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First Constraints on SU(5)xU(1) Supergravity from Trilepton Searches at the Tevatron

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ABSTRACT

We present the first constraints on the parameter space of $SU(5)\times U(1)$ supergravity (in both no-scale and dilaton scenarios) which arise from the recently announced limits on trilepton searches at the Tevatron. The trilepton rate has been calculated for those points in parameter space which satisfy not only the minimal theoretical and experimental LEP constraints, but also the *combined* effect of the following indirect experimental constraints: (i) the CLEO limits on the $b\to s\gamma$ rate, (ii) the long-standing limit on the anomalous magnetic moment of the muon, (iii) the non-observation of anomalous muon fluxes in underground detectors ("neutrino telescopes"), and (iv) the electroweak LEP high-precision measurements in the form of the ϵ_1,ϵ_b parameters. For $m_t=150\,GeV$, the trilepton constraint rules out some regions of parameter space with chargino masses as high as $m_{\chi^\pm_1}\approx 105\,GeV$, although it is not possible to establish a new absolute lower bound on the chargino mass. For $m_t=170\,GeV$, the simultaneous imposition of *all* of the above constraints excludes the dilaton scenario completely, and leaves only a few allowed points in parameter space in the no-scale scenario (with $m_{\tilde q}\approx m_{\tilde g}\lesssim 285\,GeV$). The five-fold increase in integrated luminosity expected in the upcoming Tevatron run should probe some regions of parameter space with chargino masses much beyond the reach of LEPII.

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1 Introduction

Searches for new physics at LEP have basically imposed a lower bound of $\approx \frac{1}{2}M_Z$ on the masses of all particles coupling to the Z-boson with unsuppressed strength [1]. Such is generally the case for the sleptons, squarks, and charginos of low-energy supersymmetric models. No further improvement in sensitivity is expected until LEPII turns on in early 1995. Supersymmetric particle searches have also been conducted at the Tevatron, and until recently only in the strongly interacting sector (*i.e.*, squarks and gluino) [2]. The weakly interacting sector had been neglected because of the smaller production cross sections. This situation has since changed because of the much increased integrated luminosity. In fact, the prospects for supersymmetry detection through the trilepton signal [3], which occurs in the decays of neutralino-chargino pair production, have been shown to be quite bright [4] in $SU(5)\times U(1)$ supergravity [5]. Moreover, because of the mass correlations in this model, the direct search for charginos at the Tevatron is a deeper probe of parameter space than the direct search for the heavier squarks and gluino (*i.e.*, $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 3.6 m_{\chi^\pm_1}$). Conversely, non-observation of charginos would entail strong indirect lower bounds on the gluino and squark masses in this model.

It is worth noting that in the calculation of the trilepton signal, the cross section $\sigma(p\bar{p} \to \chi^0_2\chi^\pm_1 X)$ depends only on the parameters of the neutralino-chargino sector (*i.e.*, $M_2, \mu, \tan\beta$), if the small contribution from the squark exchange diagrams is neglected. However, the leptonic branching fractions of χ^0_2 and $\chi^\pm_1$ depend additionally *and crucially* on the squark, slepton, and lightest Higgs-boson masses. This proliferation of variables leads to a wealth of possible outcomes, and within the Minimal Supersymmetric Standard Model(MSSM) to a generic lack of predictability. In contrast, in $SU(5)\times U(1)$ supergravity all model variables depend on only two parameters ($\tan\beta$ and $m_{\tilde{g}}$) and the top-quark mass, thus the predictions are quite sharp and readily falsifiable.

In this paper we present the first constraints on the parameter space of $SU(5)\times U(1)$ supergravity which arise from the recently announced limits on trilepton searches at the Tevatron [6, 7, 8]. As predicted [4], we show that this constraint is significant and for $m_t = 150\,GeV$ it rules out some regions of parameter space with chargino masses as high as $m_{\chi^\pm_1} \approx 105\,GeV$, although it is not possible to establish a new absolute lower bound on the chargino mass in $SU(5)\times U(1)$ supergravity. The five-fold increase in integrated luminosity expected in the upcoming Tevatron run should probe some regions of parameter space with chargino masses much beyond the reach of LEPII.

Our calculations of the trilepton rate have been performed as described in Ref. [4], although without neglecting the t-channel (squark-exchange) contribution to the cross section. More importantly, the parameter space presently explored is much more constrained than in Ref. [4], where only the most basic theoretical/consistency, and experimental LEP constraints were imposed (as described in detail in Ref. [9]). The present parameter space has in addition been restricted by: (i) the CLEO limits on the $b \to s\gamma$ rate [10, 11], (ii) the long-standing limit on the anomalous magnetic moment of the muon [12], (iii) the non-observation of anomalous muon fluxes in underground detectors ("neutrino telescopes") [13], and (iv) the electroweak LEP high-precision measurements in the form of the ϵ_1, ϵ_b parameters [14, 11, 15]. Furthermore, in the present analysis we consider two string-inspired universal soft-supersymmetry-breaking scenarios for $SU(5) \times U(1)$ supergravity: the no-scale [16] and dilaton [17] scenarios. Details of these analyses and further experimental consequences will appear elsewhere [18]. An important consequence of the simultaneous imposition of all the above constraints (trileptons included) is that for $m_t = 170\,GeV$, the dilaton scenario is completely excluded, and only a few allowed points in parameter space in the no-scale scenario remain (with $m_{\tilde{q}} \approx m_{\tilde{g}} \lesssim 285\,GeV$).

2 SU(5)xU(1) Supergravity

For practical purposes, the most important feature of $SU(5) \times U(1)$ supergravity is the minimality of parameters needed to describe the complete low-energy supersymmetric spectrum and its interactions. The constraints of supergravity and radiative electroweak symmetry breaking reduce the number of parameters to four: the ratio of Higgs-boson vacuum expectation values ($\tan\beta$) and three universal soft-supersymmetry breaking parameters ($m_{1/2}, m_0, A$) [19]. In addition, the top-quark mass (m_t) plays an important role through the running of the mass parameters from the unification scale down to the electroweak scale. Thus, until m_t is measured with some precision, it needs to be taken as a fifth parameter. In $SU(5) \times U(1)$ supergravity we consider two string-inspired scenarios for the *universal* soft-supersymmetry-breaking parameters, both of which belong to the general no-scale supergravity framework [20]: (i) the no-scale scenario [21], where $m_0 = A = 0$, and (ii) the dilaton scenario [22], where $m_0 = \frac{1}{\sqrt{3}} m_{1/2}$, $A = -m_{1/2}$. In this case, the number of parameters is just two ($\tan\beta, m_{1/2}$) plus the top-quark mass. For the latter we consider three values: $m_t = 130, 150, 170\,GeV$. In fact, the present lower limit on the top-quark mass, obtained by combining the CDF and D0 lower bounds is 129 GeV [23], and below we show that the case $m_t = 170\,GeV$ is seriously constrained, if not completely excluded already. Therefore, results of our calculations will be shown only for $m_t = 150\,GeV$. The other values of m_t, as well as particular cases of the no-scale and dilaton scenarios are considered in Ref. [18]. For $m_t = 150\,GeV$ we find the following allowed range of $\tan\beta$: $2 \lesssim \tan\beta \lesssim 26\,(40)$ in the no-scale (dilaton) scenario.[1] The resulting parameter space for the no-scale [16] and dilaton [17] scenarios consists of discrete pairs of points in the ($\tan\beta, m_{1/2}$) plane. In practice, we trade the $m_{1/2}$ supersymmetric mass scale parameter for the more readily measurable lightest chargino mass $m_{\chi^\pm_1}$.

In the scenarios we consider all sparticle masses scale with the gluino mass, with a mild $\tan\beta$ dependence (except for the third-generation squark and slepton

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[1] The radiative breaking mechanism requires $\tan\beta > 1$, and the LEP lower bound on the lightest Higgs boson mass ($m_h \gtrsim 60\,GeV$ [24]) is quite constraining for $1 < \tan\beta < 2$.

Table 1: The approximate proportionality coefficients to the gluino mass, for the various sparticle masses in the two supersymmetry breaking scenarios considered. The $|\mu|$ coefficients apply for $m_t = 150\, GeV$ only.

	no-scale	dilaton
$\tilde{e}_R, \tilde{\mu}_R$	0.18	0.33
$\tilde{\nu}$	$0.18 - 0.30$	$0.33 - 0.41$
$2\chi_1^0, \chi_2^0, \chi_1^\pm$	0.28	0.28
$\tilde{e}_L, \tilde{\mu}_L$	0.30	0.41
$\tilde{q}$	0.97	1.01
$\tilde{g}$	1.00	1.00
$\|\mu\|$	$0.5 - 0.7$	$0.6 - 0.8$

masses). In Table 1 we give the approximate proportionality coefficient (to the gluino mass) for each sparticle mass. Note that the relation $2m_{\chi_1^0} \approx m_{\chi_2^0} \approx m_{\chi_1^\pm}$ holds to good approximation. The third-generation squark and slepton masses also scale with $m_{\tilde{g}}$, but the relationships are smeared by a strong $\tan\beta$ dependence, and are therefore not shown in Table 1. From this table one can (approximately) translate any bounds on a given sparticle mass on bounds on all the other sparticle masses.

3 Constraints on the parameter space

The parameter space for $SU(5)\times U(1)$ supergravity in the no-scale and dilaton scenarios has been obtained in Refs. [16, 17]. However, these allowed points satisfy only the theoretical and consistency constraints, plus the most basic experimental constraints from new particle searches at LEP [9]. Several indirect experimental constraints have been recently considered in the context of $SU(5)\times U(1)$ supergravity, although until now not in a "global" way, *i.e.*, not all constraints applied at once. These constraints are significant and are now described in turn.

(i) $b \to s\gamma$: This rare radiative flavor-changing-neutral-current (FCNC) decay has been observed by the CLEOII Collaboration in the following 95% CL allowed range [25]

$$B(b \to s\gamma) = (0.6 - 5.4) \times 10^{-4}. \qquad (1)$$

The predictions for $B(b \to s\gamma)$ in the no-scale scenario were given in Ref. [10] and for the dilaton scenario in Ref. [11]. The experimental bound in Eq. (1) was seen to be quite restrictive because the model predictions could be well above the Standard Model values, as well as much suppressed relative to the SM case. For the case of $m_t = 150\, GeV$, the points in parameter space excluded by this constraint are represented by plus signs (+) in Fig. 1a (2a) for the no-scale (dilaton) scenario. In both scenarios there are points (mostly for $m_{\chi_1^\pm} <$

$100\,GeV$) where this constraint overlaps with the $(g-2)_\mu$ constraint considered next, and the resulting symbol is the overlap of a plus sign (+) with a cross sign (×). The case of $m_t = 170\,GeV$ is shown in Figs. 1b,2b and entails similar constraints on the parameter space, although these are harder to appreciate in the figures because of the overwhelming effect of the $\epsilon_{1,b}$ constraints.

(ii) $(g-2)_\mu$: The supersymmetric contributions to the anomalous magnetic moment of the muon in $SU(5)\times U(1)$ supergravity have been obtained in Ref. [12]. Comparing the long-standing experimental value for $(g-2)_\mu$ with the most accurate determination of the Standard Model contribution, one can determine a 95%CL allowed interval for the supersymmetric contribution. The latter contribution is greatly enhanced for large values of $\tan\beta$ (which become constrained) and can easily exceed the electroweak contribution and the hadronic uncertainties within the SM. The points in parameter space excluded by this constraint are represented by cross signs (×) in Figs. 1,2. As for the $B(b\to s\gamma)$ constraint, the $(g-2)_\mu$ constraint is also harder to appreciate in the $m_t = 170\,GeV$ case (*i.e.*, in Figs. 1b,2b).

(iii) "Neutrino telescopes": If neutralinos (the lightest supersymmetric particle, which is stable) are present in the galactic halo in significant numbers, as required to solve the halo dark matter puzzle [26], then some would be captured by the Sun and Earth cores. Subsequent neutralino annihilations will produce a shower of decay particles, but only the high-energy neutrinos could escape the core vicinity. These neutrinos could then interact with rock beneath underground detectors (called neutrino telescopes) and produce upwardly-moving muon events in the detector. The computation of these muon fluxes in $SU(5)\times U(1)$ supergravity has been carried out in Ref. [13]. The experimental limits on muon fluxes above background are not very restrictive at the moment, but nonetheless the points in Figs. 1,2 denoted by diamond symbols (◇) are excluded at the 90%CL. These excluded points occur mostly for the dilaton scenario and for $m_{\chi_1^\pm} \approx 100\,GeV$ (where neutralino capture by the Earth is enhanced by the ^{56}Fe nucleus [13]).

(iv) ϵ_1, ϵ_b parameters : Precision electroweak measurements at LEP can be expressed in terms of four parameters ($\epsilon_{1,2,3,b}$ [27]) which are calculated from various one-loop diagrams. The supersymmetric contributions to these parameters have been calculated in $SU(5)\times U(1)$ supergravity and found to be constraining only for ϵ_1 [14, 11] and ϵ_b [15]. Both of these parameters depend quadratically on m_t and at the 90%CL only values of $m_t \gtrsim 160\,GeV$ are constrained experimentally [15]. In fact, Figs. 1b,2b show that in order for the case $m_t = 170\,GeV$ to give values of $\epsilon_{1,b}$ within the experimental limits, it is required that the chargino be light ($m_{\chi_1^\pm} \lesssim 70\,GeV$) and $\tan\beta \gtrsim 4$.

4 The trilepton signal

It had been suggested that searches for weakly interacting supersymmetric particles at the Tevatron (and hadron colliders in general) could be a worthy pursuit [3]. This expectation was investigated in the no-scale scenario of $SU(5)\times U(1)$ supergravity in Ref. [4] and found to be exceptionally well suited for probing the parameter space of this model. The process of interest is $p\bar{p}\to\chi^0_2\chi^\pm_1 X$, where both neutralino and chargino decay leptonically: $\chi^0_2\to\chi^0_1 l^+l^-$, and $\chi^\pm_1\to\chi^0_1 l^\pm\nu_l$, with $l=e,\mu$. In Ref. [4], the t-channel (squark-exchange) contribution to $\sigma(p\bar{p}\to\chi^0_2\chi^\pm_1 X)$ was neglected. Here we include this contribution, which is found to be small (at most a $\pm 10\%$ effect) and decreasing with increasing squark masses. The irreducible backgrounds for this process are very small, the dominant one being $p\bar{p}\to W^\pm Z\to(l^\pm\nu_l)(\tau^+\tau^-)$ with a cross section into trileptons of $(\sim 1\,pb)(\frac{2}{9})(0.033)(0.34)^2\sim 1\,fb$. Much larger "instrumental" backgrounds exist when for example in $p\bar{p}\to Z\gamma$, the photon "converts" and fakes a lepton in the detector; with the present sensitivity, suitable cuts have been designed to reduce this background to acceptable levels [6].

The trilepton signal is larger in the no-scale scenario because the charged sleptons which mediate some of the decay channels can be on-shell and the leptonic branching ratios are significantly enhanced (as large as $\frac{2}{3}$) relative to a situation with heavier sparticles in the dilaton scenario, where the W, Z-exchange channels tend to dominate and the leptonic branching fractions are smaller [4]. The results of these calculations for the case of $m_t=150\,GeV$ are shown in Fig. 3 for both scenarios. Note that for light chargino masses, the trilepton signal can be rather small in the no-scale model. This occurs when the neutralino leptonic branching fraction is suppressed because the sneutrinos are on-shell and the $\chi^0_2\to\nu\tilde{\nu}$ channel dominates.

In Fig. 3 we have also shown the very recent limits obtained by the D0 [6] and CDF [7, 8] Collaborations. Both these sets of data are preliminary and the D0 limit is weakened because of the present inability to remove one candidate event from the data sample, and because the full data set has not yet been analyzed. The curves become more restrictive for larger values of $m_{\chi^\pm_1}$ because the efficiency for detecting charginos and neutralinos increases with their masses. The integrated luminosity corresponds roughly to $15\,pb^{-1}$ for D0 and $18\,pb^{-1}$ for CDF.

Clearly, at least for $\mu<0$ (and $m_t=150\,GeV$), the Tevatron (CDF) data is restrictive. Most interestingly, there are excluded points in parameter space of the no-scale scenario (with $\mu<0$) with chargino masses as high as $m_{\chi^\pm_1}\approx 105\,GeV$. These points are already beyond the reach of LEPII. The points in parameter space excluded by the trilepton constraint are shown in Figs. 1,2 as fancy star symbols. By construction, these points are not excluded by any of the previously discussed constraints. Because of the sometimes suppressed leptonic branching fractions, in general it is not possible to obtain a new absolute lower bound on the chargino mass: for $m_t=150\,GeV$, combining all constraints we obtain $m_{\chi^\pm_1}\gtrsim 65\,(45)\,GeV$ and $m_{\chi^\pm_1}\gtrsim 50\,(60)\,GeV$ in the no-scale and dilaton scenarios for $\mu>0\,(\mu<0)$ respectively.

In the case of $m_t = 170\, GeV$, the imposition of the *combined* constraints discussed above is so strong that the very few points in parameter space remain allowed. In fact, in the dilaton scenario (see Fig. 2b) the remaining points (with $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 195 - 220\, GeV$) can be excluded by the CDF lower bound on the squark and gluino masses ($m_{\tilde{q}}^{exp} \approx m_{\tilde{g}}^{exp} \gtrsim 220\, GeV$ [2]). In the no-scale scenario, for $m_t = 170\, GeV$ (see Fig. 1b) one has $m_{\chi_1^\pm} \lesssim 70\,(60)\, GeV$ and $m_{\tilde{q}} \approx m_{\tilde{g}} \lesssim 260\,(285)\, GeV$ for $\mu > 0\,(\mu < 0)$, and the analysis of the 92–93 CDF and D0 data (once completed) could possibly exclude all these points altogether.

5 Conclusions and outlook

We have calculated the effect of several experimental constraints on the parameter space of $SU(5) \times U(1)$ supergravity. An important result is that the case $m_t = 170\, GeV$ is allowed only for very light chargino masses ($m_{\chi_1^\pm} \lesssim 70\, GeV$) and $m_{\tilde{q}} \approx m_{\tilde{g}} \lesssim 285\, GeV$ in the no-scale scenario, and is completely excluded in the dilaton scenario. This is a consequence of the combined effect of *all* constraints. Of the indirect constraints, probably the future increase in sensitivity of $B(b \to s\gamma)$ at CLEO is the most effective way to explore the parameter space in the near future. Furthermore, starting in late 1994, the new Brookhaven E821 experiment should be able to eventually constrain the parameter space decisively with the high-precision measurement of $(g-2)_\mu$.

The direct trilepton search at the Tevatron looks quite promising as well. With the five-fold increase in statistics during 1994, the reach in chargino masses is limited by the handling of the backgrounds. In principle, if the backgrounds could be suppressed to levels below the signal, the experimental limits shown on Fig. 3 could drop by a factor of 5, entailing a probe of the parameter space with chargino masses as high as $m_{\chi_1^\pm} \approx 150\, GeV$. Of course, because of the details of the model, some points in parameter space with lighter chargino masses would remain unexplored. However, what matters is the fraction of the parameter space which is explored, and not which portion of it one is able to explore first. The remaining lighter chargino regions ($m_{\chi_1^\pm} < 100\, GeV$) will be fully covered at LEPII. Squark and gluino searches at the Tevatron may also become relevant with the increase in integrated luminosity in the coming run. For $m_t = 150\, GeV$, the present experimental limits [2] do not constrain the parameter space of $SU(5) \times U(1)$ supergravity in any significant way. However, for the $m_t = 170\, GeV$ case the present squark and gluino mass limits supplement the previously discussed constraints such as to exclude the dilaton scenario altogether.

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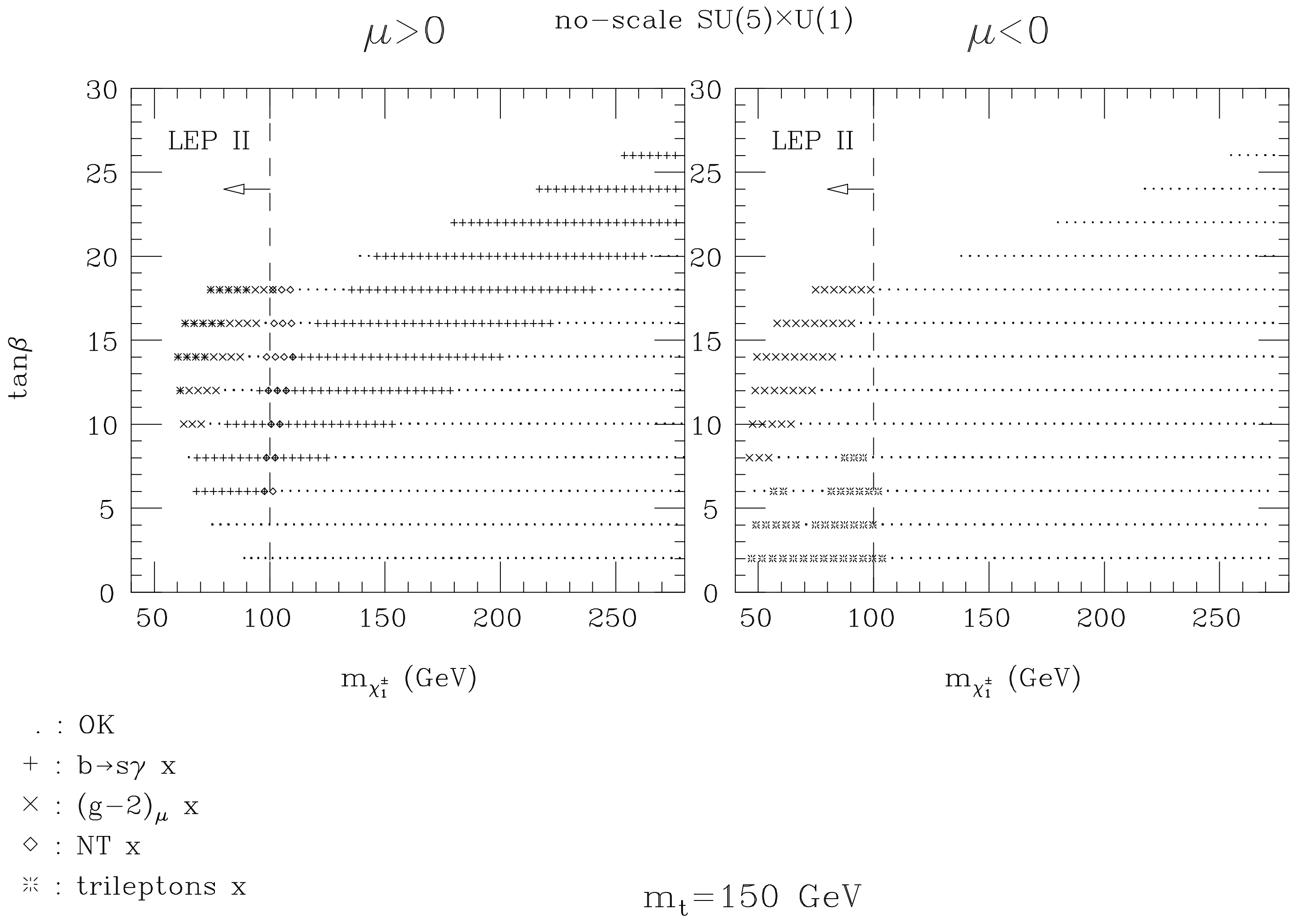
Figure Captions

Figure 1: The parameter space of the no-scale scenario in $SU(5)\times U(1)$ supergravity in the $(m_{\chi_1^\pm}, \tan\beta)$ plane for (a) $m_t = 150\,GeV$ and (b) $m_t = 170\,GeV$. The periods indicate points that passed all constraints, the pluses fail the $B(b\to s\gamma)$ constraint, the crosses fail the $(g-2)_\mu$ constraint, the diamonds fail the neutrino telescopes (NT) constraint, the squares fail the ϵ_1 constraint, the fancy pluses fail the ϵ_b constraint, and the fancy stars fail the trilepton constraint. The dashed line indicates the direct reach of LEPII for chargino masses. Note that when various symbols overlap a more complex symbol is obtained.

Figure 2: The parameter space of the dilaton scenario in $SU(5)\times U(1)$ supergravity in the $(m_{\chi_1^\pm}, \tan\beta)$ plane for (a) $m_t = 150\,GeV$ and (b) $m_t = 170\,GeV$. The periods indicate points that passed all constraints, the pluses fail the $B(b\to s\gamma)$ constraint, the crosses fail the $(g-2)_\mu$ constraint, the diamonds fail the neutrino telescopes (NT) constraint, the squares fail the ϵ_1 constraint, the fancy pluses fail the ϵ_b constraint, and the fancy stars fail the trilepton constraint. The dashed line indicates the direct reach of LEPII for chargino masses. Note that when various symbols overlap a more complex symbol is obtained.

Figure 3: The trilepton cross section at the Tevatron ($p\bar p\to\chi_2^0\chi_1^\pm X$; $\chi_2^0\to\chi_1^0 l^+l^-$, $\chi_1^\pm\to\chi_1^0 l^\pm\nu_l$, with $l=e,\mu$) in $SU(5)\times U(1)$ supergravity for both no-scale and dilaton scenarios. The CDF and D0 95%CL limits are shown. Note that some points with $m_{\chi_1^\pm} > 100\,GeV$ (in the no-scale case for $\mu<0$) are excluded.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$m_{\chi_1^\pm}$ (GeV)
. : OK
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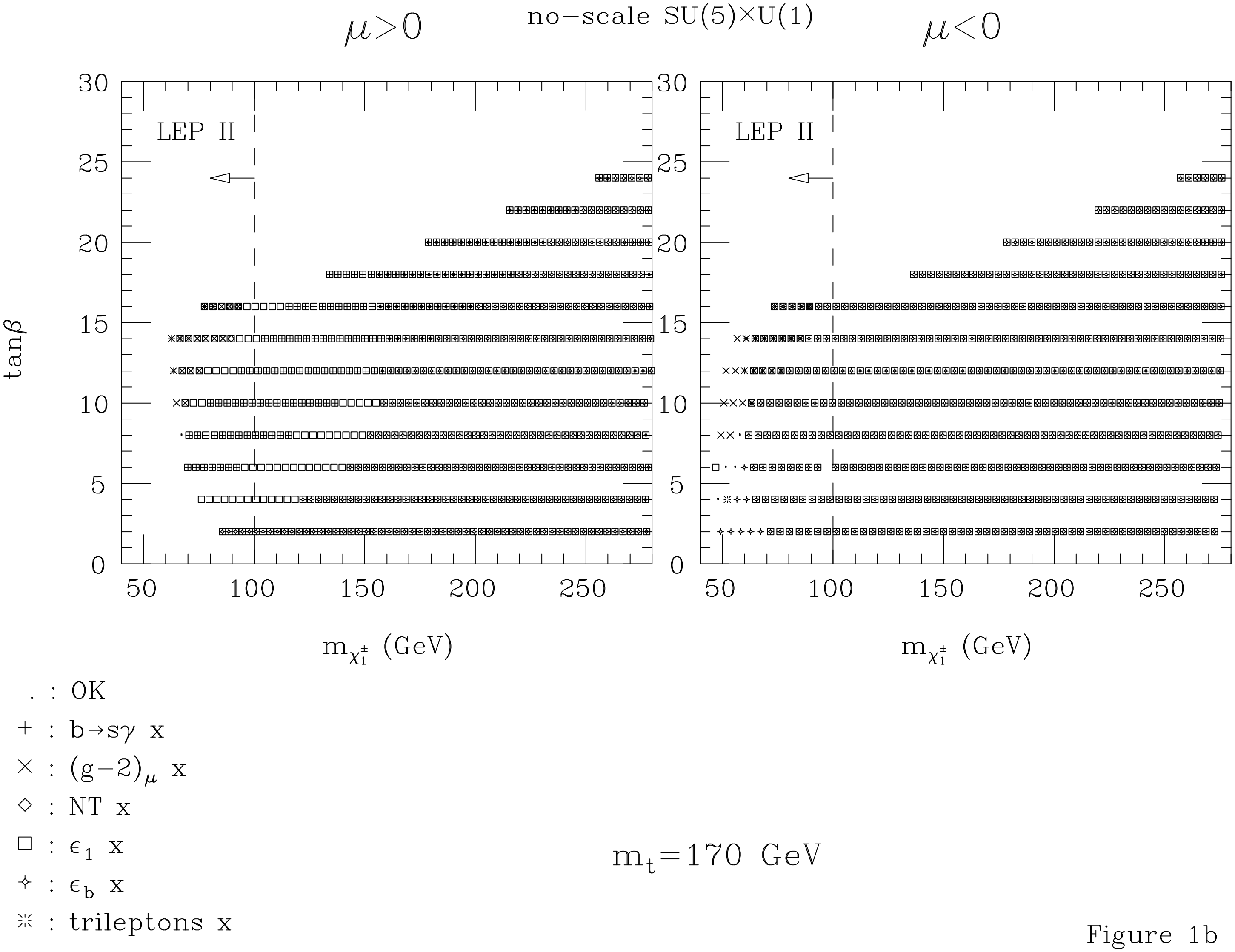
× : $(g-2)_\mu$ x
◇ : NT x
⁕ : trileptons x
$m_t=150$ GeV

Figure 1a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× : $(g-2)_\mu$ x
◇ : NT x
□ : ϵ_1 x
✧ : ϵ_b x
※ : trileptons x
m_t=170 GeV

Figure 1b

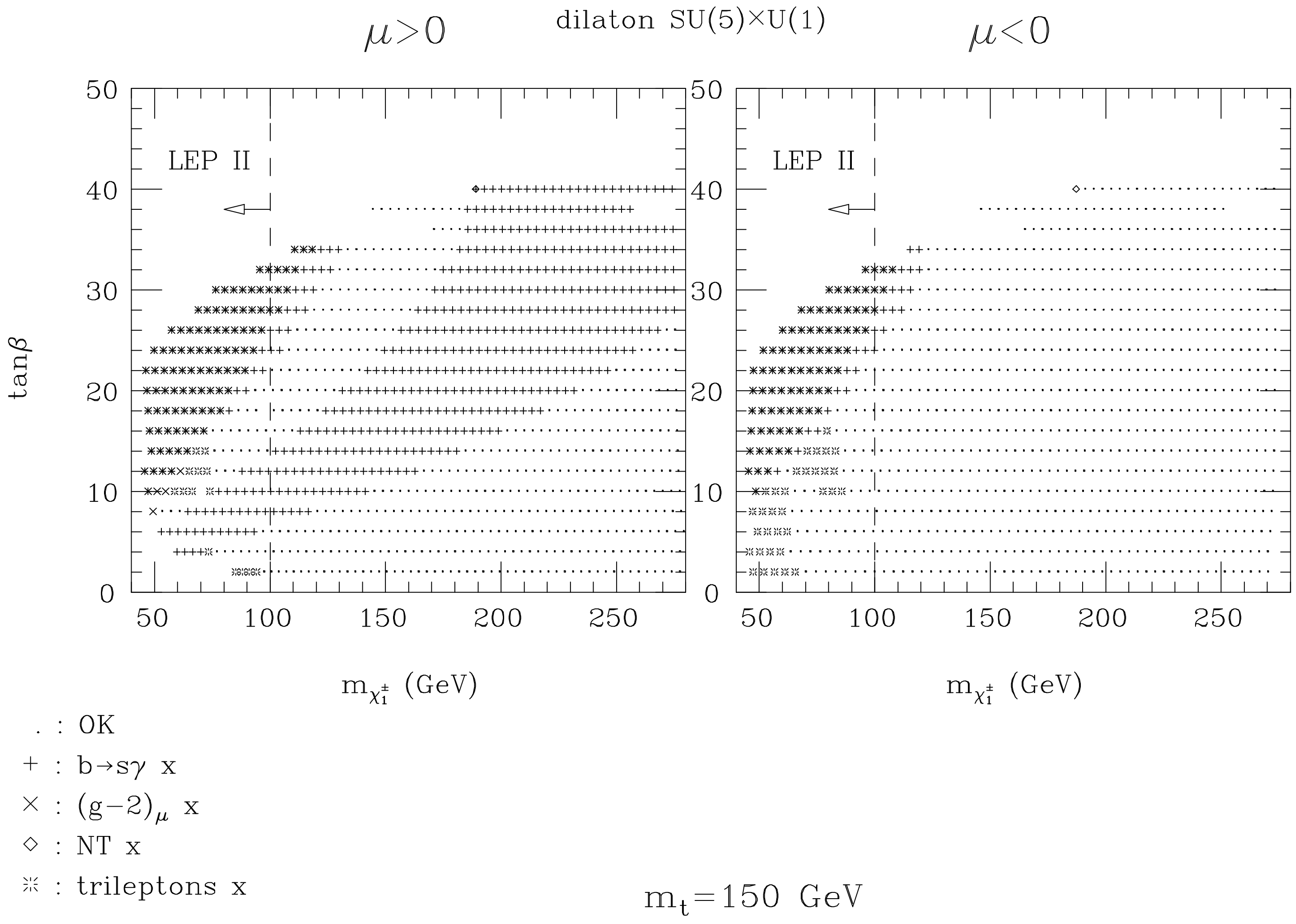
dilaton SU(5)×U(1)
$\mu>0$
$\mu<0$
LEP II
LEP II
$\tan\beta$
0
10
20
30
40
50
50
100
150
200
250
$m_{\chi_1^\pm}$ (GeV)
$m_{\chi_1^\pm}$ (GeV)
. : OK
+ : $b\to s\gamma$ x
× : $(g-2)_\mu$ x
◇ : NT x
⁂ : trileptons x
$m_t=150$ GeV

Figure 2a

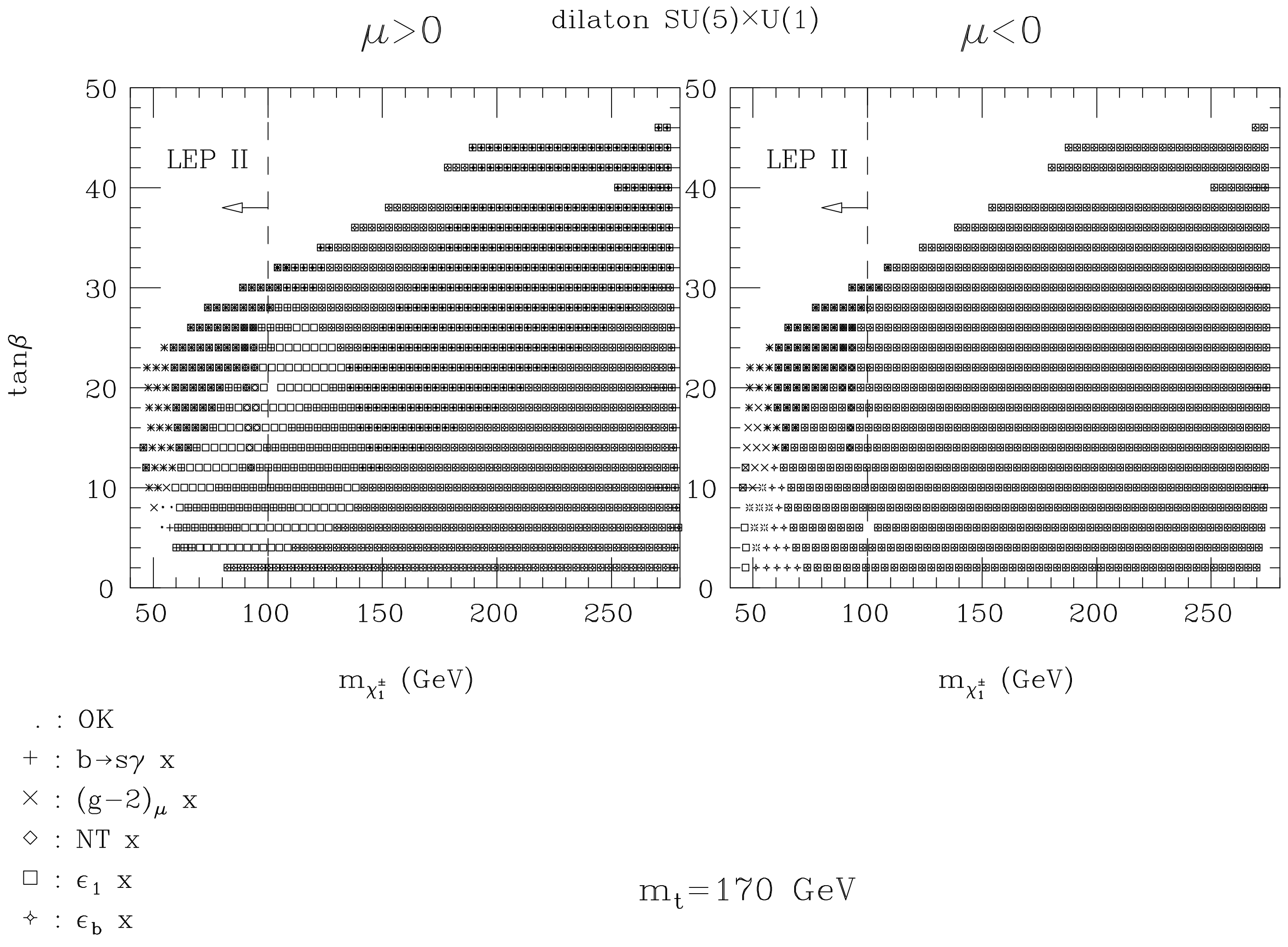
dilaton SU(5)×U(1)
μ>0
μ<0
tanβ
LEP II
LEP II
50
40
30
20
10
0
50
100
150
200
250
m_χ1± (GeV)
m_χ1± (GeV)
. : OK
+ : b→sγ x
× : (g−2)_μ x
◇ : NT x
□ : ε_1 x
✧ : ε_b x
※ : trileptons x
m_t=170 GeV

Figure 2b

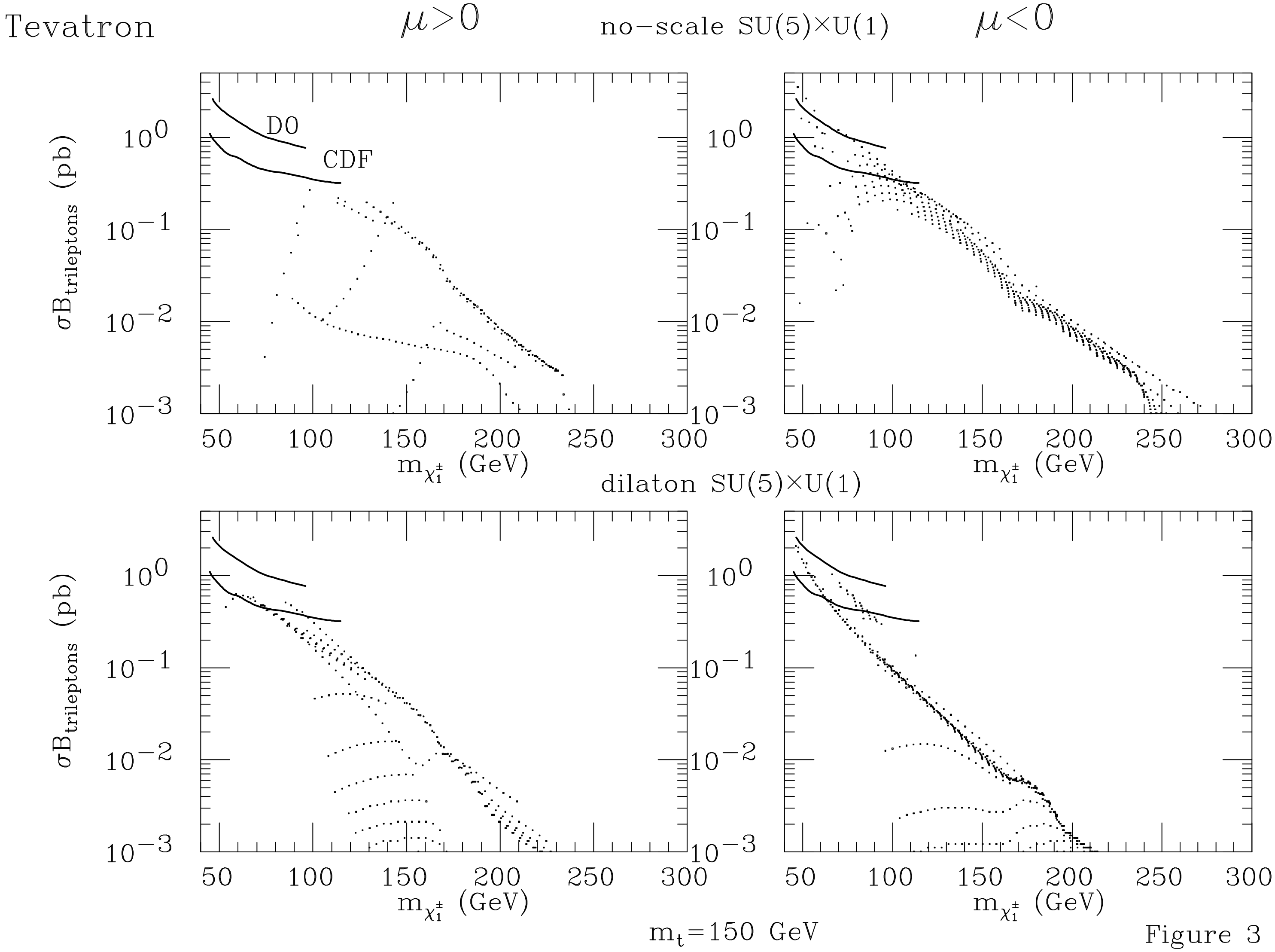
Tevatron
$\mu>0$
no-scale SU(5)×U(1)
$\mu<0$
D0
CDF
$\sigma B_{\rm trileptons}$ (pb)
10^0
10^{-1}
10^{-2}
10^{-3}
50
100
150
200
250
300
$m_{\chi_1^\pm}$ (GeV)
dilaton SU(5)×U(1)
m_t=150 GeV

Figure 3