Supersymmetry tests at Fermilab: A proposal

Jorge L. Lopez, D. V. Nanopoulos, and Xu Wang

*Center for Theoretical Physics, Department of Physics, Texas A&M University, College Station, Texas 77843-4242
and Astroparticle Physics Group, Houston Advanced Research Center (HARC), The Woodlands, Texas 77381*

A. Zichichi

CERN, Geneva, Switzerland

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We compute the number of trilepton events to be expected at Fermilab as a result of the reaction $p\bar{p} \rightarrow \chi_1^\pm \chi_2^0 X$, where $\chi_1^\pm$ is the lightest chargino and χ_2^0 is the next-to-lightest neutralino. This signal is expected to have very little background and is the best prospect for supersymmetry detection at Fermilab if the gluino and squarks are beyond reach. We evaluate our expressions for all points in the allowed parameter space of two basic supergravity models: (i) the minimal SU(5) supergravity model including the severe constraints from proton decay and a not too young universe and (ii) a recently proposed no-scale flipped SU(5) supergravity model. We study the plausible experimental scenarios and conclude that a large portion of the parameter spaces of these models could be explored with 100 pb^{-1} of integrated luminosity. In the minimal SU(5) supergravity model chargino masses as high as 100 GeV could be probed. In the no-scale flipped model it should be possible to probe some regions of parameter space with $m_{\chi_1^\pm} \lesssim 175 \text{ GeV}$, therefore, possibly exceeding the reach of the CERN LEP II for chargino and neutralino (since $m_{\chi_2^0} \approx m_{\chi_1^\pm}$) masses. In both models such probes would indirectly explore gluino masses much beyond the reach of Fermilab.

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I. INTRODUCTION

It is becoming ever more apparent that supersymmetry is “the way to go” beyond the standard model. In addition to its numerous theoretical niceties, such as its role in solving the hierarchy problem, in explaining the lightness of the Higgs boson, in the unification of the gauge couplings, in the unification with gravity, and in superstrings, supersymmetry entails a rather predictive and experimentally appealing framework. On the most general grounds, however, all one can say is that we expect the set of superpartners of the ordinary particles to appear somewhere below $\sim 1 \text{ TeV}$. Moreover, the number of parameters needed to describe the new particles is rather large (at least 21), and therefore a full exploration of the parameter space of a generic low-energy supersymmetric model is impractical.

On the other hand, things become much simpler if one studies specific models which embody a minimal set of well-motivated theoretical assumptions, including spontaneously broken supergravity with universal soft-supersymmetry breaking, and radiative electroweak symmetry breaking [1]. In fact, the dimension of the parameter space of these models is quite minimal: three soft-supersymmetry-breaking masses ($m_{1/2}, m_0, A$), the ratio of Higgs vacuum expectation values ($\tan\beta$), and the top-quark mass (m_t). Among these models there are two which stand out because of their high predictive power: (i) the minimal SU(5) supergravity model including the severe constraints from proton decay [2,3] and a not too young universe [4,5], and (ii) a recently proposed no-scale

flipped SU(5) supergravity model [6]. In fact, these two models can be viewed as prototypes of (i) traditional supergravity grand unified theory (GUT) models and (ii) string-inspired supergravity models, respectively.

In this paper we begin our study of supersymmetric signals from these two models at the Fermilab Tevatron collider by considering the trilepton signal which occurs in the decay products of the reaction $p\bar{p} \rightarrow \chi_1^\pm \chi_2^0 X$, where $\chi_1^\pm$ is the lightest chargino and χ_2^0 is the next-to-lightest neutralino. This hadronically quiet signal [7] has been shown to have very little background [8–10] and is expected to be the best one for exploring the neutralino-chargino sector of supersymmetric models at Fermilab [10]. In fact, even if the squark and gluino masses are well beyond the reach of Fermilab, the two models under consideration still predict trilepton signals that can be directly observable. Conversely, the potential exclusion of certain regions of the neutralino-chargino parameter space would entail indirect exploration of a large range of squark and gluino masses.

We first compare the features of both models and their predicted supersymmetric spectra. We then compute in succession the $p\bar{p} \rightarrow \chi_1^\pm \chi_2^0 X$ cross section, the branching ratio of $\chi_1^\pm$ to one charged lepton, and the branching ratio of χ_2^0 to two charged leptons. We find that the branching ratios in the no-scale flipped SU(5) supergravity model depend crucially on the slepton mass spectrum since it can be relatively light, and therefore differ significantly from the standard results which usually assume heavy sleptons. We conclude that with 100 pb^{-1} of integrated luminosity and optimal detection efficiencies,

it should be possible to explore a significant portion of the allowed parameter space of both models.

II. THE MODELS

Both models under study have the same light matter content as the minimal supersymmetric extension of the standard model. That is, in addition to the ordinary particles, we have (i) twelve squarks $\tilde{u}_{L,R}, \tilde{d}_{L,R}, \tilde{c}_{L,R}, \tilde{s}_{L,R}, \tilde{b}_{1,2}, \tilde{t}_{1,2}$, (ii) nine sleptons $\tilde{e}_{L,R}, \tilde{\mu}_{L,R}, \tilde{\tau}_{1,2}, \tilde{\nu}_{e,\mu,\tau}$, (iii) two charginos $\chi_{1,2}^\pm$ and four neutralinos $\chi_{1,2,3,4}^0$, and (iv) two CP -even neutral Higgs bosons h, H , one CP -odd neutral Higgs boson A , and one charged Higgs boson $H^\pm$. The masses of all these particles depend on a set of parameters which can be significantly reduced by imposing universal soft-supersymmetry breaking at the unification scale and then radiative electroweak symmetry breaking [11]. Once this is done the masses depend on only five parameters: $m_{1/2}$, $\xi_0 \equiv m_0/m_{1/2}$, $\xi_A \equiv A/m_{1/2}$, $\tan\beta$, m_t . For reference, the squark and slepton masses can be approximated by $m_i^2 \approx (\frac{1}{3}m_g)^2(c_i + \xi_0^2) + d_i \cos 2\beta M_Z^2$, where c_i and d_i are calculable coefficients with $0 < c_i < c_{\tilde{q}} \lesssim 6$, and $|d_i| \lesssim 1$. The fermion mass contribution to the respective sfermion mass is neglected except for $\tilde{b}_{1,2}, \tilde{t}_{1,2}, \tilde{\tau}_{1,2}$. The first and second generation squarks are nearly degenerate in mass, while the bottom squark and top squark mass eigenstates are split relative to the average squark mass. For the sleptons, near degeneracy

only occurs for $\xi_0 \gg 1$. The chargino and neutralino masses depend on $\tan\beta$, m_g , and the Higgs mixing parameter μ , whose magnitude is calculable from the radiative breaking constraints, but its sign remains undetermined. The Higgs boson masses receive a tree-level contribution which depends on $\tan\beta$ and m_A , and a one-loop correction which depends most importantly on m_t and the squark mass. For any given set $(m_{1/2}, \xi_0, \xi_A, \tan\beta, m_t)$ one can compute all particle masses and couplings and reject sets which violate the present experimental bounds on $m_g, m_{\tilde{q}}, m_h, m_A, m_{\chi_1^\pm}, \Gamma_Z^{\text{inv}}$, etc. Only those sets which satisfy all present phenomenological constraints (as described in detail in Ref. [11]) are kept for further analysis. All the above remarks apply to the two models under consideration. We now turn to the differences between them. For reference, in Table I we collect the gist of the following discussion.

A. The minimal SU(5) supergravity model

The model is based on the gauge group SU(5) and its minimal matter content implies that it unifies at $M_U \sim 10^{16}$ GeV. In the context of string theory, this model is in principle derivable but in practice this is hard to accomplish and no known examples exist. Symmetry breaking down to the standard model occurs through the vacuum expectation value (VEV) of the 24 of Higgs bo-

TABLE I. Comparison of the most important features describing the minimal SU(5) supergravity model and the no-scale flipped SU(5) supergravity model.

Minimal SU(5) supergravity model	No-scale flipped SU(5) supergravity model
Not easily string derivable, no known examples	Easily string derivable, several known examples
Symmetry breaking to standard model due to the VEV of 24 and independent of supersymmetry breaking	Symmetry breaking to standard model due to VEV's of 10, 10 and tied to onset of supersymmetry breaking
No simple mechanism for doublet-triplet splitting	Natural doublet-triplet splitting mechanism
No-scale supergravity excluded $m_{\tilde{q}}, m_{\tilde{g}} < 1$ TeV by <i>ad hoc</i> choice: naturalness	No-scale supergravity by construction $m_{\tilde{q}}, m_{\tilde{g}} < 1$ TeV by no-scale mechanism
Parameters 5: $m_{1/2}, m_0, A, \tan\beta, m_t$	Parameters 3: $m_{1/2}, \tan\beta, m_t$
Proton decay: $d=5$ large, strong constraints needed	Proton decay: $d=5$ very small
Dark matter: $\Omega_\chi h_0^2 \gg 1$ for most of the parameter space, strong constraints needed	Dark matter: $\Omega_\chi h_0^2 \lesssim 0.25$, acceptable with cosmology and big enough for dark matter problem
$1 \lesssim \tan\beta \lesssim 3.5$, $m_t < 180$ GeV, $\xi_0 \gtrsim 6$ $m_{\tilde{g}} \lesssim 500$ GeV $m_{\tilde{q}} > m_{\tilde{t}} > 2m_{\tilde{g}}$	$2 \lesssim \tan\beta \lesssim 32$, $m_t < 190$ GeV, $\xi_0 = 0$ $m_{\tilde{g}} \lesssim 1$ TeV, $m_{\tilde{q}} \approx m_{\tilde{g}}$ $m_{\tilde{t}_L} \approx m_{\tilde{\nu}} \approx 0.3m_{\tilde{g}} \lesssim 300$ GeV $m_{\tilde{t}_R} \approx 0.18m_{\tilde{g}} \lesssim 200$ GeV
$2m_{\chi_1^0} \sim m_{\chi_2^0} \sim m_{\chi_1^\pm} \sim 0.3m_{\tilde{g}} \lesssim 150$ GeV $m_{\chi_3^0} \sim m_{\chi_4^0} \sim m_{\chi_2^\pm} \sim \mu $ $m_h \lesssim 100$ GeV	$2m_{\chi_1^0} \sim m_{\chi_2^0} \approx m_{\chi_1^\pm} \sim 0.3m_{\tilde{g}} \lesssim 285$ GeV $m_{\chi_3^0} \sim m_{\chi_4^0} \sim m_{\chi_2^\pm} \sim \mu $ $m_h \lesssim 135$ GeV
No analogue	Strict no scale: $\tan\beta = \tan\beta(m_{\tilde{g}}, m_t)$ $m_t \lesssim 135$ GeV $\implies \mu > 0$, $m_h \lesssim 100$ GeV $m_t \gtrsim 140$ GeV $\implies \mu < 0$, $m_h \gtrsim 100$ GeV

sons. The light Higgs doublets come together with colored Higgs triplets (H_3) in SU(5) pentaplets. The H_3 fields mediate dangerous dimension-five proton decay operators and must be heavy ($M_{H_3} \gtrsim M_U$). This needed “doublet-triplet splitting” is not explained in a simple way in this model and requires either an *ad hoc* choice of parameters or the introduction of additional large GUT-mass representations. Requiring that $M_{H_3} < 3M_U$ so that the high-energy theory remains perturbative, and imposing the naturalness condition $m_{\tilde{g}}, m_{\tilde{q}} < 1$ TeV, it has been shown that the five-dimensional parameter space of this model is severely constrained by the experimental lower bound on the proton lifetime [2]. Adding on the requirement of a not too young universe, $\Omega_\chi h_0^2 \leq 1$, where Ω_χ is the present abundance of the lightest neutralino and $0.5 \leq h_0 \leq 1$ is the scaled Hubble parameter, constrains the model significantly more [4,5]. Yet stricter constraints follow from the recalculation of the unification mass to a higher level of precision [3]. The finally allowed set of points in parameter space is highly restricted and entails the following constraints: (i) parameter space variables

$$1 \lesssim \tan\beta \lesssim 3.5, \quad m_t \lesssim 180 \text{ GeV}, \quad \xi_0 \gtrsim 6, \quad (2.1)$$

(ii) gluino, squark, and slepton masses

$$m_{\tilde{g}} \lesssim 500 \text{ GeV}, \quad m_{\tilde{q}} > m_{\tilde{l}} > 2m_{\tilde{g}}, \quad (2.2)$$

(iii) chargino and neutralino masses^{1,2}

$$2m_{\chi_1^0} \sim m_{\chi_2^0} \sim m_{\chi_1^\pm} \sim 0.3m_{\tilde{g}} \lesssim 150 \text{ GeV}, \quad (2.3a)$$

$$m_{\chi_3^0} \sim m_{\chi_4^0} \sim m_{\chi_2^\pm} \sim |\mu|, \quad (2.3b)$$

(iv) the one-loop corrected lightest Higgs boson mass

$$m_h \lesssim 100 \text{ GeV}. \quad (2.4)$$

B. The no-scale flipped SU(5) supergravity model

This recently proposed model [6] is based on the gauge group $SU(5) \times U(1)$ and has additional intermediate scale matter particles that delay unification until $M_U \sim 10^{18}$ GeV, as expected to occur in string-derived models. The minimal choice of the extra particles is a pair of vector-like quark doublets $Q, \bar{Q}$ with $m_Q \sim 10^{12}$ GeV and a pair of vector-like charge $-1/3$ quark singlets $D, \bar{D}$ with $m_D \sim 10^6$ GeV. There exist several string models based

on this gauge group [12] and at least one with the additional matter particles [13]. Symmetry breaking down to the standard model gauge group occurs through VEV's of 10, 10 representations along flat directions of the scalar potential, and thus it is tied to the onset of supersymmetry breaking. The doublet-triplet splitting of the Higgs pentaplets alluded to in Sec. II A is realized naturally in this model through gauge symmetry allowed couplings which occur in all known examples. This mechanism also ensures that the potentially dangerous dimension-five proton decay operators are highly suppressed and innocuous. The no-scale supergravity component of the model implies that $m_0 = A = 0$ [14] and therefore the model depends only on three parameters: $m_{1/2}, \tan\beta, m_t$. Furthermore, consistency of the no-scale model requires $m_{1/2} \lesssim 1$ TeV [15] which explains the naturalness requirement which otherwise would need to be imposed by hand. The relic abundance of the lightest neutralino is found to be $\Omega_\chi h_0^2 \lesssim 0.25$, which is well within cosmological requirements and may be large enough to explain the dark matter problem.

This model also entails constraints on its parameters and correlations among the various particle masses:

(i) parameter space variables

$$2 \lesssim \tan\beta \lesssim 32, \quad m_t \lesssim 190 \text{ GeV}, \quad \xi_0 = 0, \quad \xi_A = 0, \quad (2.5)$$

(ii) gluino, squark, and slepton masses

$$m_{\tilde{g}} \lesssim 1 \text{ TeV}, \quad m_{\tilde{q}} \approx m_{\tilde{g}}, \quad (2.6a)$$

$$m_{\tilde{L}} \approx m_{\tilde{\nu}} \approx 0.3m_{\tilde{g}} \lesssim 300 \text{ GeV}, \quad (2.6b)$$

$$m_{\tilde{R}} \approx 0.18m_{\tilde{g}} \lesssim 200 \text{ GeV}, \quad (2.6c)$$

(iii) chargino and neutralino masses

$$2m_{\chi_1^0} \sim m_{\chi_2^0} \approx m_{\chi_1^\pm} \sim 0.3m_{\tilde{g}} \lesssim 285 \text{ GeV}, \quad (2.7a)$$

$$m_{\chi_3^0} \sim m_{\chi_4^0} \sim m_{\chi_2^\pm} \sim |\mu|, \quad (2.7b)$$

(iv) the one-loop corrected lightest Higgs boson mass

$$m_h \lesssim 135 \text{ GeV}. \quad (2.8)$$

In addition, a strict version of the no-scale scenario allows $\tan\beta$ to be determined as a function of $m_{\tilde{g}}$ and m_t . This special case of “no-scale” has two very interesting consequences: (i) determination of the sign of μ and (ii) determination of whether m_h is above or below 100 GeV. One finds that $\mu > 0$ and $m_h \lesssim 100$ GeV if $m_t \lesssim 135$ GeV, whereas $\mu < 0$ and $m_h \gtrsim 100$ GeV if $m_t \gtrsim 140$ GeV.

III. THE TRILEPTON SIGNAL

The set of diagrams that needs to be calculated is the same for both models, only the input masses and couplings differ, and so do the resulting signals. Two diagrams contribute to $p\bar{p} \rightarrow \chi_1^+ \chi_2^0 X$: (i) s -channel virtual W exchange $u\bar{d} \rightarrow W^* \rightarrow \chi_1^+ \chi_2^0$, and (ii) t -channel squark exchange. The second diagram has been neglected since $m_{\tilde{q}} \gtrsim 200$ GeV in the no-scale flipped SU(5) model and $m_{\tilde{q}} \gtrsim 600$ GeV in the minimal SU(5) model, and the

¹The $\sim$ signs in Eqs. (2.3) and (2.7) indicate that these relations are only qualitative, although the majority of points in the allowed parameter space follow them closely.

²The result $m_{\chi_1^\pm} < 150$ GeV is the weakest possible bound which applies to both signs of μ . For $\mu > 0$ ($\mu < 0$) the upper bound is 150 GeV (120 GeV). In the subsequent figures [1(a), 3,5], for $\mu > 0$, there is an isolated point shown for $m_{\chi_1^\pm} \approx 145$ GeV and no other points appear until ≈ 105 GeV. This gap is sparsely populated by fine-tuned points in parameter space [3].

FIG. 1. The cross section for $p\bar{p} \rightarrow \chi_1^\pm \chi_2^0$ vs the chargino mass at $\sqrt{s} = 1.8$ TeV for all points in the allowed parameter space of (a) the minimal SU(5) supergravity model and (b) the no-scale flipped SU(5) supergravity model.

$W\chi_1^\pm\chi_2^0$ coupling only vanishes if χ_2^0 is a pure b -ino which does not occur in practice. In Figs. 1(a) and 1(b) we show the cross section (summed over $\chi_1^+\chi_2^0$ and $\chi_1^-\chi_2^0$) for $\sqrt{s} = 1.8$ TeV, computed using the parton distribution functions of Ref. [16] [fit S -MS scheme]. This set of parton distribution functions is given in a convenient, compact, analytical form and describes well the small- x behavior relevant for our present purposes (i.e., $x \gtrsim 0.01$). For the points in parameter space in common with Ref. [10], we have checked that our numerical results agree well with theirs.³ The scatter plots include all allowed points in parameter space as obtained in Ref. [3] for the minimal SU(5) model and in Ref. [6] for the no-scale flipped model.⁴ In the former case m_t takes values

throughout the interval 100–160 GeV, whereas in the latter case only the reference values $m_t = 100, 130, 160$ GeV are shown (since there are many more allowed points in parameter space). From the figure one can see that, in both models,

$$\sigma(p\bar{p} \rightarrow \chi_1^\pm \chi_2^0) \gtrsim 1 \text{ pb for } m_{\chi_1^\pm} \lesssim 100 \text{ GeV}. \quad (3.1)$$

One can also show that for $m_{\chi_1^\pm} < 100$ GeV the *maximum* indirectly explorable gluino masses are given by (i) 320 (460) GeV [for $\mu > 0$ ($\mu < 0$)] in the minimal SU(5) case, and (ii) 490 (515) GeV in the no-scale flipped case.

The $\chi_1^\pm$ decay channels which are kinematically open in these models are (i) $\chi_1^\pm \rightarrow \chi_1^0 \nu_l l^\pm$, which proceeds through virtual W , $\tilde{l}_L$, and $\tilde{\nu}_l$ exchanges, and (ii) $\chi_1^\pm \rightarrow \chi_1^0 q \bar{q}'$, through virtual W and $\tilde{q}_L$ exchanges. Channels with χ_2^0 in the final state are either closed or phase space suppressed (since $m_{\chi_2^0} \approx m_{\chi_1^\pm}$) and have been neglected. If the sleptons and squarks are heavy enough, the W -exchange diagrams dominate and the branching ratio into $e^\pm$ and $\mu^\pm$ should be close to $(1+1)/(1+1+1+3+3) = 2/9 \approx 22\%$, independently of

³Note that our sign convention for μ is opposite to that used in Ref. [10].

⁴For the no-scale flipped model, in Ref. [6] $\alpha_3(M_Z) = 0.118$ was used. For the minimal SU(5) model, in Ref. [3] $\alpha_3(M_Z) = 0.126$ was instead chosen in order to maximize the proton lifetime and therefore the size of the allowed parameter space. Larger values of $\alpha_3(M_Z)$ quickly reduce the fraction of points which give calculated values of $\sin^2\theta_W$ within the present experimental bounds [3].

the model parameters.⁵ This is precisely the result we obtained for the minimal SU(5) supergravity model:

$$B(\chi_1^\pm \rightarrow \chi_1^0 \nu_e e^\pm, \chi_1^0 \nu_\mu \mu^\pm)_{\text{minimal}} \approx 0.222 \pm 0.008. \quad (3.2)$$

The results for the no-scale flipped SU(5) model are shown in Fig. 2 for (a) $m_t = 100$ GeV, (b) $m_t = 130$ GeV, and (c) $m_t = 160$ GeV. We find

$$B(\chi_1^\pm \rightarrow \chi_1^0 \nu_e e^\pm, \chi_1^0 \nu_\mu \mu^\pm)_{\text{flipped}} \lesssim 2/3. \quad (3.3)$$

This upper bound is model independent and occurs when the slepton exchange diagrams dominate (e.g., when the sleptons go on-shell), in particular the sneutrino one since $m_{\tilde{\nu}} < m_{e_L}$ for low chargino masses. (In the flipped model the squarks are always significantly heavier than the sleptons and therefore basically irrelevant for the present discussion.) As $m_{1/2}$ grows, all masses grow and the sleptons become heavier than the W boson. In fact, the two-body decay mode $\chi_1^\pm \rightarrow W^\pm \chi_1^0$ becomes kinematically allowed for $m_{\chi_1^\pm} \gtrsim 2M_W$. At the same time, the two-body chargino decay into sleptons $\chi_1^\pm \rightarrow l^\pm \tilde{\nu}$ becomes kinematically suppressed since $m_{\tilde{\nu}} \rightarrow m_{\chi_1^\pm}$ in this limit [see Eqs. (2.6b) and (2.7a)]. Therefore, the leptonic branching generally shows a transition from 2/3 (slepton dominance) down to 2/9 (W dominance). We note that the transition may be delayed somewhat if the $W\chi_1^\pm \chi_1^0$ coupling is dynamically suppressed as it occurs in some “pure” limits, i.e., when $\chi_1^\pm \rightarrow \tilde{W}^\pm$ and $\chi_1^0 \rightarrow \tilde{B}$, which occurs for $|\mu| \gg M_2 \approx 0.3m_g$. In fact, Figs. 2(b) and 2(c) show that as m_t grows, the transition is delayed a bit. This is understandable since $|\mu|$ grows with m_t (for fixed m_g) and the “pure” limits are then approached. Figure 2 (especially for $m_t = 100$ GeV) also shows that during the transition between the two regimes, destructive interference between the slepton-exchange and W -exchange diagrams can be important and the branching ratio can drop down to a few percent.

It is important to investigate the energy spectrum of the daughter lepton in chargino decays in order to identify possible regions of parameter space where the lepton may be too soft to be detectable. In the minimal SU(5) model the W -exchange diagram dominates the decay amplitude. For $m_{\chi_1^\pm} > m_{\chi_1^0} + m_W$ (two-body decay) the daughter lepton energy in the W rest frame is $E_l = \frac{1}{2}m_W$. For $m_{\chi_1^\pm} < m_{\chi_1^0} + m_W$ (three-body decay) the lepton energy peaks for the largest W four-momentum, $p_W^2 = (m_{\chi_1^\pm} - m_{\chi_1^0})^2 < m_W^2$, which in the chargino rest frame corresponds to χ_1^0 at rest and $E_l = \frac{1}{2}(m_{\chi_1^\pm} - m_{\chi_1^0}) \approx \frac{1}{4}m_{\chi_1^\pm} > 10$ GeV. In the flipped SU(5) model things are more complicated because of the

many contributing amplitudes. A concern is the case when the $\tilde{\nu}$ goes on shell ($m_{\tilde{\nu}} < m_{\chi_1^\pm}$) and dominates the decay amplitude. If $m_{\tilde{\nu}} \approx m_{\chi_1^\pm}$, then the daughter lepton will be soft, i.e., $E_l = (m_{\chi_1^\pm}^2 - m_{\tilde{\nu}}^2)/2m_{\chi_1^\pm}$. This kinematical configuration (i.e., $m_{\tilde{\nu}} < m_{\chi_1^\pm}$) occurs for 18% (1%) of the points in parameter space for $\mu > 0$ ($\mu < 0$). Assuming that only the $\tilde{\nu}$ -exchange amplitude contributes, we find that $\sim \frac{1}{3}$ of these points lead to soft leptons ($E_l < 5$ GeV). More generally (i.e., including all two-body and three-body decay amplitudes) we have computed the probability that $E_l < 5$ GeV, and find it over 75% for each of these points; i.e., soft leptons are indeed likely for $m_{\tilde{\nu}} < m_{\chi_1^\pm}$. For $m_{\tilde{\nu}} > m_{\chi_1^\pm}$ the two-body decay $\chi_1^\pm \rightarrow W^\pm \chi_1^0$ dominates when kinematically accessible ($m_{\chi_1^\pm} \gtrsim 2M_W$), and no soft leptons occur. If this channel is closed or suppressed, three-body decays are the norm and for each of these points the lepton has > 75 – 90% probability of having $E_l > 5$ GeV. Finally, when soft leptons are likely to occur [$< 6\%$ ($< 1\%$) of the total number of allowed points in parameter space], no range of chargino masses is preferentially singled out and therefore exploration of points in parameter space for all possible chargino masses should not be a problem.

The χ_2^0 decay channels which are possibly kinematically open are several: (i) $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$, through virtual $Z, \tilde{L}_L, \tilde{L}_R$ exchanges, (ii) $\chi_2^0 \rightarrow \chi_1^0 \nu_l \bar{\nu}_l$, through $Z, \tilde{\nu}_l$, (iii) $\chi_2^0 \rightarrow \chi_1^0 q \bar{q}$, through $Z, \tilde{q}_L, \tilde{q}_R$, and (iv) the “spoiler mode” $\chi_2^0 \rightarrow \chi_1^0 h$. In analogy with the chargino decay, if the sleptons and squarks are heavy enough, and the $Z\chi_1^0 \chi_2^0$ coupling is not too small, then the Z -exchange diagrams dominate and $B(\chi_2^0 \rightarrow \chi_1^0 e^+ e^-, \chi_1^0 \mu^+ \mu^-) \approx B(Z \rightarrow e^+ e^-, \mu^+ \mu^-) \approx 6.6\%$. In the minimal SU(5) supergravity model this situation occurs quite often (especially for $\mu < 0$), see Fig. 3. In fact, from Fig. 3 (bottom row) in Ref. 5 one can see that the χ_1^0 composition is away from a pure b -ino state (which would drive the $Z\chi_1^0 \chi_2^0$ coupling to zero) for most of the parameter space. Exceptions to this situation occur for $\mu > 0$ when m_g is low (and thus so is $m_{\chi_1^\pm}$), while for $\mu < 0$ when $m_g \sim 300$ GeV $\Rightarrow m_{\chi_1^\pm} \sim 90$ GeV. Figure 3 here shows that in these cases the branching ratio is higher, since the Z -exchange channels are highly suppressed and the slepton and squark exchanges play a role. The largest value the branching ratio could take is $\approx 2/3$, although in this model it remains $\lesssim 25\%$. This result agrees well with that in Ref. [10] for the relevant case ($m_{\tilde{q}} = 2m_g$) in that paper. When the spoiler mode is open ($m_{\chi_2^0} > m_{\chi_1^0} + h$ or approximately $m_{\chi_1^\pm} \gtrsim 2m_h$) the dilepton branching ratio vanishes, although this occurs only for a small portion ($\lesssim 10\%$) of the allowed parameter space.⁶

⁵This assumes that the $\chi_1^\pm \rightarrow \chi_1^0 t \bar{b}$ channel is closed (i.e., $m_{\chi_1^\pm} < m_{\chi_1^0} + m_t + m_b$) which is certainly true for $m_{\chi_1^\pm} < 100$ GeV. Using the approximate relations in Eqs. (2.3a) and (2.7a) this channel will not be open until $m_{\chi_1^\pm} \gtrsim 2(m_t + m_b) \gtrsim 190$ GeV.

⁶In fact, it has been recently shown [17] that improved lower bounds from the CERN e^+e^- collider LEP on the lightest Higgs boson mass in this model ($m_h \gtrsim 60$ GeV) actually *exclude* all points in parameter space where the spoiler mode is open.

FIG. 2. The branching ratio for $\chi_1^\pm \rightarrow \chi_1^0 \nu_e e^\pm, \chi_1^0 \nu_\mu \mu^\pm$ in the no-scale flipped SU(5) supergravity model for (a) $m_t = 100$ GeV, (b) $m_t = 130$ GeV, and (c) $m_t = 160$ GeV. Note that the branching ratio is bounded above by $2/3$ (when the slepton exchange diagrams dominate) and can be lower than $2/9$ (when the W -exchange diagrams dominate) due to destructive interference effects.

FIG. 3. The branching ratio for $\chi_2^0 \rightarrow \chi_1^0 e^+ e^-$, $\chi_1^0 \mu^+ \mu^-$ in the minimal SU(5) supergravity model. The points on the horizontal axis occur when the spoiler mode is open. The accumulation of points around 6% occurs when the Z-exchange diagrams dominate.

The results for the χ_2^0 dilepton branching ratio for the no-scale flipped model are shown in Fig. 4 and exhibit quite a bit of structure with values ranging from zero up to $\approx 2/3$. For a given chargino mass, the various points correspond to different values of $\tan\beta$. For example, in Fig. 4(a) for fixed $m_{\chi_1^\pm} \gtrsim 100$ GeV, $\tan\beta$ starts at the bottom of the pack of curves at 28 and then decreases in steps of two until it becomes 4 (8) for $\mu > 0$ ($\mu < 0$) at the top. (The isolated curve for $\mu > 0$ corresponds to $\tan\beta = 2$.) A new spoiler mode opens when the sneutrino is sufficiently light, but this one and the original spoiler mode can be overtaken by an “antispoiler mode” when the $\tilde{l}_{L,R}$ are sufficiently light. In fact, the branching ratio approaches its maximum value in this case. Note that if $m_{\chi_2^0} - m_{\tilde{l}_{L,R}}$ is small, then the daughter lepton will be soft [$E_l = (m_{\chi_2^0}^2 - m_{\tilde{l}_{L,R}}^2)/2m_{\chi_2^0}$] and difficult to detect. Since in the flipped model $m_{\chi_2^0} \sim 0.3m_{\tilde{g}}$, $m_{\tilde{l}_L} \approx 0.3m_{\tilde{g}}$, and $m_{\tilde{l}_R} \approx 0.18m_{\tilde{g}}$ (see Table I), the two-body decay amplitude $\chi_2^0 \rightarrow l^\pm \tilde{l}_R^\mp$ dominates and it is not likely to lead to soft leptons. However, because of uncertainties in the above mass relations, $\sim 4\%$ ($\sim 6\%$) of the points for $\mu > 0$ ($\mu < 0$) do give $E_l < 5$ GeV. We have checked though that the soft leptons always occur for chargino masses below ≈ 110 GeV.

For large values of the chargino mass, the analogue of the W dominance in chargino decays occurs here, as the two-body decay $\chi_2^0 \rightarrow \chi_1^0 Z$ becomes kinematically allowed for $m_{\chi_1^\pm} \gtrsim 2M_Z$. Furthermore, the usual spoiler mode $\chi_2^0 \rightarrow \chi_1^0 h$ also turns on and the branching ratio drops quickly. Since $m_h \lesssim 105$ (120) GeV for $m_t = 130$ (160) GeV (see Fig. 6 in Ref. [6]), one would expect $m_{\chi_2^0} > m_{\chi_1^0} + m_h$ to be always satisfied for $m_{\chi_2^0} \gtrsim 2m_h \gtrsim 210$ (204) GeV, which is in good agreement with the actual results in Fig. 4. The opening of these two channels is seen clearly in Figs. 4(b) and 4(c) which

show a successive two-step drop in the neutralino branching ratio for large chargino masses.

Finally we compute the number of trilepton events per 100 pb^{-1} of integrated luminosity for both models, summed over all possible e and μ combinations. In the minimal SU(5) supergravity model (see Fig. 5) we find at least one event for all allowed points in parameter space and as high as 127 (129) events for $\mu > 0$ ($\mu < 0$) for low chargino masses. The actual fraction of points which could be probed at Fermilab depends on the ultimate integrated luminosity achieved and on the experimental efficiencies for the detection of these signals. Statistically speaking, only points in parameter space for which three or more events are predicted could be experimentally verified or excluded. An across-the-board 30% efficiency cut appears reasonable, with lower (higher) efficiencies expected for lighter (heavier) chargino masses [18]. This situation will probe points in the parameter space with 10 or more predicted events, i.e., about half of the allowed parameter space in this model. An idealized situation would occur with 200 pb^{-1} (e.g., combining the data from both detectors) and a 60% efficiency for the heavier chargino masses. In this case, values down to 2.5 in Fig. 5 could be probed which constitutes a large portion of the allowed parameter space (*all* points for $\mu < 0$) and chargino masses as high as ≈ 100 GeV. Bearing in mind the mass correlations in this model, this probe would explore indirectly gluino masses as high as 320 (460) GeV for $\mu > 0$ ($\mu < 0$).

The results for the no-scale flipped model are shown in Fig. 6 (excluding points for which the spoiler modes are open). Generally we see a wide ranging number of events for $m_{\chi_1^\pm} \lesssim 100$ GeV and a settling down for heavier chargino masses. The number of events for light charginos can be quite large, as high as 443 for $m_t = 160$ GeV and $\mu < 0$. In the conservative scenario discussed above one could probe as high as $m_{\chi_1^\pm} \approx 120$ –150 GeV depending on m_t , although a large unexplored region with chargino

FIG. 4. The branching ratio for $\chi_2^0 \rightarrow \chi_1^0 e^+ e^-, \chi_1^0 \mu^+ \mu^-$ in the no-scale flipped SU(5) supergravity model for (a) $m_t = 100$ GeV, (b) $m_t = 130$ GeV, and (c) $m_t = 160$ GeV. The accumulation of points near the horizontal axis correspond to a new spoiler mode $\chi_2^0 \rightarrow \chi_1^0 \tilde{\nu}_l$. The maximum values are reached when the “antispoyer mode” $\chi_2^0 \rightarrow \chi_1^0 l^{\pm} \tilde{l}_{L,R}^{\mp}$ opens up. For large chargino masses, the usual spoiler mode $\chi_2^0 \rightarrow \chi_1^0 h$ dominates.

FIG. 5. The number of trilepton events per 100 pb^{-1} for the minimal SU(5) supergravity model. Note that with 200 pb^{-1} and 60% efficiency it should be possible to probe as high as $m_{\chi_1^\pm} \approx 100 \text{ GeV}$.

FIG. 6. The number of trilepton events per 100 pb^{-1} for the no-scale flipped SU(5) supergravity model (excluding points for which the spoiler modes are open) for (a) $m_t = 100 \text{ GeV}$, (b) $m_t = 130 \text{ GeV}$, and (c) $m_t = 160 \text{ GeV}$. Note that with 200 pb^{-1} and 60% efficiency it should be possible to probe up to $m_{\chi_1^\pm} \approx 175 \text{ GeV}$.

FIG. 6. (Continued).

masses all the way down to the LEP limit will remain. In the idealized situation, the unexplored regions will diminish considerably and the reach could be extended up to $m_{\chi_1^\pm} \approx 175$ GeV. Note that in this model the range of Fermilab for chargino masses could exceed that of LEP II. This statement needs to be viewed from the proper perspective since at LEP II the region $m_{\chi_1^\pm} \lesssim 100$ GeV will be studied quite thoroughly, whereas at the Tevatron some of this region will remain unexplored. The indirect reach for m_g due to the mass correlations in this model could be as high as $m_g \approx 600\text{--}750$ GeV. As discussed above, a small fraction of points in parameter space are likely to lead to soft daughter leptons. However, these points are not concentrated on any particular values of chargino masses and thus should not impair the search for charginos up to the highest possible masses.

Before we conclude let us also present the number of trilepton events for the strict case of the no-scale flipped

SU(5) supergravity model. As discussed in Sec. II B, this allows us to determine $\tan\beta$ and the sign of μ . The values for the cross section and branching ratios are more precise here, since they only depend on m_t for fixed $m_{\chi_1^\pm}$, but they still fall within the limits found above. In Fig. 7 we show the results. The same general remarks as for the regular no-scale model apply here, although this time one could easily *exclude* ranges of $m_{\chi_1^\pm}$, since the spoiler modes are only open for $m_{\chi_1^\pm} \lesssim 75$ GeV. For the conservative scenario, it should be possible to fully explore $75 \text{ GeV} \lesssim m_{\chi_1^\pm} \lesssim 150$ GeV, whereas in the idealized situation the upper end could be pushed up to 175 GeV.

Note that any excluded range of chargino masses or more generally any excluded portion of the parameter space, implies constraints on the sparticle masses. In particular, the chargino mass ranges discussed above apply *also* to the second-to-lightest neutralino masses [see Eqs.

FIG. 7. The number of trilepton events per 100 pb^{-1} for the strict case of the no-scale flipped SU(5) supergravity model for the indicated values of the top-quark mass in GeV. The spoiler modes are only open for $m_{\chi_1^\pm} \lesssim 75$ GeV. Note that with 200 pb^{-1} and 60% efficiency it should be possible to *fully* probe $75 \text{ GeV} \lesssim m_{\chi_1^\pm} \lesssim 175$ GeV.

(2.3a) and (2.7a)]. This correspondence is quite *accurate* for the no-scale flipped model, and more qualitative for the minimal SU(5) model.

IV. CONCLUSIONS

We have studied the signal for the best prospect to detect supersymmetry at Fermilab, short of actually observing the gluino and squarks. The neutralino-chargino sector in the class of unified, supersymmetric models we have explored has the potential of probing a very large portion of the whole parameter space of these models, without actually seeing the traditionally sought for strongly interacting supersymmetric particles. We have considered the minimal SU(5) supergravity model and a recently proposed no-scale flipped SU(5) supergravity model. These are well motivated models which can be taken as typical examples of nonstringlike and stringlike models, respectively. Results in the class of models we consider, are expected to differ from those obtained in the minimal supersymmetric standard model (MSSM) since there (i) the large dimension of the parameter space does not allow its complete exploration, (ii) important theoretical constraints which exclude large regions of parameter space are not taken into account, and (iii) the interdependence of the various sparticle and Higgs boson masses is absent. Our computations of the branching ratios in the

no-scale flipped model provide a clear example of this situation.

We have considered two experimental scenarios which could be realized in due time and have shown that a large fraction of the parameter space for both models could be probed. For the minimal SU(5) supergravity model it should be possible to explore as high as $m_{\chi_1^\pm} \approx 100$ GeV (and indirectly $m_{\tilde{g}}$ as high as 460 GeV), whereas in the no-scale flipped model it may be possible to reach up to $m_{\chi_1^\pm} \approx 175$ GeV (and indirectly $m_{\tilde{g}}$ as high as 750 GeV) and therefore greatly exceed the reach of LEP II for chargino and neutralino masses, at least in some regions of parameter space.

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