematically accessible: In case 4, \( \tilde{t}_1 \) decays via \( \tilde{t}_1 \rightarrow b\tilde{W}_1 \), while in case 5 this channel is inaccessible and \( \tilde{t}_1 \) decays via the loop mode \( \tilde{t}_1 \rightarrow c\tilde{Z}_1 \). The size of the tagged \( b \)-jet cross section is worth noting. The wiggles in the curve reflect the statistical fluctuations in the simulations. The total SM background is shown by the crosses. We see that if squarks are heavy (case 3, dotted) the background substantially exceeds the signal in all the channels and for the entire \( E_T \) range where the signal cross section remains observable, and it appears unlikely that gluinos (whose mass is 380 GeV) will be detectable even at TeV33. We also see that for some signals (e.g. the OS channel), the choice of \( E_T \) significantly changes the signal to background ratio depending on the decay pattern of the gluino (compare cases 1 and 2 with 4 and 5). Clearly some optimization should be possible if the very large data sample as envisioned at TeV33 become available.

In order to assess the observability of the various SUSY signals at the Tevatron for integrated luminosities of 0.1 fb\(^{-1}\), 2 fb\(^{-1}\) and 25 fb\(^{-1}\), we have generated SUSY events for a grid of points in the \( m_0 - m_{\tilde{\chi}} \) plane, for \( \tan \beta = 2 \) and \( \tan \beta = 10 \) for both signs of \( \mu \) with \( A_0 \) being fixed at zero. Our scan should be taken as spanning a representative portion of the parameter space for small and modest values of \( \tan \beta \). Since \( A_0 \) mainly affects the phenomenology of the third generation, we expect the signals to be relatively insensitive to variation of \( A_0 \) (except for signals involving third generation fermions, such as the cross section for \( E_T \) events with tagged \( b \) jets. We will return to this point later. We have then run the generated SUSY events through our toy detector simulation and classified them into the various topologies A–F introduced above. Finally, for each SUGRA point, we
have checked whether the SUSY signals are observable above SM backgrounds for each of the three values of integrated luminosities. Here, we consider a signal to be observable if, for the given integrated luminosity, we have (i) at least 5 signal events, (ii) the statistical significance of the signal exceeds "5σ", i.e. \( N_{\text{signal}} > 5\sqrt{N_{\text{back}}} \), and (iii) \( N_{\text{signal}} > 0.2N_{\text{back}} \).

The third requirement, while somewhat arbitrary, is to ensure that we do not classify the \( \frac{E_T}{T} \) signal with \( E_T^c = 25 \text{GeV} \) (see Fig. 3a) with a cross section of 300 \( \text{fb} \) to be observable above the background of \( 3 \times 10^4 \text{fb} \). It seems evident to us that because there is no characteristic kinematic distribution whose shape the signal would grossly distort, this “1% excess”, while “observable” according to criteria (i) and (ii), would be impossible to detect. We check the observability of SUSY events for \( E_T^c = 15, 40, 60, 80, 100, 120 \) and 140 GeV and consider the signal to be observable if it is so for any one of the values of \( E_T^c \).

The results of our computation are illustrated in Fig. 4–Fig. 9, for each of the event topologies A–F, respectively for the same four choices of other SUGRA parameters as in Fig. 1. The theoretically and experimentally excluded regions, denoted by bricks and hatches, are identical to Fig. 1. The regions of the \( m_0 - m_1^2 \) plane where a signal is observable are shown for an integrated luminosity of 100 \( \text{pb}^{-1} \) (black squares) corresponding to the data sample of Run I, of 2 \( \text{fb}^{-1} \) (gray squares) corresponding to a data sample that might be available at the MI, and finally, of 25 \( \text{fb}^{-1} \) (white squares) corresponding to a data sample that might become available after a few years of operation of the proposed TeV33 upgrade.

Several comments are worth noting.

- By comparing the distribution of the solid squares in Fig. 4–Fig. 9, we conclude that the \( E_T^c \) channel should provide the maximal reach when the data of Run I is analyzed. Values of \( m_1^2 \) up to about 100 GeV should be accessible if \( m_0 \leq 200 \text{ GeV} \). For positive values of \( \mu \) this region would already have been accessible via the chargino search at LEP1.5 (from Fig. 1 it is clear that \( \tilde{W}_1 \) tends to be heavier for \( \mu < 0 \), with all other parameters the same) which is why we have no solid squares in Fig. 4b and Fig. 4d. We stress, however, that this depends crucially on the assumed gaugino mass unification, and a direct for the gluino signal (even for parameters in the hatched regions) is extremely important. Also, note from Fig. 4a that Tevatron experiments may probe regions of parameter space not accessible at LEP2.

- It is interesting to see that even with an integrated luminosity of 100 \( \text{pb}^{-1} \), we see that there are regions of the parameter space where there should be confirmatory signal also in other channels. Except for isolated corners in the small \( m_0 \) region (where the leptonic branching fraction of charginos and neutralinos may be enhanced because their two-body leptonic decays are accessible), the leptonic or tagged-\( b \) channels are unlikely to be discovery channels for supersymmetry at least for Run I of the Tevatron.

- With a data sample of 2 \( \text{fb}^{-1} \) Tevatron experiments should be able to probe \( m_1^2 \) values up to 150 GeV (corresponding to \( m_{\tilde{g}} \sim 400 \text{ GeV} \) in the \( E_T^c \) channel if \( m_0 \lesssim 200 \text{ GeV} \). This is considerably beyond the reach of LEP2. At the high values of \( m_1^2 \) that should be explorable at the MI, it is worth noting that electroweak production of charginos and neutralinos is a significant contributor to even the \( E_T^c \) channel: the production of gluinos and squarks is kinematically suppressed, so that the signals
from the electroweak production of charginos and neutralinos which have masses \( \sim (\frac{1}{6} - \frac{1}{3})m_\tilde{g} \) become independent. The same is true in the leptonic channels — in the \( 3\ell \) channel, the jets then mainly come from QCD radiation, which is included in the shower approximation in ISAJET. For larger values of \( m_0 \), squarks become inaccessible, and the range of \( m_\tilde{1} \) that might be probed becomes smaller. Not only is the reach at the MI considerably larger, we see that there should be confirmatory signals in the various leptonic channels (particularly if \( m_0 \) is not very large) and even in the tagged \( b \)-channel. Once again, we see that the maximum reach is obtained in the \( E_T \) channel, and that the trilepton channel enhances the reach only for isolated values of SUGRA parameters.

- We see from Figs. 4 that TeV33 should be able to probe \( m_\tilde{1} \) values about 25 GeV beyond what may be explored at the MI in the \( E_T \) channel; this corresponds to an increase in the gluino mass reach of about 65 GeV. The increase in the reach may be somewhat larger in the leptonic channels, as can be seen from Figs. 5–8. However, the maximal reach is still obtained via the \( E_T \) channel. We thus conclude that if Tevatron experiments are able to accumulate about 25 fb\(^{-1}\) of data, they would be able to probe gluino masses about 20-25\% beyond what might be probed at the MI (\( m_\tilde{g} \simeq 300 - 500 \) GeV). It is, however, important to note that with such a large data sample, one would be almost guaranteed to see a signal in several channels over much of the parameter range where there is a signal in the \( E_T \) channel.

- Turning to the prospects for identifying tagged \( b \)-jets in the sample of \( E_T \) events, we see from Fig. 9 that it is unlikely from an analysis of the data from Run I. \( b \)-tagged \( E_T \) events should be identifiable over a significant range of parameters at both the MI or TeV33. Measurement of the tagged \( b \) cross section, as well as the multiplicity of \( b \)-jets in SUSY events, could serve to yield information about the A-parameter or the \( b \)-quark Yukawa coupling, if a sufficient number of SUSY events can be accumulated. We warn the reader that the observability of this signal is rather sensitive to the assumptions about \( b \)-tagging and mistagging. We have checked that the signal to background ratio becomes smaller if the mistagging probability is taken to be zero instead of 2\%; i.e. the signal contains a larger fraction of mistagged events than the background. This is mainly due to the fact that the main SM background to the \( b \)-tagged sample comes from top quark production, and the background rate from misidentification of QCD jets in \( W \) and \( Z \) events adds little to the main physics background. In addition, the larger jet multiplicity, and the resulting greater probability of mistagging jets in the signal sample should lead to a larger “fake” background for the signal events relative to SM events.

Up to now, we have fixed the soft breaking parameter \( A_0 = 0 \). In order to investigate the sensitivity of the cross sections to variation of \( A_0 \) we show the Tevatron cross sections after cuts in the six channels A–F in Fig. 10. We fix \( m_0 = 100 \) GeV and \( m_\tilde{1} = 120 \) GeV, which yields \( m_\tilde{q} \simeq m_\tilde{g} - 30 \) GeV \( \simeq 315 \) GeV for \( A_0 = 0 \). The masses of the gluino and the first two generations of squarks are only very weakly dependent on \( A_0 \). Thus, for the cases studied in Fig. 10, \( \tilde{q}\tilde{q}, \tilde{g}\tilde{g} \) and \( \tilde{g}\tilde{g} \) processes all contribute to the signals, and gluinos decay to squarks. We examine values of \( A_0 \) for which the squared stop masses are positive. The following features are worth noting:
1. In case (a) the various topological cross sections are quite insensitive to $A_0$. As we vary $A_0$ over the complete range, sparticle masses do not change very much, and no thresholds for new decays are encountered. The gluinos and squarks each decay via two body modes, with branching fractions relatively insensitive to $A_0$.

2. In case (b), as we consider decreasing values of $A_0$, starting with large positive values, the cross sections are relatively constant until $A_0$ becomes negative enough so that $\tilde{t}_1$, the lighter of the $t$-squarks, becomes accessible via gluino decays. The scalar top decays via $\tilde{t}_1 \rightarrow b\tilde{W}_1$, so that the number of $b$-jets in gluino events is significantly increased. Direct production of $\tilde{t}_1\tilde{t}_1$ pairs also contributes to the increase in the tagged $b$-jet cross section and should be independently detectable \cite{30} if $m_{\tilde{t}_1}$ is not too large. The increased cross sections in the OS and SS lepton channels also have their origin in $\tilde{g} \rightarrow t\tilde{t}_1$ decays followed by the semileptonic decays of the top family; $\tilde{t}_1\tilde{t}_1$ production contributes to the increase in the OS as well as the $E_T$ cross sections.

3. Cases (c) and (d) show roughly similar features as case (b) — as $A_0$ decreases from large positive values, the cross sections again show an increase because $\tilde{t}_1$ becomes relatively light. However, a new feature is now seen for large negative values of $A_0$ in case (c) — the $E_T$ cross section shows a sharp increase, while all other cross sections drop sharply. This occurs when $\tilde{t}_1$ becomes lighter than the chargino, so that the loop decay mode $\tilde{t}_1 \rightarrow c\tilde{Z}_1$ dominates $\tilde{t}_1$ decays, leading to a drop in the $b$-jet multiplicity from gluino and stop decays. The leptonic cross sections decrease because the chargino now decays via $\tilde{W}_1 \rightarrow b\tilde{t}_1$ with a branching fraction of essentially 100%; because $|m_{\tilde{W}_1} - m_{\tilde{t}_1}|$ is small, the $b$-jets are presumably too soft to satisfy the tagging requirements. If SUSY parameters happen to be in this range, the promising clean trilepton signal from $\tilde{W}_1\tilde{Z}_2$ production will be absent, and $E_T$ events will be the main signature for chargino pair production. Finally, we remark that in case (d), $|m_{\tilde{W}_1} - m_{\tilde{t}_1}|$ is somewhat larger (at extreme negative values of $A_0$) and the $b$-jet appears to be sufficiently hard. As a result, while the leptonic cross sections exhibit a sharp decrease, the $E_T$ and tagged $b$ topologies do not.

IV. REACH VIA CLEAN MULTILEPTON CHANNELS

If gluinos and squarks are beyond the reach of the Tevatron, it is possible that SUSY might manifest itself through electroweak processes, via events with two or more hard isolated leptons and $E_T$ but with essentially no jet activity. We will refer to these as clean multilepton channels. The spectacular trilepton event signature from the reaction $p\bar{p} \rightarrow \tilde{W}_1\tilde{Z}_2 \rightarrow \ell\nu\tilde{Z}_1 + \ell'\bar{\nu}\tilde{Z}_1$ has recently been the focus of considerable attention \cite{3} but observable signals may also be present in dilepton channels \cite{3}. Sources of clean dilepton events include chargino and slepton pair production. Since we have studied these channels in detail elsewhere, here we will mostly focus on the comparison of the capabilities of the three luminosity options, and refer the reader to our earlier paper \cite{3} for details about the features of the SUSY signal and SM backgrounds.
A. Trilepton Channel

To facilitate efficient computation of the signal levels in the clean $3\ell$ channel we generated all chargino, neutralino and slepton production subprocesses using ISAJET even though the signal is dominated by $q\bar{q} \rightarrow \tilde{W}_1 \tilde{Z}_2$ production. Gluino and squark production very seldom leads to events without any jet activity. Following our earlier analysis [6] we implement the following cuts:

- We require 3 isolated leptons within $|\eta_\ell| < 2.5$ in each event, with $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 15$ GeV, and $p_T(\ell_3) > 10$ GeV;
- We require $E_T > 25$ GeV;
- We require that the invariant mass of any opposite-sign, same flavor dilepton pair not reconstruct the $Z$ mass, i.e. we require that $|m(\ell\bar{\ell}) - M_Z| \geq 10$ GeV;
- Finally require the events to be clean, i.e. we veto events with jets.

SM backgrounds to the clean $3\ell$ sample mainly come from $t\bar{t}$ and $WZ$ production. Lepton isolation plays a crucial role in reducing the top quark background. After the cuts, we are left with [6] a SM physics background of just 0.2 fb (mainly from $WZ$ events where $Z \rightarrow \tau\bar{\tau}$ with subsequent leptonic decays of the $\tau$s). Assuming that detector-dependent backgrounds from particle misidentification or jets or photons faking a lepton are under control, the observation of just a handful of such events in the current run (or at the MI) could signal new physics.

In Fig. 11, we show the regions of the $m_0 - m_{1/2}$ plane where the SUSY signal is expected to be observable at the $5\sigma$ level (with a minimum of 5 signal events) at the MI (gray squares) and at TeV33 (white squares) for the same cases (a)–(d) as in Fig. 1. We did not find any region (compatible with current experimental constraints) where this signal might be observable for an integrated luminosity of 100 pb$^{-1}$ only because our cuts in this channel were optimized for the higher Tevatron luminosity options. The following features are worthy of note.

1. We see that for small values of $m_0$ (for which sleptons are light enough so that two body slepton-lepton decays of charginos and neutralinos are kinematically allowed, while $\tilde{q}\bar{q}$ modes are forbidden) the MI reach extends to $m_{1/2} = 200 - 250$ GeV depending on $\tan \beta$ and the sign of $\mu$; the gap around $m_0 \approx 50$ GeV is where the decay $\tilde{Z}_2 \rightarrow \tilde{\ell}_L\ell$ becomes kinematically forbidden and where $\tilde{Z}_2$ dominantly decays via $\tilde{Z}_2 \rightarrow \nu\bar{\nu}$. For still larger values of $m_0$ sneutrinos become too heavy and $\tilde{Z}_2 \rightarrow \tilde{\ell}_R\ell$ dominates, so that the trilepton signal is again observable. The kinematic boundaries for these various two body slepton decay channels of $\tilde{Z}_2$ are shown by the three slanting contours in the small $m_0$ region of the Figure. Ultimately, of course, the sleptons become virtual, so that the neutralino decays via three-body modes. Then the hadronic decay of $\tilde{Z}_2$ are no longer negligible, leading to a reduction in the trilepton cross section. In fact for $m_0 > 150 - 200$ GeV, the $3\ell$ signal falls below the observable level at the MI except in the small $\tan \beta, \mu < 0$ case (a), where the range of $m_{1/2}$ that can be probed slowly decreases with increasing $m_0$. 
2. TeV33 should be able to probe the SUSY signal in this channel for substantial regions of parameter space not accessible at the MI. This should not be surprising, since the signal is essentially rate limited, assuming that non-physics instrumental backgrounds will be in control even in the high luminosity environment. Experiments at TeV33 should not only be able to fill in most of the “gaps” at small $m_0$ where the signal is not observable at the MI, but should also be able to substantially extend the $m_0$ range where the signal might be observable.

3. At TeV33 the clean trilepton signal may be observable well beyond where the “spoiler” decay modes of $\tilde{Z}_2$ become accessible if two body slepton decays of $\tilde{Z}_2$ are kinematically accessible; the kinematic boundaries for these decays are shown by the approximately horizontal contours. For a limited range of parameters, the TeV33 reach extends out to $m_{\tilde{Z}_2} = 280$ GeV which corresponds to $m_{\tilde{g}} = 700$ GeV! There are, however, even larger ranges of parameters where this signal will not be observable at TeV33 even if the chargino mass is at its current experimental bound. This has been traced to a negative interference term which leads to a large suppression of the leptonic decay of $\tilde{Z}_2$. It is for the same reason that the signal is not observable all the way up to the limit of the “spoiler” mode in cases (b)-(d). The non-observation of a trilepton signal at TeV33 cannot, therefore, be translated into a lower limit on the $\tilde{W}_1$ and $\tilde{Z}_2$ masses.

### B. Dilepton Channels

We have also investigated the possibility of discovering supersymmetry in the OS clean acollinear dilepton channel. Although the main contributions to the signal might be expected to come from chargino and slepton pair production, we generate all possible SUSY production reactions and implement the following set of cuts, designed to extract signal from these backgrounds.  

- We require exactly two isolated OS (either $e$ or $\mu$) leptons in each event, with $p_T(\ell_1) > 10$ GeV and $p_T(\ell_2) > 7$ GeV, and $|\eta(\ell)| < 2.5$. In addition, we require no jets, which effectively reduces most of the $t\bar{t}$ background.

- We require $E_T > 25$ GeV to remove backgrounds from Drell-Yan dilepton production, and also the bulk of the background from $\gamma^*, Z \rightarrow \tau\bar{\tau}$ decay.

- We require $\phi(\ell\bar{\ell}) < 150^0$, to further reduce $\gamma^*, Z \rightarrow \tau\bar{\tau}$ background.

- We require the $Z$ mass cut: invariant mass of any opposite-sign, same flavor dilepton pair not reconstruct the $Z$ mass, i.e. $m(\ell\bar{\ell}) \neq M_Z \pm 10$ GeV.

The SM background, after these cuts, is about 44 fb, bulk of which comes from $WW$ production. The regions of parameter space where the signal might be observable in this channel is shown in Fig. 12, again for the same cases (a)-(d). The horizontal (inclined) contours denote the kinematic boundaries for the decay(s) $\tilde{W}_1 \rightarrow W\tilde{Z}_1$ (\tilde{L}_L \nu, \tilde{\nu}$. A comparison with Fig. 11 shows that this region is a subset of the regions that might be explored via the clean $3\ell$ channel, both at the MI as well as at TeV33. In particular, the
clean 2ℓ channel does not lead to an observable signal in the regions of parameter space where the 3ℓ signal is unobservable due to the strong suppression of the branching fraction for leptonic $\tilde{Z}_2$ decays [32]. Also, for the most part, the region of parameters that might be probed at TeV33 via the clean dilepton channel may be probed at the MI via the clean 3ℓ channel.

It should be possible to confirm a signal from $\tilde{W}_1\tilde{Z}_2$ production by searching for OS like-flavor dileptons plus jets plus $E_T$ events which arise when the chargino decays hadronically and the neutralino leptonically. The invariant mass of the lepton pair in these events should match up with the mass of the OS like-flavor dilepton pair in the $\ell^+\ell^-\ell'$ sample of clean trilepton events. These events generally tend to be softer than events from the production of gluinos and squarks studied in Sec. III. We have examined where in SUGRA parameter space this jetty dilepton signal might be observable, with the same cuts as in Ref. [6]. Because these events are detectable only over a subset of parameters where the clean 3ℓ signal is observable, this channel does not lead to an improved reach. We will content ourselves with a qualitative discussion of this channel.

The SM background which, after cuts, mainly comes from vector boson pair production and Drell-Yan $\tau\bar{\tau}$ production is about 25 fb. The OS lepton plus jets plus $E_T$ signal region is observable over a subset of the regions where the trilepton signal is observable. This region has roughly similar shape as the region in Fig. 11, but covers only just over half as many points. For small values of $m_0$ where the charginos predominantly decay via the two-body lepton-slepton mode, these events mainly come from slepton and chargino pair production with jets coming from QCD radiation. For $m_0 \geq 200$ GeV, the signal is observable for a rather limited range of parameters except in case (a) where $m_{\tilde{\chi}}$ values up to 100 (140) GeV may be probed at the MI (TeV33).

It is worth mentioning that a measurement of $\sigma(3\ell)/\sigma(\ell^+\ell^-+\text{jets}+E_T)$ could potentially yield a measure of the hadronic branching fraction of $\tilde{W}_1$, provided that these events could be separated from other SUSY sources (gluinos and squarks) which lead to the same event topology. For very small $m_0$, we have already mentioned that $\tilde{W}_1\tilde{W}_1$, with jets coming from QCD radiation, is the biggest source of these events. We have checked that for larger values of $m_0$ the $n_j \geq 2$ plus OS dilepton events, with the cuts of Ref. [6] indeed come mainly from $\tilde{W}_1\tilde{Z}_2$ production: for example, for $(m_0, m_{\tilde{\chi}})$=(300 GeV, 120 GeV) in case (a) almost 90% of these events originate in the chain $\tilde{W}_1 \rightarrow q\bar{q}\tilde{Z}_1$, $\tilde{Z}_2 \rightarrow \ell^+\ell^-\tilde{Z}_1$. Even for the (100 GeV, 80 GeV) case, this fraction exceeds 50%; several other signals should be expected in such a scenario. Although we have not attempted to explore this, it may be interesting to examine whether the determination of the chargino decay pattern at a high luminosity upgrade such as TeV33 is indeed viable. (At the LHC, one may be swamped by squark and gluino production processes.)

V. SUMMARY AND CONCLUSIONS

Motivated by the recent proposal for upgrading the luminosity of the Fermilab Tevatron by another order of magnitude beyond the Main Injector era, we have examined the impact that experiments at such a facility (should its construction prove technically and fiscally feasible) would have on the search for supersymmetric particles. We have used ISAJET
to compute the reach of TeV33, under the optimistic assumption of an integrated luminosity of \(25 \text{ fb}^{-1}\) and compared it with the corresponding reach of the MI, for which we assume a data sample of \(2 \text{ fb}^{-1}\). In our analysis, we simply assume identical detector performance at the two facilities. We make no representation as to whether upgrades of the detector and the electronics that would be necessary for functioning in this high luminosity environment can be achieved in a timely fashion. Thus, while our estimates for the reach of the MI are probably realistic, our conclusions regarding the reach of TeV33 might be on the optimistic side. We have also discussed what might be possible from an analysis of the current Tevatron data sample of \(\sim 100 \text{ pb}^{-1}\). This enables us to compare how experiments at the MI will improve on what we can learn from the data sample of Run I of the Tevatron, and put in perspective the capabilities of any upgrades that might be possible in the future.

For definiteness, we have adopted the SUGRA framework (with its assumptions about universal scalar and gaugino masses at an ultra-high scale) for our analysis. We have examined the multi-jets plus \(E_T\) plus \(n_\ell = 1\)–\(3\) lepton channels (Sec. III) as well as the hadronically quiet dilepton and trilepton channels (Sec. IV) and delineated regions of the \(m_0\)–\(m_1\) plane where the various signals might be observable above SM backgrounds for the three values of integrated luminosity mentioned above. Our main result is summarized in Fig. 13, where we show the regions of SUGRA parameter space where at least one of the SUSY signals is observable with the criteria defined above. We show our results for the same cases \((a)-(d)\) in Fig. 1. The black squares are the points that can be probed at the “5\(\sigma\)” level with an integrated luminosity of \(100 \text{ pb}^{-1}\), while the gray (white) squares are where the signal should be observable with a luminosity of \(2 \text{ fb}^{-1}\) (\(25 \text{ fb}^{-1}\)). Several features are worth emphasizing:

- The analysis of the data from the current run will allow experiments at the Tevatron to probe only a little beyond the current experimental bounds. The most promising channel is the multi-jets plus \(E_T\) channel from the production of gluinos and squarks; beyond \(m_\tilde{g} = 100 \text{ GeV}\) \((m_\tilde{q} \simeq 300 \text{ GeV})\), their production cross section is kinematically suppressed, while the signals from electroweak chargino/neutralino production are still rate limited. We stress, however, that Tevatron experiments are direct probes of gluinos and squarks, and it is important to look for their signals even below the hatched region, since it is entirely possible that the assumption of gaugino mass unification (which is crucial to translate the LEP chargino mass bound to a bound in this plane) may prove to be incorrect.

- Experiments at the MI should probe a significant portion of the \(m_0\)–\(m_1\) plane, as can be seen from the distribution of gray squares in Fig. 13. Here, the important contributing channels are the multi-jets plus \(E_T\) channel and, especially in the small \(m_0\) region, the clean \(3\ell\) channel. We see that the region of the \(m_0\)–\(m_1\) plane that can be explored is sensitive to both \(\tan \beta\) and \(\text{sgn} \mu\): for favourable values of these parameters, the experiments may probe \(m_1\) as large as \(250 \text{ GeV}\) if \(m_0 \leq 150 \text{ GeV}\) via the clean trilepton channel; but for somewhat larger values of \(m_0\), we see from Figs. 13 \((b)-(d)\) that there may be no SUSY signal at the MI even if charginos are at their current experimental bound.

- Assuming an integrated luminosity of \(25 \text{ fb}^{-1}\), we see that experiments at TeV33 may be able to substantially expand the region where a SUSY signal might be observable.
Generally speaking, the reach is most enhanced in the rate-limited $3\ell$ channel (where the gain is proportional to the integrated luminosity ($L$), unlike the background-limited multi-jet channels where the statistical significance of the signal improves only as $\sqrt{L}$). Nevertheless, it is important to note that there are significant ranges of parameters which cannot be efficiently probed at TeV33 even if charginos are just beyond the reach of LEP2 (recall that LEP2 will probe the region $m_{\tilde{W}} \leq 80 - 90$ GeV well before the TeV33 commences operation). It will thus be difficult to obtain an unambiguous lower bound on sparticle masses if no SUSY signal is observed in experiments at TeV33.

- We also see from Fig. 13 that experiments at the MI and TeV33 will substantially expand the SUSY reach of the Tevatron. An important virtue of TeV33, however, is that there is an observable SUSY signal in several channels over a substantial portion of parameter space where SUSY should be detectable. Furthermore, if a signal for supersymmetry is found at the MI, then the order of magnitude increase in collider luminosity at TeV33 should allow more detailed information about the underlying SUSY parameters to be extracted from the event sample.

Our analysis was performed within the minimal framework where the conservation of $R$-parity is assumed. If instead $R$-parity is violated by baryon number non-conserving operators so that the LSP decays hadronically, the $E_T$ as well as the multilepton signals are greatly diminished, and the reach may be significantly smaller \cite{34} than that outlined in Fig. 13.

At this point it is worth recalling that in order for supersymmetry to ameliorate the fine-tuning problem of the SM, sparticles cannot be arbitrarily heavy \cite{3}; qualitatively, one requires that sparticles are not much heavier than the weak scale. Several authors \cite{35,36} have attempted to quantify this and obtained upper limits on sparticle masses. While these bounds are admittedly subjective, they could be regarded as providing rough benchmarks for future facilities; e.g. Anderson and Castaño \cite{36} have argued that the most favoured region from this point of view is where $m_{\tilde{\chi}} \lesssim 150 - 200$ GeV, $m_0 \lesssim 200 - 300$ GeV. It is also interesting to note that the lightest neutralino would be an acceptable mixed dark matter candidate if SUGRA parameters happen to be in this range \cite{37}. These arguments suggest that experiments at the MI and TeV33 would probe some of the most promising regions of SUGRA parameter space. We believe, however, that while fine-tuning and cosmological considerations are indeed suggestive, the upper bounds on sparticle masses that are obtained from these should be regarded as qualitative, and that a sufficient “safety margin” should be allowed for any experiment that is designed to decisively confirm or exclude weak scale supersymmetry. This is only possible at hadron supercolliders such as the LHC where it is possible to probe the $m_0 - m_{\tilde{\chi}}$ plane over the region $m_0 \leq 1.5$ TeV, $m_{\tilde{\chi}} \leq 800$ GeV \cite{23}, or at future electron-positron colliders operating at $\sqrt{s} \geq 1 - 1.5$ TeV, where it should be possible to probe chargino and slepton masses up to the beam energy.

ACKNOWLEDGMENTS

This research was supported in part by the U. S. Department of Energy under contract number DE-FG05-87ER40319, DE-FG03-91ER40674, DE-AC02-76CH00016, and DE-FG-03-94ER40833.
REFERENCES

[1] F. Abe et. al., Phys. Rev. Lett. 73, 225 (1994) and Phys. Rev. D50, 2966 (1994); F. Abachi et. al., Phys. Rev. Lett. 74, 2632 (1995).

[2] D. Amidei, C. Brock et. al., Report of the TeV 2000 Study Group on Future Electroweak Physics at the Tevatron (to appear).

[3] For a review of the minimal model and SUSY phenomenology, see H. P. Nilles, Phys. Rep. 110, 1 (1984); H. Haber and G. Kane, Phys. Rep. 117, 75 (1985); X. Tata, in The Standard Model and Beyond, p. 304, edited by J. E. Kim, World Scientific (1991); R. Arnowitt and P. Nath, Lectures presented at the VII J. A. Swieca Summer School, Campos do Jordao, Brazil, 1993 CTP-TAMU-52/93; V. Barger and R. J. N. Phillips, in Recent Advances in the Superworld, J. Lopez and D. Nanopoulos, Editors, World Scientific (1994); Properties of SUSY Particles, L. Cifarelli and V. Khoze, Editors, World Scientific (1993); X. Tata, Lectures presented at TASI95, University of Colorado at Boulder, Hawaii preprint UH-511-833-95 (1995).

[4] A phenomenological summary of the current experimental situation as well as a survey of the reach of various colliders may be found in H. Baer et. al., to appear in Electroweak Symmetry Breaking and New Physics at the TeV Scale, edited by T. Barklow, S. Dawson, H. Haber and J. Seigrist, (World Scientific) 1995.

[5] T. Kamon, J. Lopez, P. McIntyre and J. T. White, Phys. Rev. D50, 5676 (1994).

[6] H. Baer, C-H. Chen, C. Kao and X. Tata Phys. Rev. D52, 1565 (1995).

[7] S. Mrenna, G. Kane, G. D. Kribbs and J. D. Wells, Phys. Rev. D53, 1168 (1996).

[8] For instance, while Ref. [3] uses a real detector (CDF) simulation for the analysis of the background to the clean trilepton signal, the background to the $E_T$ channel is evaluated by computing the background from $Z \rightarrow \nu\nu+jets$ and multiplying it by five. In contrast, Ref. [6] has focussed on only the di and trilepton signal using a toy simulation. Unlike these analyses which use ISAJET, the work of Ref. [7] is based on PYTHIA. These authors have studied the reach in the clean trilepton as well as in the $E_T$ channel but we will see that our estimates of SM backgrounds are frequently considerably larger than those in Ref. [4]. Finally, we note that although all three groups have performed their studies within the SUGRA framework, it is difficult to directly compare the reach that they obtain because of the way that the three groups choose to present the results. In Ref. [5,7], random points are generated across the entire allowed parameter space, but then the experimental cross sections are shown as a function of some particular sparticle mass (and all information about the underlying SUGRA parameters is lost), while in Ref. [6] the results are shown in the $m_0 - m_{\frac{1}{2}}$ plane, for particular choices of $A_0$, tan $\beta$ and $sgn(\mu)$.

[9] H. Baer, C-H. Chen, R. Munroe, F. Paige and X. Tata, Phys. Rev. D51, 1046 (1995).

[10] S. Martin and M. Vaughn, Phys. Lett. B318, 331 (1993).

[11] S. Abachi et al. Fermilab Pub-95/057-E (1995).

[12] L. Montanet et al., Phys. Rev. D50, 1173 (1994).

[13] L. Rolandi, H. Dijkstra, D. Strickland and G. Wilson, representing the ALEPH, DELPHI, L3 and OPAL collaborations, Joint Seminar on the First Results from LEP1.5, CERN, Dec. 12th, 1995.

[14] F. Paige and S. Protopopescu, in Supercollider Physics, p. 41, ed. D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in Proceedings of
the Workshop on Physics at Current Accelerators and Supercolliders, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory, 1993).

[15] H. Baer, X. Tata and J. Woodside, Phys. Rev. D41, 906 (1990).
[16] R. M. Barnett, J. F Gunion and H. Haber, Phys. Lett. B315, 349 (1993).
[17] D. P. Roy, Phys. Lett. B283, 270 (1992).
[18] H. Baer, C. Kao and X. Tata, Phys. Rev. D51, 2180 (1995) and Phys. Rev. D48, R2978 (1993).
[19] R. Arnowitt and P. Nath, Mod. Phys. Lett. A2, 331 (1987).
[20] H. Baer and X. Tata, Phys. Rev. D47, 2739 (1993).
[21] H. Baer, C. Kao and X. Tata, Phys. Rev. D48, 5175 (1993).
[22] S. Abachi et. al. (D0 Collaboration), Phys. Rev. Lett. 76, 2228 (1996) and F. Abe et. al. (CDF Collaboration), Fermilab Pub. 96/029-E, from an analysis of just about 10-20 pb$^{-1}$ of the Tevatron data have obtained limits on the chargino mass from the non-observation of an excess of events in the clean trilepton channel. While these limits are not competitive with the chargino bound from LEP 1.5, these analyses serve to demonstrate the viability of this signature in future studies. It is also worth remembering that the clean 3$\ell$ channel may be the only way of directly probing $\tilde{Z}_2$; the cross section for $\tilde{Z}_2$ production at LEP may be very small if $\tilde{Z}_2$ is dominantly gaugino-like (and the selectron is moderately heavy), as is the case in SUGRA type models.
[23] H. Baer, C. H. Chen, F. Paige and X. Tata, Phys.Rev. D52, 2746 (1995) and FSU-HEP-951215, Phys. Rev. D (in press).
[24] H. Baer, X. Tata and J. Woodside, Phys. Rev. D45, 142 (1992); H. Baer, M. Bisset, X. Tata and J. Woodside, Phys. Rev. D46, 303 (1992); C. Albajar et. al. in Aachen LHC Collider Workshop, CERN90-10 (1990); F. Pauss, ibid; H. Baer et. al. in Research Directions for the Decade, E. Berger, Editor (World Scientific, 1992); H. Baer, M. Drees, C. Kao, M. Nojiri and X. Tata, Phys. Rev. D50, 2148 (1994); A. Bartl, W. Majerotto and W. Porod, Z. Phys. C64, 499 (1994).
[25] J. Botts et. al., Phys. Lett. B304, 159 (1993).
[26] Our background for $E_T$ events tends to be higher than that obtained in Ref. [7]. This is due mainly to a larger choice for parton shower virtuality in ISAJET in W or Z plus jets events to match tree level calculations. Without this scaling, our results are much closer to those in Ref. [4], but about three times smaller than the results we use in this paper. We are grateful to S. Mrenna for detailed correspondence about this issue.
[27] K. Hikasa and M. Kobayashi, Phys. Rev. D36, 724 (1987).
[28] H. Baer, M. Drees, R. Godbole, J. Gunion and X. Tata, Phys. Rev. D44, 725 (1991).
[29] The current version of ISAJET does not include some of the effects from Yukawa couplings of $b$-quarks and $\tau$ leptons. Because these may become important for large values of $\tan \beta$, we have not included cases with $\tan \beta \simeq \frac{m_t}{m_b}$ in our study.
[30] H. Baer, J. Sender and X. Tata, Phys. Rev. D50, 4517 (1994).
[31] A. Bartl (private communication).
[32] This conclusion differs from that in our previous study [6] where we found (see Fig. 8 of that paper) that the clean 2$\ell$ signal might be observable at TeV33 within the “hole region” for the trilepton signal. The range of parameters where this occurred is now excluded by the LEP1.5 constraint on the chargino mass.
[33] After cuts, $\sigma(3\ell) (\sigma(\ell^+\ell^-+jets))$ is 5 fb and 30 fb (17 fb and 88 fb) for the two cases
just mentioned. A measurement of the branching fraction thus does not appear to be feasible with the MI data sample.

[34] We are not aware of any detailed calculations of the SUSY reach of TeV33 in these scenarios. At the MI, it is possible that there may be no observable signal even if gluinos are relatively light and squarks are heavy as reviewed in Ref. [18]. The statistical significance of the signal should be better at TeV33, but not dramatically so since the channels are mostly background-limited. Of course, in the other case where the LSP decays only into $e$ or $\mu$ via $R$-parity interactions that violate lepton number, it should be possible to probe gluino masses of 500-600 GeV even at the Main Injector [18].

[35] R. Barbieri and G. Giudice, Nucl. Phys. B306, 63 (1988).

[36] G. Anderson and D. Castaño, Phys.Rev. D53, 2403 (1995).

[37] Some recent papers include M. Drees and M. Nojiri, Phys. Rev. D47, 376 (1993); G. Kane, C. Kolda, L. Roszkowski and J. Wells, Phys. Rev. D49, 6173 (1994); H. Baer and M. Brhlik, Phys. Rev. D53, 597 (1993).
FIGURES

FIG. 1. Contours of squark (dashed), gluino (solid) and chargino (dotted) masses in the $m_0-m_{1/2}$ plane of the minimal SUGRA model. Frames are shown for a) $\tan \beta = 2$, $\mu < 0$, b) $\tan \beta = 2$, $\mu > 0$, c) $\tan \beta = 10$, $\mu < 0$, and d) $\tan \beta = 10$, $\mu > 0$. We take $m_t = 170$ GeV and $A_0 = 0$. The bricked regions are excluded by theoretical constraints discussed in Ref. [23] while the shaded regions are excluded by experiment.

FIG. 2. Component SM background cross sections as a function of the cut parameter $E_T^c$ defined in the text for multijet plus a) $\ell + E_T^c$, b) $1\ell + E_T^c$, c) OS dileptons+$E_T^c$, d) SS dileptons+$E_T^c$, e) $3\ell + E_T^c$ and f) tagged $B + E_T^c$ event topologies with cuts as defined in Sec. III of the text. The backgrounds that we have computed are $t\bar{t}$ (long-dashed), QCD (long-dashed-single-dotted), $W+\text{jets}$ (long-dashed-double-dotted), Z+jets (long-dashed-triple-dotted), WW (short-dashed), WZ (short-dashed-dotted) and ZZ (short-dashed-double-dotted). The sum of these backgrounds is shown as the solid curve.

FIG. 3. Variation of the SUSY signals and total SM background with $E_T^c$ for the same event topologies as in Fig. 2. We have fixed $m_1 = 120$ GeV, $\tan \beta = 2$, and chosen $A_0 = 0$ and $\mu < 0$ with $m_0 = 100$ GeV (solid), $m_0 = 200$ GeV (dashed) and $m_0 = 800$ GeV (dotted). In the other two cases, we take $\mu > 0$ and fix $A_0 = -400$ GeV (dot-dashed) and $A_0 = -430$ GeV (dot-dot-dashed). The SM background level is denoted by crosses.

FIG. 4. Regions of the $m_0 - m_{1/2}$ plane where the multijets plus $E_T^c$ signal is observable at a 2 TeV $p\bar{p}$ collider according to the criteria discussed in Sec. III of the text for the same choices of parameters as in Fig. 1. We consider three values for the integrated luminosity: 100 pb$^{-1}$ corresponding to Run I of the Tevatron (black squares), 2 fb$^{-1}$ which is expected to be accumulated at the Main Injector (gray squares) and 25 fb$^{-1}$ to be accumulated at the proposed TeV33 (white squares). The bricked and hatched regions are the same as in Fig. 1.

FIG. 5. The same as Fig. 4 except for the multijet plus $1\ell + E_T^c$ channel.

FIG. 6. The same as Fig. 4 except for the multijet plus OS dilepton +$E_T^c$ channel.

FIG. 7. The same as Fig. 4 except for the multijet plus SS dilepton +$E_T^c$ channel.

FIG. 8. The same as Fig. 4 except for the multijet plus $3\ell + E_T^c$ channel.

FIG. 9. The same as Fig. 4 except for the multijet plus tagged $B + E_T^c$ channel.

FIG. 10. The $A_0$ dependence of the SUSY signal cross sections in the six channels in Fig. 3. for $m_0 = 100$ GeV, $m_{1/2} = 120$ GeV, $E_T^c = 15$ GeV for $\tan \beta = 2$ and 10 and for either sign of $\mu$. 
FIG. 11. The same as Fig. 4 except for the clean, i.e. jet-free $3\ell + E_T$ channel discussed in Sec. IV. The three slanting contours (from left to right) mark the boundaries of the regions where the two body decays $\tilde{Z}_2 \rightarrow \tilde{\ell}_L \ell, \tilde{\nu} \nu$ and $\tilde{\ell}_R \ell$ become forbidden, whereas the (almost) horizontal contours mark the corresponding boundaries for the “spoiler” decays $\tilde{Z}_2 \rightarrow \tilde{Z} \tilde{Z}_1$ or $H \ell \tilde{Z}_1$. Outside the hatched region, we found no points where this signal would be observable from an analysis of the data from Run I of the Tevatron.

FIG. 12. The same as Fig. 11 except for the clean dilepton channel. The slanting contours, from left to right, mark the kinematic boundary for the decays $\tilde{W}_1 \rightarrow \tilde{\ell}_L \nu, \tilde{\nu} \ell$, while the roughly horizontal line marks the boundary for the decay $\tilde{W}_1 \rightarrow \tilde{W} \tilde{Z}_1$.

FIG. 13. The cumulative reach for supersymmetry of the Tevatron and its upgrades via any of the channels in Figs. 4-12 with the same labelling as in Fig. 4.