Supersymmetry dileptons and trileptons at the Fermilab Tevatron

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We consider the production of supersymmetry neutralinos and charginos in $p\bar{p}$ collisions at the Fermilab Tevatron, and their subsequent decay via hadronically quiet dileptons and trileptons. We perform our computations in the context of a variety of supergravity models, including generic four-parameter supergravity models, the minimal SU(5) supergravity model, and SU(5)×U(1) supergravity with string-inspired two- and one-parameter moduli and dilaton scenarios. Our results are contrasted with estimated experimental sensitivities for dileptons and trileptons for integrated luminosities of 100 pb^{-1} and 1 fb^{-1}, which should be available in the short and long terms. We find that the dilepton mode is a needed complement to the trilepton signal when the latter is suppressed by small neutralino branching ratios. The estimated reaches in chargino masses can be as large as 100 (150) GeV for 100 pb^{-1} (1 fb^{-1}). We also discuss the task left for CERN LEP II once the Tevatron has completed its short-term search for dilepton and trilepton production.

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Experimental searches for supersymmetric particles have come a long way since the commissioning of the Tevatron $p\bar{p}$ collider at Fermilab and the LEP e^+e^- collider at CERN. The strengths and weaknesses of these two types of colliders are well known. A hadron collider is best suited for searching the highest accessible mass scales since a sharp kinematical limit does not exist, but discoverability depends on the event rate and the cleanliness of the signal. An e^+e^- collider is capable of discovery essentially up to the kinematical limit, but this is much lower than what would be accessible in a hadron collider. In fact, it has become apparent that an e^+e^- linear collider with a center-of-mass energy in the multihundred GeV range would be ideal for what has been termed "sparticle spectroscopy." At present though, in the search for new physics we have to make the best possible use of existing facilities, since information gathered there would illuminate the path towards higher energy machines. One such effort is being conducted at the Tevatron, where the search for weakly interacting sparticles (charginos and neutralinos) has become quite topical, in view of the fact that the reach of the machine for the traditional strongly interacting sparticles has been nearly reached. This effort will benefit from an integrated luminosity in excess of 100 pb^{-1} by the end of the ongoing run IB, and possibly 1–2 fb^{-1} during the Main Injector era around the year 2000.

In this paper we reexamine the prospects for supersymmetry discovery at the Tevatron via the hadronically quiet trilepton signal[1] which occurs in the production and decay of charginos and neutralinos in $p\bar{p}$ collisions [1–3]. Our previous study [3] considered the trilepton signal with an estimated 100 pb^{-1} of accumulated data. Here we update this analysis by incorporating the latest experimental information on the trilepton signal and prospects for its detection with $\sim 1\ \mathrm{fb}^{-1}$ data. We also extend our analysis of this signal to a much broader class of supergravity models than those considered in Ref. [3]. In this paper we also discuss (for the first time) the dilepton signal which arises in chargino pair production at the Tevatron. This signal has been recently shown to be experimentally extractable [4], and as we discuss, has the advantage of allowing a significant exploration of the parameter space for chargino masses in the LEP II accessible range. Our calculations are performed in the context of a broad class of unified supergravity models, which have the virtue of having the least number of free parameters and are therefore highly predictive and straightforwardly testable through a variety of correlated phenomena at different experimental facilities. Our study should give a good idea of the range of possibilities open to experimental investigation, and allow quantitative checks of specific models which yield the largest rates.

We consider unified supergravity models with universal soft supersymmetry breaking at the unification scale, and radiative electroweak symmetry breaking at the weak scale. Following a standard procedure [5] we evolve numerically the coupled set of renormalization group equations from the unification scale down to the electroweak scale. At the electroweak scale we enforce radiative electroweak symmetry breaking by minimizing the one-loop effective potential, as described in Ref. [6]. These constraints reduce the number of parameters needed to describe the models to four, which can be taken to be $m_{\chi_1^\pm}, \xi_0 \equiv m_0/m_{1/2}, \xi_A \equiv A/m_{1/2}, \tan\beta$, with a specified value for the top-quark mass (m_t). In what follows we

[1]This signal contains no hadronic activity, except for initial state radiation effects, and is thus distinct from the usual multilepton signals in squark and gluino production.

take $m_t^{\rm pole} = 160$ GeV which is the central value obtained in fits to all electroweak and Tevatron data in the context of supersymmetric models [7]. We should note that when we consider "string-inspired" models below, the unification scale is taken to be the string scale ($\sim 10^{18}$ GeV). This is accomplished by inserting intermediate scale particles, as discussed in Ref. [8]. In all the other models the unification scale is the usual grand unified theory (GUT) scale ($\sim 10^{16}$ GeV). Of relevance to our discussion, we note that in all models considered the following relation holds to various degrees of approximation:

$$m_{\chi_1^\pm} \approx m_{\chi_2^0} \approx 2m_{\chi_1^0} \; . \tag{1}$$

Among these four-parameter supersymmetric models we consider generic models with continuous values of $m_{\chi_1^\pm}$ and discrete choices for the other three parameters:

$$\tan\beta = 2, 10, \quad \xi_0 = 0, 1, 2, 5, \quad \xi_A = 0 \; . \tag{2}$$

The choices of $\tan\beta$ are representative; higher values of $\tan\beta$ are likely to yield values of $B(b \to s\gamma)$ in conflict with present experimental limits [9]. The choices of ξ_0 correspond to $m_{\tilde q} \approx (0.8, 0.9, 1.1, 1.9)m_{\tilde g}$. The choice of A has little impact on the results. We also consider the case of minimal SU(5) supergravity, where the parameter space is still four dimensional but restricted by the additional constraints from proton decay and cosmology (a not too young Universe). In this case we sample a wide range of $\tan\beta, \xi_0, \xi_A$ discrete values and only keep points in parameter space which satisfy these two constraints. One can show that the parameter space becomes bounded by $\tan\beta \le 10, \xi_0 \ge 4$, and $m_{\chi_1^\pm} \le 120$ GeV [10].

We also consider the case of no-scale SU(5)×U(1) supergravity [5]. In this class of models the supersymmetry-breaking parameters are related in a string-inspired way. In the two-parameter *moduli* scenario $\xi_0 = \xi_A = 0$ [11], whereas in the *dilaton* scenario $\xi_0 = 1/\sqrt{3}, \xi_A = -1$ [12]. We also compute the rates in the *one-parameter* moduli [$B(M_U) = 0$] and dilaton [$B(M_U) = 2m_0$] scenarios, where M_U is the string unification scale, and with this extra condition $\tan\beta$ is determined as a function of $m_{\chi_1^\pm}$, which is the only free parameter in the model. A series of experimental constraints and predictions for these models have been given in Refs. [8] and [13], respectively.

The processes of interest are the following.

Trileptons. $p\bar p \to \chi_2^0\chi_1^\pm$, where the next-to-lightest neutralino decays leptonically ($\chi_2^0 \to \chi_1^0 l^+l^-$), and so does the lightest chargino ($\chi_1^\pm \to \chi_1^0 l^\pm \nu_l$). The cross section proceeds via s-channel exchange of an off-shell W and (small) t-channel squark exchange, and thus peaks at $m_{\chi_1^\pm} \approx \frac{1}{2}M_W$, and otherwise falls off smoothly with increasing chargino masses with a small $\tan\beta$ dependence.

Dileptons. $p\bar p \to \chi_1^+\chi_1^-$, where both charginos decay leptonically. The cross section proceeds via s-channel exchange of off-shell Z and γ and t-channel squark exchange, and peaks for $m_{\chi_1^\pm} \approx \frac{1}{2}M_Z$. Dileptons could also come from $p\bar p \to \chi_1^0\chi_2^0, \chi_2^0\chi_2^0$, with the appropriate leptonic or invisible decays of χ_2^0. Both of these processes are negligible [2] because the couplings of the Z and γ to neutralinos are highly suppressed when the neutralinos have a high gaugino content, as is the case when Eq. (1) holds. Yet another source of dileptons via $p\bar p \to \tilde e_R^+ \tilde e_R^-$ suffers from small rates for selectron masses above the LEP limit [14].

The more important factors in the dilepton and trilepton yields are the leptonic branching fractions which can vary widely throughout the parameter space [3]. If all sparticles are fairly heavy, the decay amplitude is dominated by W or Z exchange. In this case the branching fractions into electrons plus muons are $B(\chi_1^\pm \to \chi_1^0 l^\pm \nu_l) \approx 2/9$ and $B(\chi_2^0 \to \chi_1^0 l^+ l^-) \approx 6\%$. On the other hand, if some of the sparticles are relatively light, most likely the sleptons, the branching fractions are altered. The extreme, although not unusual, case occurs when the sleptons are on shell. These two-body decays then dominate and the chargino leptonic branching fraction is maximized, i.e., $B(\chi_1^\pm \to \chi_1^0 l^\pm \nu_l)_{\rm max} = 2/3$. Light sleptons[2] also affect the neutralino leptonic branching ratio. When the sneutrino is on shell and is lighter than the corresponding right-handed charged slepton ($\tilde e_R, \tilde\mu_R$), the channel $\chi_2^0 \to \nu_l \tilde\nu_l$ dominates the amplitude, and the neutralino leptonic branching ratio is suppressed. This situation is reversed when the charged slepton is on shell and is lighter than the sneutrino, which leads to an enhancement of the neutralino leptonic branching ratio. For sufficiently high neutralino masses, both leptonic branching ratios decrease because the W and Z go on shell and dominate the decay amplitudes. In the case of the neutralino, the spoiler mode $\chi_2^0 \to \chi_1^0 h$ also becomes kinematically allowed. These high-mass suppressions do not kick in until chargino and neutralino masses $m_{\chi_1^\pm} \approx m_{\chi_2^0} \sim 2M_Z, 2m_h \sim 200$ GeV. We should note that in computing the production cross sections we have used the parton distribution functions from Ref. [15] [fit S in the modified minimal subtraction ($\overline{\rm MS}$) scheme] with a scale Q equal to the sum of the masses of the final state particles. The results are not very sensitive to this choice because this scale enters as $\ln[\ln(Q/\Lambda_{\rm QCD})]$.

The product of the total hadronic cross section times the relevant leptonic branching fractions (i.e., σB with no cuts) is shown for the models of interest in Figs. 1–6. The various curves in the figures terminate at the low end because of theoretical and experimental (i.e., LEP) constraints on the parameter space. At the high end the curves are cut off when the yields fall below the foreseeable sensitivity.[3] In the case of the minimal SU(5) supergravity model (Fig. 3) we do not have curves, but rather discrete points because of the sampling of parameter space discussed above. The separation into different curves at the low mass end is an artifact of the limited sampling statistics; the whole range spanned by the shown points should be considered as viable.

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[2]In supergravity models $m_{\tilde e_R} = m_{\tilde\mu_R} < m_{\tilde e_L} = m_{\tilde\mu_L}$.

[3]For $\xi_0 = 5$, radiative electroweak symmetry breaking is only possible for $\tan\beta \le 4$. This is why there is no curve for $\xi_0 = 5$ in Fig. 2 ($\tan\beta = 10$), whereas there is such a curve in Fig. 1 ($\tan\beta = 2$).

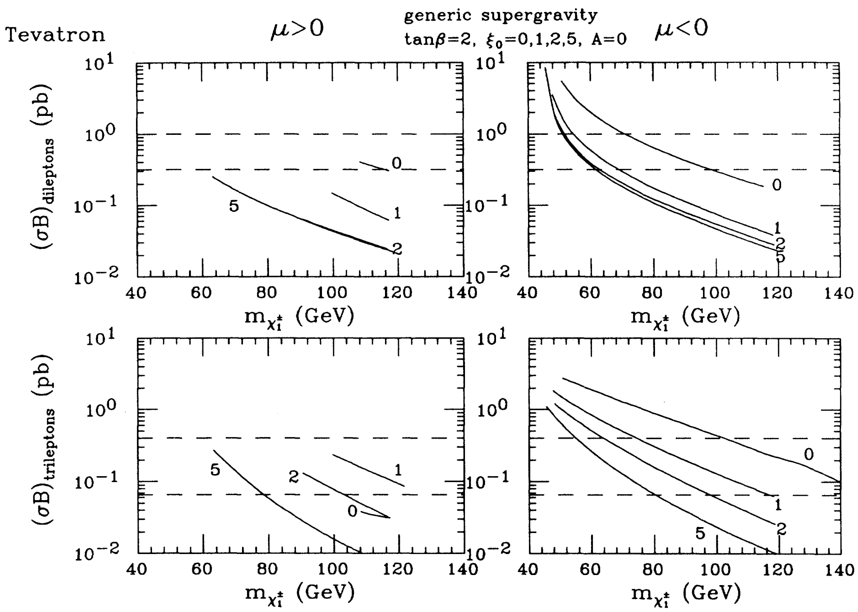

FIG. 1. The dilepton and trilepton rates at the Tevatron versus the chargino mass in a generic unified supergravity model with $\tan\beta = 2, \xi_0 = 0, 1, 2, 5$ (as indicated), and $A = 0$. The upper (lower) dashed lines represent estimated reaches with 100 pb^{-1} (1 fb^{-1}) of data.

In most cases we note that the rates are higher for $\mu < 0$. This is a consequence of suppressed branching fractions for $\mu > 0$, but also of a generally smaller allowed parameter space which requires minimum values of the chargino mass which may exceed significantly the present experimental lower limit. We can also observe that the dilepton rates indeed peak near $\frac{1}{2}M_Z$, whereas the trilepton rates are not as large for light chargino masses, since they peak at $\frac{1}{2}M_W$. It is also evident in the figures that for chargino masses below $\sim$ 100 GeV, the trilepton rates can be highly suppressed, while the dilepton rates are not, thus producing a rather complementary effect. This "threshold" phenomenon is most evident in the bottom panels of Figs. 4–6 and, as discussed above, corresponds to a suppression of the neutralino leptonic branching ratio for light sleptons, i.e., when $\chi_2^0 \to \nu\tilde{\nu}$ is allowed.

In more detail, in Fig. 5 the trilepton rates for $\mu > 0$ and low values of $m_{\chi_1^\pm}$ are very suppressed because $m_{\chi_2^0} \geq m_{\tilde{\nu}}$ for $m_{\chi_1^\pm} \leq 50$ GeV, and thus $\chi_2^0 \to \nu\tilde{\nu}$ is kinematically allowed. For $\mu < 0, m_{\chi_2^0} < m_{\tilde{\nu}}$ and no suppression occurs. The same phenomenon is responsible for the behavior of the trilepton rates in Fig. 6, as can be seen by studying the spectrum of these models shown in Fig. 3 of Ref. [13]. The behavior of the trilepton rates in Fig. 4 can also be understood by the above mechanism, which is effective for both signs of μ. For $\mu < 0$ there is no large suppression for $\tan\beta = 2$ because $m_{\chi_2^0} < m_{\tilde{\nu}}$. Larger values of $\tan\beta$ (6 and 10 in Fig. 4) decrease $m_{\tilde{\nu}}$ and allow $m_{\chi_2^0} > m_{\tilde{\nu}}$, with the corresponding large sup-

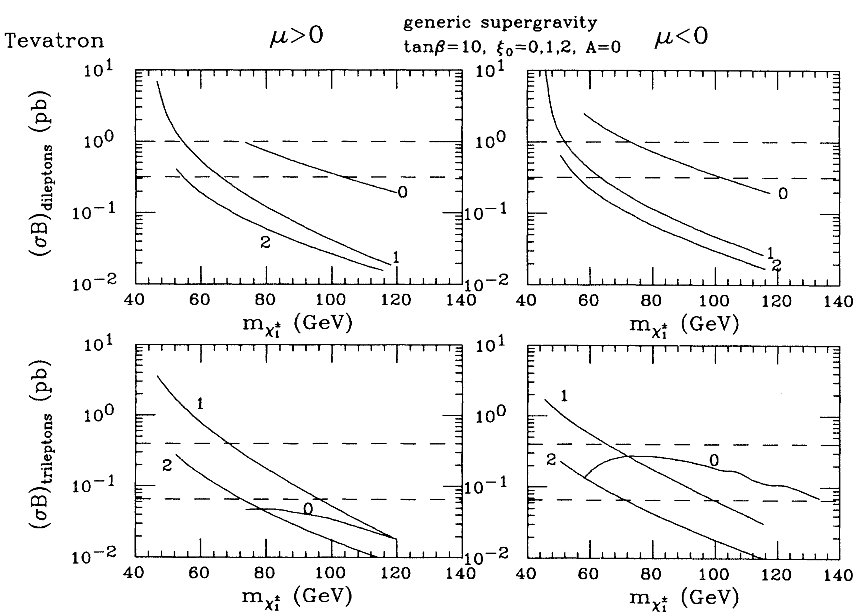

FIG. 2. The dilepton and trilepton rates at the Tevatron versus the chargino mass in a generic unified supergravity model with $\tan\beta = 10, \xi_0 = 0, 1, 2$ (as indicated), and $A = 0$. The upper (lower) dashed lines represent estimated reaches with 100 pb^{-1} (1 fb^{-1}) of data.

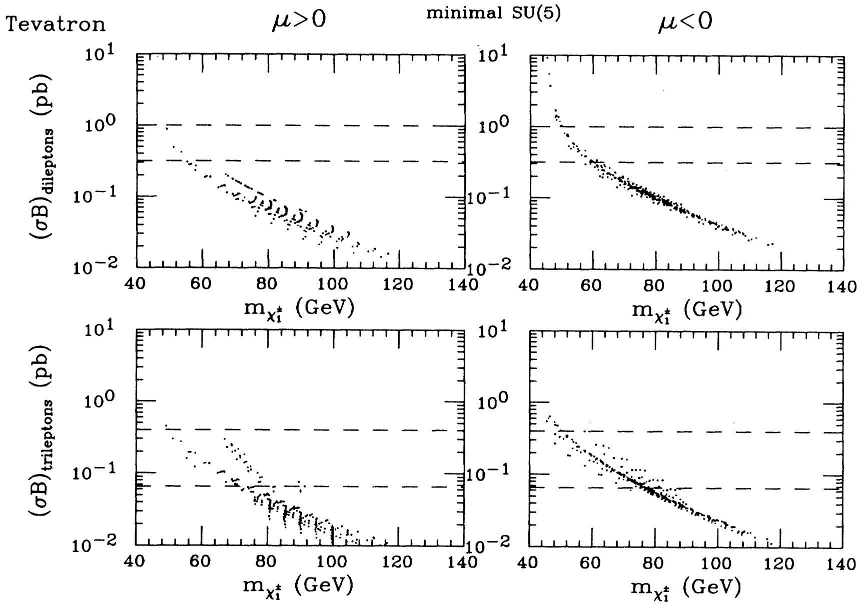

FIG. 3. The dilepton and trilepton rates at the Tevatron versus the chargino mass in the minimal SU(5) supergravity model (where $\tan\beta < 10$, $\xi_0 > 4$). The upper (lower) dashed lines represent estimated reaches with 100 pb^{-1} (1 fb^{-1}) of data.

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The significance of our results is quantified by the horizontal dashed lines in the figures, which represent estimates of the experimental sensitivity to be reached with 100 pb^{-1} (upper limits) and 1 fb^{-1} (lower lines). The lesser sensitivity should be achievable at the end of Run IB (i.e., prior to the LEP II upgrade), whereas the higher sensitivity should be available with the Main Injector upgrade [i.e., after the LEP II shutdown but before the commissioning of the CERN Large Hadron Collider (LHC)].

The trilepton sensitivity with 100 pb^{-1} (i.e., 0.4 pb) has been estimated by simply scaling down by a factor of 5 the present Collider Detector at Fermilab (CDF) experimental limit of $\sim$ 2 pb obtained with 20 pb^{-1} of recorded data [16]. The factor of 5 is the expected increase in recorded luminosity, and a simple $\mathcal{L}$ scaling is appropriate assuming the trilepton signal has no standard model backgrounds at this level of sensitivity. We should note that the experimental sensitivities are actually chargino-mass dependent,[4] following a curve shaped similarly to the signal (i.e., improving with larger masses) and which asymptotes to the indicated dashed lines for $m_{\chi_1^\pm} \geq 100$ GeV. The decrease in sensitivity for the lower masses is typically compensated by a corresponding increase in signal. The sensitivity at 1 fb^{-1} requires a study of the background since small standard model processes and detector-dependent instrumental backgrounds become important at this level of sensitivity [17]. The sensitivity in the figures (i.e., 0.07 pb) is obtained by scaling up by $\sqrt{\mathcal{L}}$ the value given in Table II of Ref. [17].

The dilepton (plus $\not{p}_T$) signal suffers from several standard model backgrounds, most notably $Z \to \tau\tau$ and WW production. A study based on the D0 detector [4] reveals that with suitable cuts, in 100 pb^{-1} an estimated background of eight events is expected, which would require eight signal events at 3σ significance. The efficiencies for dilepton detection have also been studied [4], and they improve with increasing chargino masses; 8% is a typical value. All this implies a sensitivity of 1 pb for dilepton detection. With 1 fb^{-1} one can scale down the sensitivity with $\sqrt{\mathcal{L}}$, obtaining a sensitivity of 0.3 pb. As in the

TABLE I. Estimated chargino mass reaches in various supergravity models for chargino-neutralino production in $p\bar{p}$ collisions at the Tevatron via dilepton and trilepton modes for integrated luminosities of 100 pb^{-1} and 1 fb^{-1}. All masses in GeV. Dashes (-) indicate negligible sensitivity.

Generic $\tan\beta$	ξ_0	$\mu > 0$ 100 pb^{-1}	$\mu > 0$ 1 fb^{-1}	$\mu < 0$ 100 pb^{-1}	$\mu < 0$ 1 fb^{-1}
2	0	-	120	100	145
	1	-	125	75	115
	2	-	100	65	100
	5	-	80	55	80
10	0	-	105	70	135
	1	70	95	65	100
	2	-	70	-	70

Model	$\tan\beta$	$\mu > 0$ 100 pb^{-1}	$\mu > 0$ 1 fb^{-1}	$\mu < 0$ 100 pb^{-1}	$\mu < 0$ 1 fb^{-1}
moduli	2	-	115	100	150
(2-par)	6	75	160	100	150
	10	75	160	70	150
dilaton	2	95	135	80	120
(2-par)	6	80	130	80	120
	10	80	125	80	120
moduli (1-par)		N/A	N/A	70	150
dilaton (1-par)		N/A	N/A	80	125
minimal SU(5)		50	80	50	75

[4]The present CDF upper limit as a function of chargino mass is shown in Fig. 12 of Ref. [8].

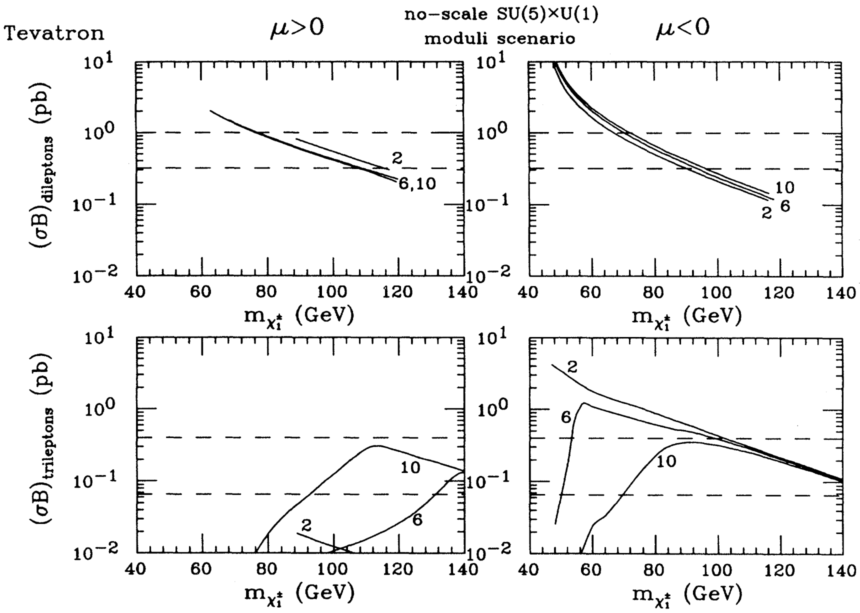

FIG. 4. The dilepton and trilepton rates at the Tevatron versus the chargino mass in two-parameter SU(5)×U(1) supergravity-moduli scenario ($\xi_0 = \xi_A = 0$) for the indicated values of $\tan\beta$. The upper (lower) dashed lines represent estimated reaches with 100 pb^{-1} (1 fb^{-1}) of data.

trilepton case, the actual sensitivities are chargino-mass dependent, reaching the indicated asymptotic values for sufficiently high masses.

The reaches in chargino masses in the various models can be readily obtained from the figures by considering both dilepton and trilepton signals, and are summarized in Table I for the two integrated luminosity scenarios. The reaches in Table I translate into indirect reaches in every other sparticle mass, since they are all related. In particular, $m_{\chi_1^\pm} \sim 0.3 m_{\tilde{g}}$ and $m_{\tilde{q}} \approx (m_{\tilde{g}}/2.9)\sqrt{6+\xi_0^2}$ [in the SU(5)×U(1) models the numerical coefficients in this relation are slightly different, implying $m_{\tilde{q}} \approx m_{\tilde{g}}$]. It is also interesting to point out that the pattern of yields for the various models is quite different; therefore observation of a signal will disprove many of the models, while supporting a small subset of them.

It has been pointed out that the dilepton and trilepton data sample may be enhanced by considering presumed trilepton events where one of the leptons is either missed or has a p_T below 5 GeV ("2-out-of-3") [18]. Such enhancements would alter our reach estimates above, making them even more promising.

From Table I it is clear that in some regions of parameter space, the reach of the Tevatron for chargino masses is quite significant. With 100 pb^{-1} it should be possible to probe chargino masses as high as 100 GeV in the generic models for $\tan\beta = 2$, $\xi_0 = 0$, and $\mu < 0$, and in the two-parameter SU(5)×U(1) moduli scenario for

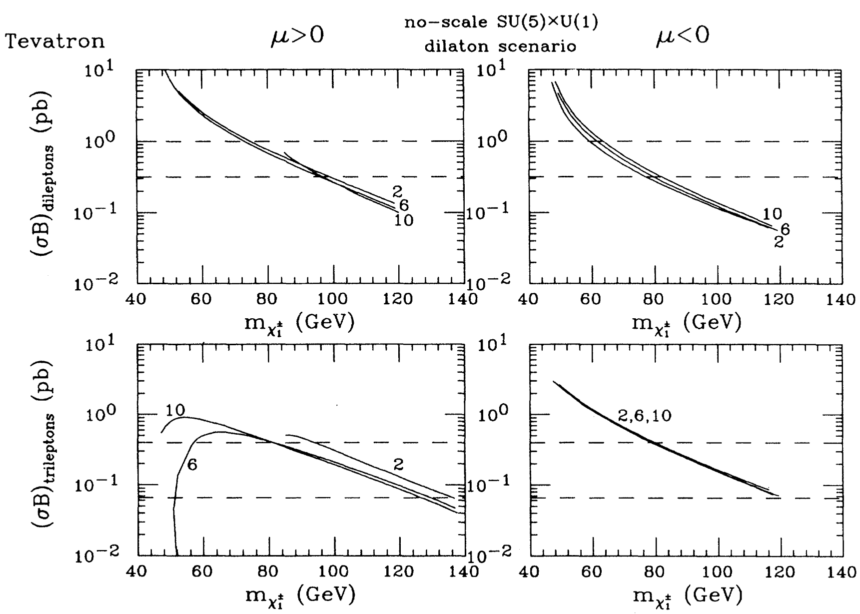

FIG. 5. The dilepton and trilepton rates at the Tevatron versus the chargino mass in two-parameter SU(5)×U(1) supergravity-dilaton scenario ($\xi_0 = 1/\sqrt{3}, \xi_A = -1$) for the indicated values of $\tan\beta$. The upper (lower) dashed lines represent estimated reaches with 100 pb^{-1} (1 fb^{-1}) of data.

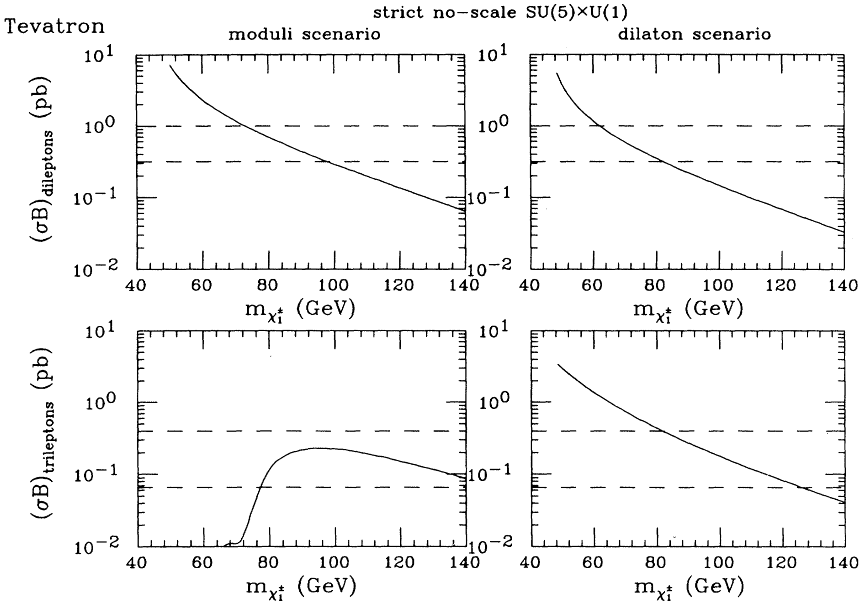

FIG. 6. The dilepton and trilepton rates at the Tevatron versus the chargino mass in one-parameter SU(5)×U(1) supergravity-moduli and dilaton scenarios ($\mu < 0$ in both cases). The upper (lower) dashed lines represent estimated reaches with 100 pb^{-1} (1 fb^{-1}) of data.

tan$\beta \leq 10$. More generally, the accessible region of parameter space should overlap with that within the reach of LEP II, although it would have been explored before LEP II turns on. However, LEP II has an important task: chargino searches at LEP II will not be hindered by small branching fractions, and thus a more model-independent lower limit on the chargino mass should be achievable, i.e., $m_{\chi_1^\pm} \approx \frac{1}{2}\sqrt{s}$.[5] We would like to conclude with Fig. 6, where we show the predictions for the dilepton and trilepton rates in our chosen one-parameter SU(5)×U(1) models, which are the most predictive supersymmetric models to date. It is interesting to note that in the moduli scenario, the mass reach for charginos could be as high as 150 GeV with an integrated luminosity of 1 fb^{-1}. Further proposed increases in luminosity or center-of-mass energy of the Tevatron collider have the potential of probing even deeper into the parameter space [17]. We conclude that detection of weakly interacting sparticles at the Tevatron may well bring the first direct signal for supersymmetry.

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[5]At LEP II it might be possible to extend the indirect reach for charginos by studying the process $e^+e^- \to \chi_1^0\chi_2^0$ with $\chi_2^0 \to \chi_1^0 + 2j$. Equation (1) implies a kinematical reach of $m_{\chi_1^\pm} \approx \frac{2}{3}\sqrt{s}$.

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