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A string no-scale supergravity model and its experimental consequences

JORGE L. LOPEZ[1,2], D. V. NANOPOULOS[1,2], and A. ZICHICHI[3]

[1] *Center for Theoretical Physics, Department of Physics, Texas A&M University College Station, TX 77843–4242, USA*
[2] *Astroparticle Physics Group, Houston Advanced Research Center (HARC) The Mitchell Campus, The Woodlands, TX 77381, USA*
[3] *CERN, 1211 Geneva 23, Switzerland*

Abstract

We propose a string-derived model based on the gauge group $SU(5)\times U(1)$ which satisfies the stringent constraints from no-scale supergravity, allows gauge coupling unification at the string scale, and entails previously unexplored correlations among various sectors of the model. All supersymmetric observables are given in terms of a single mass parameter with self-consistency of the model determining the rest, including $\tan\beta = 2.2-2.3$ and $m_t \approx 175\,\mathrm{GeV}$. A small non-universality of the scalar masses at the string scale produces a downward shift in the right-handed slepton masses at the electroweak scale, such that for $m_{1/2} \gtrsim 180\,\mathrm{GeV}$ these particles become lighter than the lightest neutralino. This cutoff in the parameter space entails the imminent discovery of charginos at the Tevatron via trilepton events ($m_{\chi^\pm_1} < 90\,\mathrm{GeV}$). Also, the lightest Higgs boson ($m_h < 90\,\mathrm{GeV}$), the lightest chargino, and the right-handed sleptons ($m_{\tilde\ell_R} < 50\,\mathrm{GeV}$) should be readily observable at LEPII. We also discuss the model predictions for $B(b\to s\gamma)$, $(g-2)_\mu$, R_b, and the prospects for direct neutralino dark matter detection.

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Despite all the experimental evidence in support of the Standard Model of the strong and electroweak interactions, many physicists believe that it must be extended so that its many ad-hoc parameters may find explanation in a more fundamental theory. Among the various avenues that lead away from the Standard Model, the ideas of supersymmetry, supergravity, and superstrings are particularly compelling in tackling the shortcomings of the Standard Model. Low-energy supersymmetry predicts the existence of a superpartner for each of the Standard Model particles with well determined interactions but undetermined supersymmetry-breaking masses, although these should not exceed the TeV scale if the gauge hierarchy problem is to remain at a tolerable level. Supergravity provides an effective theory of supersymmetry breaking in terms of two input functions, the Kähler function and the gauge kinetic function. With these inputs all supersymmetry-breaking masses can be calculated in terms of a single parameter: the gravitino mass ($m_{3/2}$). Superstrings provide the final link by allowing a first-principles calculation of these two input functions in any given string model, therefore having a single parameter effectively describing the physics of supersymmetry breaking. At low-energies a new parameter arises, namely the ratio of vacuum expectation values ($\tan\beta$) of the two Higgs-boson doublets minimally required in supersymmetric models. However, minimization of the electroweak scalar potential with respect to the two neutral Higgs fields provides two additional constraints which effectively reduce the number of parameters to zero, and a *no-parameter* model is obtained.

In this Letter we describe one such no-parameter model obtained in the context of string no-scale supergravity [1, 2]. In contrast with traditional unified models with ad-hoc "string-inspired" choices for the supersymmetry breaking parameters, in our string-derived model the parameters describing the various sectors of the model (*i.e.*, gauge group, matter spectrum, superpotential, and supersymmetry breaking) are calculated from first principles. Our model is also consistent with the postulates of no-scale supergravity that open the way for a dynamical determination of all mass scales (*e.g.*, $m_{3/2}$ and M_Z), which must otherwise be self-consistently or experimentally determined. The existence of such model is particularly remarkable given the strong restrictions that no-scale supergravity imposes on string model-building. In practice we are unable to extract all of the in principle available string information, and thus our model in fact has one free parameter (*i.e.*, $m_{3/2}$ or the mass scale of the supersymmetric spectrum). However, self-consistency constraints of the model strongly restrict the allowed range of this one parameter, and the same holds for the various experimental predictions of the model.

Since there are so many possible string models, we guide our search for a realistic model by a few principles: (i) a unified gauge group which can break down to the Standard Model gauge group, (ii) a matter content which reduces to the supersymmetric Standard Model at low energies and that allows unification of the gauge couplings at the string scale ($M_U \sim 10^{18}\,\mathrm{GeV}$), and (iii) a low-energy effective theory with the no-scale supergravity structure with vanishing vacuum energy [3, 4, 5].

A string model satisfying the first two constraints was derived in Ref. [6]. This model has the observable sector gauge group $SU(5)\times U(1)$ [7], three generations of quark and lepton superfields, and two light Higgs doublet superfields. The unified gauge symmetry is broken down to the Standard Model gauge group via vacuum expectation values of scalar Higgs fields in $\mathbf{10}$,$\overline{\mathbf{10}}$ representations. Moreover, the gauge symmetry constraints entail superpotential interactions which suppress naturally dangerous dimension-five proton decay operators, provide an elegant solution to the doublet-triplet splitting problem, and a novel see-saw mechanism for neutrino masses [8]. The model also predicts the existence of intermediate-scale vector-like particles ($Q, \bar{Q}$ and $D^c, \bar{D}^c$) contained in one set of $\mathbf{10}$,$\overline{\mathbf{10}}$ representations, with masses consistent [6] with those that allow unification of the gauge couplings at the string scale (*i.e.*, $m_Q \sim 10^{12}\,\mathrm{GeV}$, $m_{D^c} \sim 10^6\,\mathrm{GeV}$ [9]) .

In Ref. [1] a study was performed of the constraints imposed by no-scale supergravity on free-fermionic string model-building. No-scale supergravity requires particular forms of the Kähler function such that the vacuum energy vanishes and the potential possesses flat directions which leave the gravitino mass undetermined [3]. Minimization of the electroweak-scale scalar potential with respect to the gravitino mass (the no-scale mechanism) then determines its value [4]. This mechanism becomes unstable to loop corrections unless the quantity $\mathrm{Str}\,\mathcal{M}^2 = 2Qm_{3/2}^2$ (a weighted sum of scalar and fermion supersymmetry-breaking masses) vanishes at the scale of supersymmetry breaking. In Ref. [1] it was shown that the string model derived in Ref. [6] possesses a Kähler function that depends on a *single* modulus field (τ), besides the dilaton (S), with vanishing vacuum energy (the goldstino field is $\tilde{\eta} \propto S + \sqrt{2}\,\tau$) and with the desired flat direction of the scalar potential. Moreover, the quantity Q was shown to be sufficiently small in first approximation, and plausibly vanishing in a complete (although impracticable) calculation. We should remark that the constraints from string no-scale supergravity are not satisfied automatically. In fact, most of the string models explored in Ref. [1] did not satisfy them. Also, the dynamical determination of $m_{3/2}$ via the no-scale mechanism is at the moment hampered by a new uncalculated parameter quantifying a remnant vacuum energy at high energies [10].

In our string no-scale supergravity model it is possible to compute all the soft-supersymmetry-breaking parameters at the string scale in terms of $m_{3/2}$ [1]:

- Gaugino masses (universal): $m_{1/2} = m_{3/2}$
- Scalar masses:
  - First generation: $m^2_{Q_1,U^c_1,D^c_1,L_1,E^c_1} = 0$
  - Second generation: $m^2_{Q_2,U^c_2,D^c_2,L_2,E^c_2} = 0$
  - Third generation: $m^2_{Q_3,D^c_3} = m^2_{3/2}$, $m^2_{U^c_3,L_3,E^c_3} = 0$
  - Higgs masses: $m^2_{H_1} = m^2_{H_2} = 0$
- Trilinear scalar couplings (universal): $A = m_{3/2}$
- Bilinear scalar coupling: $B = m_{3/2}$

In addition, the parameters in the superpotential have been calculated [6]. Among these one finds the Higgs mixing term $\mu H_1 H_2$, which arises as an effective coupling at the quintic level in superpotential interactions, and gives rise to the B parameter quoted above [1]. Our present inability to reliably estimate the value of μ makes this the single parameter of the model.

Another important superpotential coupling is the top-quark Yukawa coupling, which in Ref. [6] was originally found to be $\lambda_t = g\sqrt{2}$, where $g \approx 0.83$ is the unified gauge coupling at the string scale, obtained by running up to the string scale the Standard Model gauge couplings [9]. The properly normalized top-quark Yukawa coupling is however found to be $\widehat{\lambda}_t = g^2$, once a recently derived normalization factor is inserted [1]. The top-quark mass itself cannot be yet determined since it also depends on the low-energy parameter $\tan\beta$ (*i.e.*, $m_t \propto \sin\beta$).

The low-energy theory, obtained by renormalization group evolution from the string scale down to the electroweak scale, thus depends on only one parameter ($m_{3/2}$ or $m_{1/2}$) since the magnitude of the Higgs mixing term $|\mu|$ and $\tan\beta$ can be self-consistently determined from the minimization of the one-loop electroweak effective potential. Moreover, we find that the constraint $B = m_{3/2}$ can only be satisfied for $\mu < 0$. This general procedure has been carried out before in supergravity models [12], however, with the further specification of B, the numerical computations which determine the value of $\tan\beta$ become rather elaborate [9, 13]. In the present case a novelty arises because the scalar masses given above are not universal at the string scale. This non-universality entails a modification of the usual renormalization group equations [14], which amounts to shifts in the squared scalar mass parameters at low energies: $\Delta m_i^2 = -c^2 Y_i f$, where Y_i is the hypercharge,

$$c^2 = m^2_{H_2} - m^2_{H_1} + \sum_{i=1,2,3} \left(m^2_{Q_i} + m^2_{D^c_i} + m^2_{E^c_i} - m^2_{L_i} - 2m^2_{U^c_i} \right) = 2m^2_{1/2} \ , \qquad (1)$$

is the non-universality coefficient at the string scale, and $f \approx 0.060$ is an RGE coefficient [14]. These shifts are most significant for the right-handed sleptons ($\tilde{\ell}_R = \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$) whose masses are

$$m^2_{\tilde{\ell}_R} = a\, m^2_{1/2} + \tan^2\theta_W M^2_W (\tan^2\beta - 1)/(\tan^2\beta + 1) \ , \qquad (2)$$

with $a = 0.153$ in the usual universal case, but $a = 0.153 - 0.120 = 0.034$ in our non-universal case. For the other scalars the (usual) coefficient a is much larger and the effect of the shift ($\mathcal{O}(0.1)$) is relatively small. The significance of the downward shift on $m_{\tilde{\ell}_R}$ relates to the lightest supersymmetric particle, which is stable and should be neutral and colorless [15]. For the lowest allowed values of $m_{1/2}$, this particle is the lightest neutralino χ^0_1 with $m_{\chi^0_1} \approx 0.25 m_{1/2}$. From Eq. (2) we see that as $m_{1/2}$ increases there is a critical value $m^c_{1/2}$ above which the $\tilde{\ell}_R$ become the lightest supersymmetric particles. Since this is phenomenologically unacceptable, we cutoff the single parameter of the model at this critical value. This cutoff turns out to be rather restrictive. Another novelty in our model is that the top-quark mass is self-consistently determined by the value of $\tan\beta$ which results from the various other constraints.

Once the calculations described above are performed we find $m^{\rm c}_{1/2} \approx 180\,{\rm GeV}$ and $\tan\beta = 2.2-2.3$. The latter result allows a precise determination of the ("pole") top-quark mass

$$m_t \approx 175\,{\rm GeV}\ , \tag{3}$$

which depends on $\sin\beta = \tan\beta/\sqrt{1+\tan^2\beta}$, as shown in Fig. 1. With such small value of $\tan\beta$, the bottom and tau Yukawa couplings at the string scale should be comparable $\lambda_b \sim \lambda_\tau \sim 0.01$ [11]. This matter will be addressed in the context of this model elsewhere. The full mass spectrum is shown in Fig. 2. Note that the right-handed sleptons ($m_{\tilde\ell_R} < 50\,{\rm GeV}$), the lightest chargino ($m_{\chi^\pm_1} < 90\,{\rm GeV}$), and the lightest Higgs boson ($m_h < 90\,{\rm GeV}$), should all be within the reach of the Tevatron or LEPII, as we now discuss.

At the present-day Tevatron the strongly interacting gluino and squarks are not accessible ($m_{\tilde g,\tilde q} \gtrsim 300\,{\rm GeV}$), although they should be easily detectable at the LHC (note that top-squarks ($\tilde t_{1,2}$) are considerably split relative to the other squarks). On the other hand, the weakly interacting neutralinos and charginos are quite reachable in this model via the trilepton signal in $p\bar p \to \chi^0_2\chi^\pm_1 X$ [16] and the dilepton signal in $p\bar p \to \chi^+_1\chi^-_1 X$ [17]. The chargino ($\chi^\pm_1$) branching ratio into leptons ($e+\mu$) is ≈ 0.5, whereas that into jets is ≈ 0.25, for all allowed points in parameter space. Also, the neutralino (χ^0_2) decays exclusively to dileptons because of the dominant two-body decay mode $\chi^0_2 \to \tilde\ell^\pm_R \ell^\mp$. Therefore, the trilepton and dilepton signals are nearly maximized. The corresponding rates are shown in Fig. 3. The expected experimental sensitivities with $100\,{\rm pb}^{-1}$ of accumulated data (end of 1995) are indicated by the dashed lines,[1] which shows guaranteed discovery of the chargino via the trilepton mode. Right-handed slepton pair-production at the Tevatron ($p\bar p \to \tilde\ell^+_R\tilde\ell^-_R X$) will produce exclusively dileptons since $B(\tilde\ell_R \to \ell\chi^0_1) = 1$. However, the cross section is not large [19]: $1\,(0.1)\,{\rm pb}$ for $m_{\tilde\ell_R} = 45\,(50)\,{\rm GeV}$ and the backgrounds are not small. With $100\,{\rm pb}^{-1}$ and 10% detection efficiency the lower end of the allowed range could be explored.

At LEPII, starting in 1996 with a center-of-mass energy of $\sqrt{s} = 180\,{\rm GeV}$, it should be possible to observe the lightest Higgs boson, the lightest chargino, and the right-handed sleptons. The Higgs-boson coupling to gauge bosons is indistinguishable from the Standard Model prediction ($\sin^2(\alpha-\beta) = 0.996 - 0.998$), although its branching ratio into $b\bar b$ may be eroded somewhat for the lightest allowed masses, because of the supersymmetric decay channel with $B(h \to \chi^0_1\chi^0_1) < 0.18$. The reach of LEPII for Higgs masses is estimated at $\sqrt{s} - 95 = 85\,{\rm GeV}$ [20], and thus an increase of center-of-mass energy to $\sqrt{s} = 190\,{\rm GeV}$ would allow full discovery potential for the Higgs boson. The charginos would be pair produced ($e^+e^- \to \chi^+_1\chi^-_1$) and in the preferred "mixed" decay mode (1 lepton + 2 jets) one chargino decays leptonically and the other one hadronically. Since neither of the chargino branching fractions

[1] The sensitivities are actually chargino-mass dependent, following a curve shaped similarly to the signal and which asymptotes to the indicated dashed lines. With the CDF data from Run IA ($\approx 20\,{\rm pb}^{-1}$), this asymptote is at $\approx 2\,{\rm pb}$ [18].

is suppressed, we find a cross section into the mixed mode as large as 2.1 pb and decreasing down to 0.62 pb at the upper end of the allowed interval. This signal should be readily detectable [21]. One would also produce $\chi_1^0\chi_2^0$ with a cross section from 1.4 pb down to 0.6 pb, which could only be detected via the dilepton mode (since $B(\chi_2^0 \to 2j) \approx 0$). The right-handed selectrons (smuons) have a pair-production cross section exceeding 2 pb (0.9 pb) and should be easily detectable over the WW background [21].

One can also test the model via rare processes. The prediction for $B(b \to s\gamma)$ varies widely with the supersymmetric spectrum [22] and is subject to large QCD uncertainties, accounting for these as described in Ref. [23] we get a range: $(4.2 \to 5.3)\times 10^{-4}$ for the lower end and $(3.9 \to 5.1)\times 10^{-4}$ for the upper end of the spectrum. These predictions are in fair agreement with the present experimentally allowed range of $(1-4)\times 10^{-4}$ [24]. For the supersymmetric contribution to the anomalous magnetic moment of the muon [25] we get $a_\mu^{\rm susy} = (-2.4 \to -1.7) \times 10^{-9}$, which is not in conflict with present experimental limits but could be easily observable at the new E821 Brookhaven experiment which aims at a sensitivity of 0.4×10^{-9}. We have also computed the supersymmetric contribution to the ratio $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ [26] which is measured at LEP. We find $R_b^{\rm susy} = (4.4 \to 3.2) \times 10^{-4}$, which would require a four-fold increase in the experimental sensitivity to be observable.

Finally we discuss the cosmological implications of our model. The relic abundance of the lightest neutralino has been calculated following the methods of Ref. [27] and determined to be $\Omega_\chi h^2 \approx 0.025$ with a dip towards the end of the allowed range when the Z pole is encountered in the neutralino annihilation. Such small cold dark matter density would be of interest in models of the Universe with a significant cosmological constant [28]. Such neutralinos would populate the galactic halo and could be detected in cryogenic detectors. The calculated rate [29] in the soon-to-be-operational Stanford Germanium detector is enhanced for $m_{\chi_1^0} \approx \frac{1}{2} m_{\rm Ge} \approx 37\,{\rm GeV}$, reaching a maximum of $R = 0.06$ (events/day/kg). With an expected sensitivity of $R = 0.1$ (or perhaps $R = 0.01$ eventually) this discovery channel does not appear especially promising.

In conclusion, we have presented a string-derived no-scale supergravity model where all parameters are calculated from first principles and where all sectors of the model are correlated for the first time. This model can be described in terms of a single parameter which is phenomenologically strongly restricted, so much that the lighter charginos, neutralinos, sleptons, and Higgs boson would become observable at the Tevatron and LEPII in the very near future.

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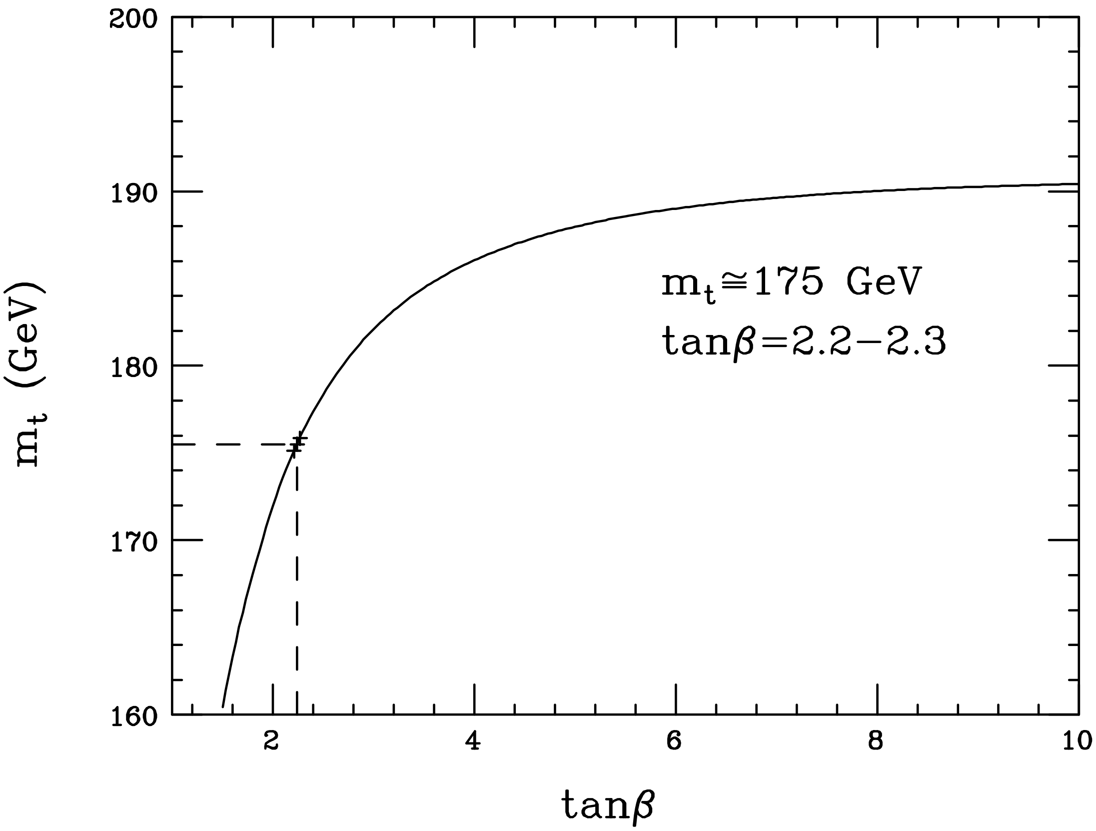

Figure 1: The top-quark mass versus $\tan\beta$. Self-consistency of the model requires $\tan\beta = 2.2 - 2.3$ and thus $m_t \approx 175\,\mathrm{GeV}$.

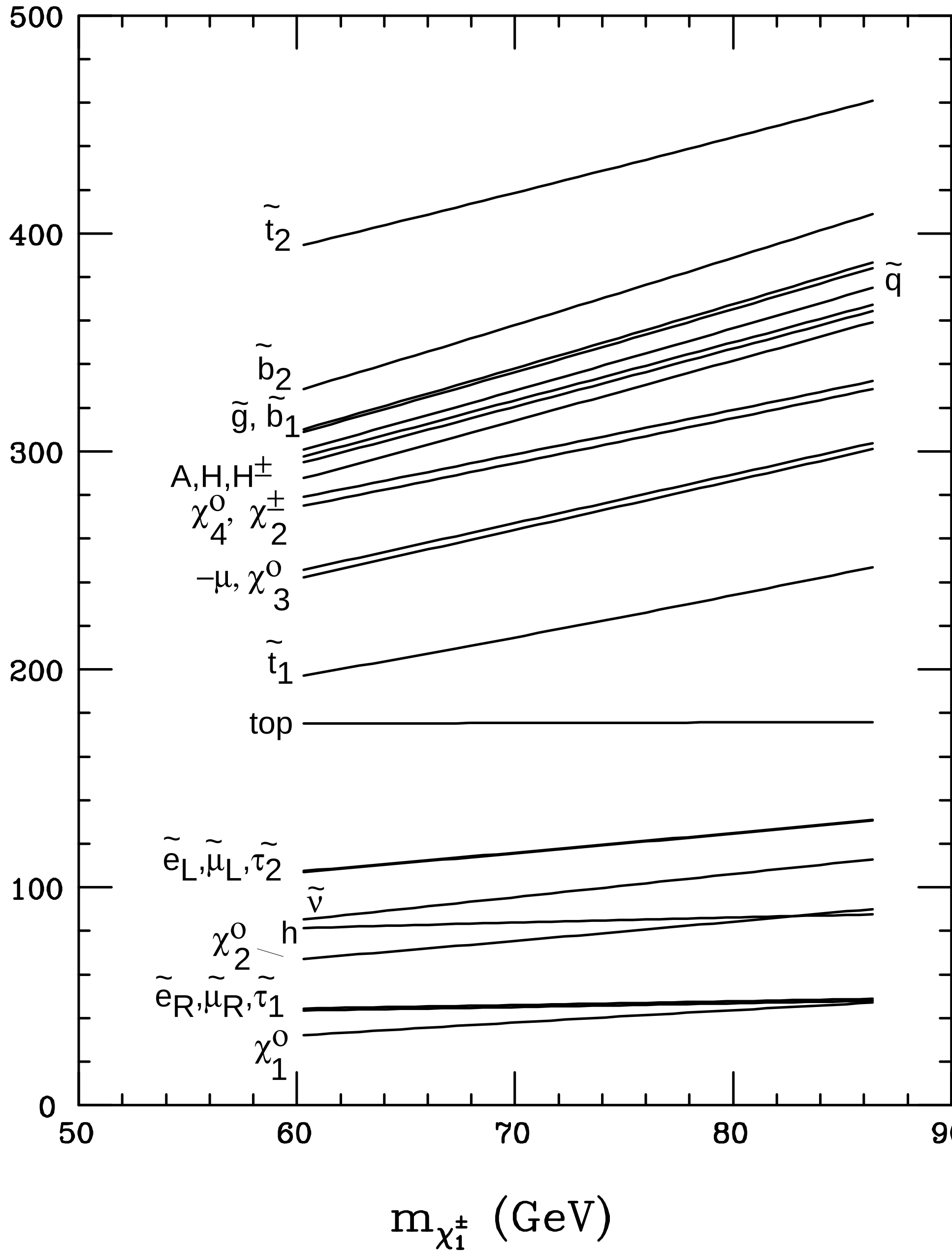

Figure 2: The full sparticle and Higgs-boson mass spectrum versus the chargino mass. Here $m_{\tilde{q}}$ is the average first- and second-generation squark mass. Note that the spectrum cuts off when $m_{\tilde{e}_R,\tilde{\mu}_R,\tilde{\tau}_1} = m_{\chi^0_1}$.

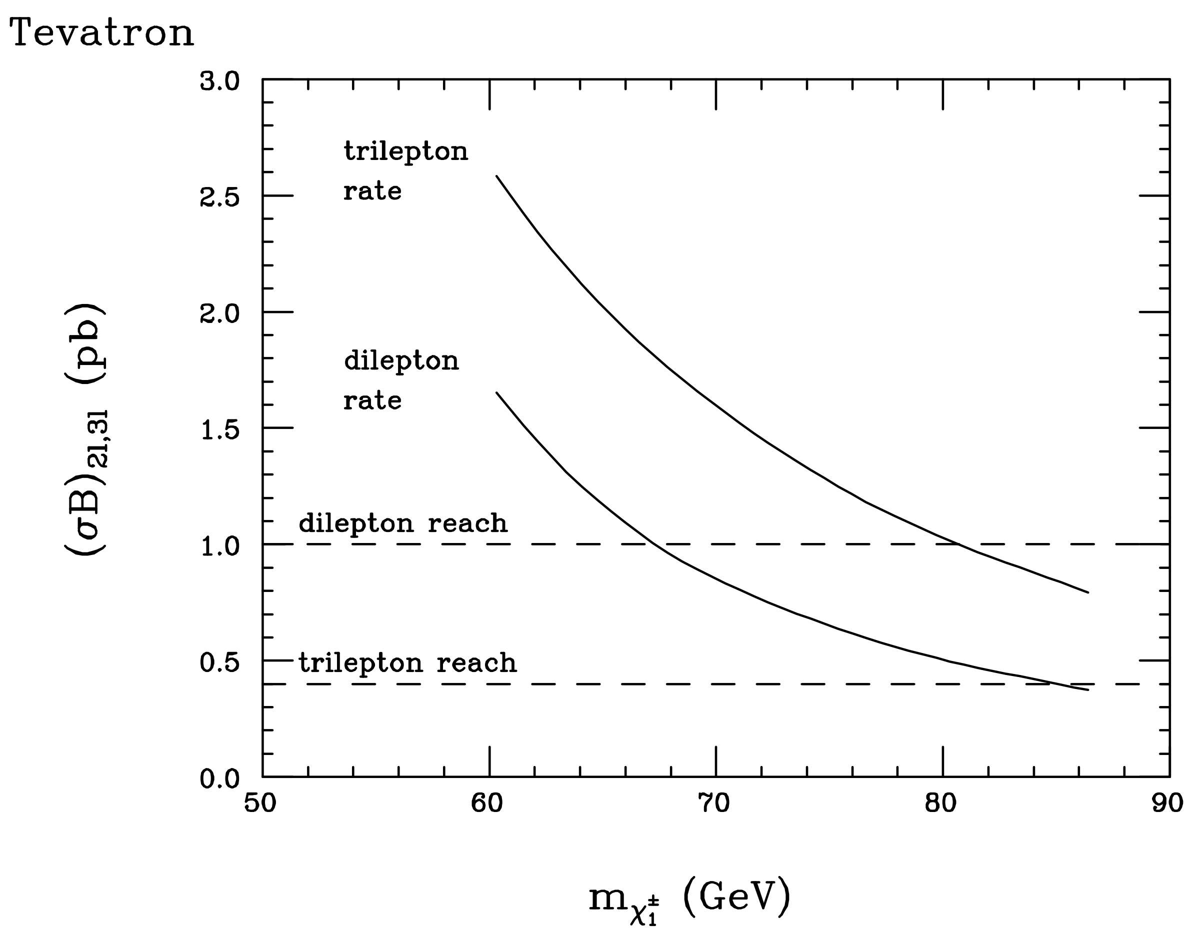

Figure 3: The dilepton and trilepton rates at the Tevatron versus the chargino mass originating from neutralino and chargino production. The indicated reaches are expected with $100\,\mathrm{pb}^{-1}$ of accumulated data.