Update of the effect of cascade decays on the Fermilab Tevatron gluino and squark mass bounds

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We present an improved and updated analysis of the effect of cascade decays on the gluino and squark mass bounds recently obtained by the Collider Detector at Fermilab (CDF) Collaboration under the assumption that gluinos and squarks only decay to the lightest supersymmetric particle. We delineate regions of parameter space of the minimal model excluded by our cascade analysis, and combine these regions with regions excluded by recent CERN LEP data. We find that the gluino bound is diminished by 10–30 GeV from its CDF value depending on model parameters. We show that a gluino as light as 135 GeV is allowed, in contrast with the absolute lower bound of 150 GeV obtained by the CDF Collaboration. Corresponding bounds on the squark mass are reduced by typically 15–20 GeV, unless the lightest supersymmetric particle is very heavy.

Supersymmetry [1] (SUSY) can stabilize the standard-model Higgs sector provided that the superpartner masses are lighter than ~ 1 TeV. Considerable effort has been expended in the search for sparticles at high-energy colliders. From the absence [2] of anomalous decays of Z^0 at CERN LEP as well as from a precise measurement of its line shape [3], lower limits close to $M_Z/2$ have been inferred on the masses of sleptons ($\tilde{l}$), squarks ($\tilde{q}$), sneutrinos ($\tilde{\nu}$), and charginos ($\widetilde{W}_i$). Somewhat stronger limits have been obtained on the masses of squarks and gluinos ($\tilde{g}$) since they would be copiously produced at hadron colliders if they are sufficiently light. Assuming that R parity is conserved, these would then rapidly decay to the lightest supersymmetric particle (LSP) which would escape detection resulting in an apparent imbalance of transverse energy ($\not{E}_T$) in gluino and squark events. Nonobservation of an excess of $\not{E}_T$ events above standard-model expectations has led the UA2 Collaboration [4] to conclude that

$$m_{\tilde{q}} > 74 \text{ GeV}, \quad m_{\tilde{g}} > 79 \text{ GeV} \quad (\text{UA2})\ . \tag{1a}$$

The CDF Collaboration at the Fermilab Tevatron has also published comparable limits [5] of

$$m_{\tilde{q}} > 74 \text{ GeV}, \quad m_{\tilde{g}} > 73 \text{ GeV} \quad (\text{CDF—1989})\ , \tag{1b}$$

based on an integrated luminosity of just 25 nb^{-1}. The bound on the squark and gluino mass has been obtained assuming that only the direct decays $\tilde{q} \to q\widetilde{Z}_1$ and $\tilde{g} \to q\bar{q}\widetilde{Z}_1$ are possible, where $\widetilde{Z}_1$, the lightest neutralino, is assumed to be the LSP.

It is well known [6], however, that once $\tilde{q}$ and $\tilde{g}$ become heavy enough so that their decays into charginos and neutralinos other than the LSP are kinematically accessible, these often dominate the direct decays to the LSP. This is particularly true for the decays $\tilde{g} \to q\bar{q}\widetilde{W}_-$ and $\tilde{q}_L \to q\widetilde{W}_-$ which occur via the large SU(2) gauge coupling, whereas direct decays to the LSP usually dominate the decays of $\tilde{q}_R$ [7]. The chargino (or the heavier neutralino) subsequently decays to the LSP which is typically softer than an LSP produced by the direct decay of the squark or gluino. As a result, a smaller fraction of squark or gluino events satisfy the experimental $\not{E}_T$ requirement resulting in a somewhat weaker bound on $m_{\tilde{g}}$ or $m_{\tilde{q}}$ as compared to the case where cascade decays are ignored. In a previous analysis [8], we have shown that the cascade decays can reduce the $\tilde{g}$ bound from its value in (1b) by 3–30 GeV, whereas the squark bound is reduced by $\lesssim 10$ GeV unless the LSP is relatively heavy. For even heavier sparticle masses, the cascade decays become even more important; for instance, the branching fraction for $\tilde{g} \to q\bar{q}\widetilde{Z}_1$ never exceeds about 55% for $m_{\tilde{g}} = 120$ GeV, and is often considerably smaller.

Since the publication of the bound (1b), the CDF collaboration has accumulated an integrated luminosity of over 4 pb^{-1}, which represents more than a 150-fold increase in the size of their earlier data sample. Based on a nonobservation of a significant excess of $\not{E}_T$ events in this larger data sample, the CDF Collaboration has announced preliminary bounds [9,10]

$$m_{\tilde{g}} > 150 \text{ GeV}, \quad m_{\tilde{q}} > 170 \text{ GeV(if } m_{\tilde{g}} < 400 \text{ GeV)} \quad (\text{CDF—1991})\ , \tag{2}$$

where it is once again assumed that the sparticles can only decay to a massless LSP.

We present here an updated analysis of the effect of cascade decays on the bounds obtained from the new CDF data for several reasons. First, the CDF Collaboration has reported a preliminary mass bound of about 150 GeV on $m_{\tilde{q}}$ for over a year now. Secondly, we have made a number of improvements in our Monte Carlo program SUSYSM. SUSYSM generates simultaneously $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, and $\tilde{g}\tilde{q}$ events while keeping track of squark flavor and left (L) and right (R) types. This is important because $\tilde{q}_L$ and $\tilde{q}_R$ are produced in different combinations, and have different decays. We have also included [11] radiative gluino decays $\tilde{g}\to g\tilde{Z}_i$, which can become important when the supersymmetric Higgsino mass μ is small; this enables us to extend our analysis to a region of parameter space not previously [8] accessible. SUSYSM incorporates the predicted decays of gluinos, squarks, charginos, and neutralinos as given by the minimal supersymmetric model (MSSM). It has the option of being run at the parton level, or in conjunction with the JETSET hadronization [12] routines. Thirdly, important new constraints from LEP data exclude significant regions of the parameter space of the minimal model. It is interesting to see how these regions compare with those excluded by the CDF results.

Our basic strategy for obtaining the modification to the CDF bounds is described in Ref. [8]. Briefly, we generate at the parton-level gluino and squark events with $m_{\tilde{g}}$ and $m_{\tilde{q}}$ equal to the CDF limit [9,10], allowing only direct decays of squarks and gluinos to a massless LSP. We take into account the CDF experimental cuts (described below) to find the resulting signal cross section for $\not\!\!E_T$ events. We then run the SUSYSM program at various sparticle masses to obtain a matching cross section. The matching cross section is always attained at higher sparticle masses than the CDF limit due mainly to the softer $\not\!\!E_T$ spectrum from cascade decays. Within the minimal supersymmetric model [1] (MSSM), all the cascade decays are completely determined [6,7,11,13] by fixing the parameter set $(m_{\tilde{g}}, m_{\tilde{q}}, \mu, \tan\beta, m_{H^+}, m_t)$, where we have assumed all gaugino masses are equal at the unification scale. The parameter μ (also referred to as $-2m_1$) is the supersymmetric Higgsino mass parameter, while $\tan\beta = v/v'$ is the ratio of Higgs-field vacuum expectation values. Finally, m_{H^+} is the charged-Higgs-boson mass and m_t is the top-quark mass.

In our Monte Carlo simulation of $\not\!\!E_T$ events from squarks and gluinos, we have attempted to simulate the CDF conditions [10] via the following acceptance criteria.

(1) We coalesce partons within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.7$ into single jets. We also require that all the jets satisfy $|\eta_j| < 3.5$, and each jet must have $E_T > 15$ GeV. The highest E_T cluster is also required to be central ($|\eta| < 1$).

(2) We require that there be no jet with $E_T > 5$ GeV within a 30° cone back to back in azimuth with the leading jet.

(3) We require

$$\not\!\!E_T > 2.4 \times \sqrt{\Sigma E_T}\ ,$$

where ΣE_T is the total scalar transverse energy in the event, including a soft scattering E_T contribution.

(4) We require $|\phi_{\rm jet} - \phi_{\not E_T}| > 30°$.

(5) We require no electrons or muons with $E_T > 15$ GeV.

(6) For $m_{\tilde{g}} < m_{\tilde{q}}$, we require the jet multiplicity $n_j \geq 4$ and $\not\!\!E_T > 40$ GeV. For $m_{\tilde{q}} < m_{\tilde{g}}$, we require $n_j \geq 2$ and $\not\!\!E_T > 100$ GeV.

The gluino mass bound is shown in Fig. 1 for various squark masses. The various lines correspond to the cases (i) $m_{\tilde{q}} = 400$ GeV (solid), (ii) $m_{\tilde{q}} = 1$ TeV (dashes), (iii) $m_{\tilde{q}} = m_{\tilde{g}} + 10$ GeV (double-dot-dashed), and (iv) $m_{\tilde{g}} = m_{\tilde{q}} + 10$ GeV (dot-dashed). The CDF bounds [9,10] correspond to the horizontal lines while the dependence of the cascade decay limits on the SUSY Higgsino mass μ is shown by the different curves. We have taken $\tan\beta = 2$, $m_{H^+} = 500$ GeV, and $m_t = 150$ GeV. The dotted region of Fig. 1 is excluded by the LEP constraints discussed below. Our results are insensitive to the charged-Higgs-boson mass as long as $m_{H^+} \gg M_W$.

All the CDF limits have been given explicitly in Refs. [9, 10] except case (ii), where $m_{\tilde{q}} = 1$ TeV. Here, we have found $m_{\tilde{g}} > 158$ GeV by equating the cut cross section obtained assuming that gluinos decay via $\tilde{g}\to q\bar{q}\tilde{Z}_1$, with that obtained for case (i), where $m_{\tilde{g}} = 150$ GeV and $m_{\tilde{q}} = 400$ GeV. The CDF bound on $m_{\tilde{g}}$ is larger for very large squark masses due to a reduction of the destructive interference between production amplitudes involving initial state quarks.

From Fig. 1, we note the following.

(a) For each of the four cases, the incorporation of realistic decays of squarks and gluinos results in a diminution

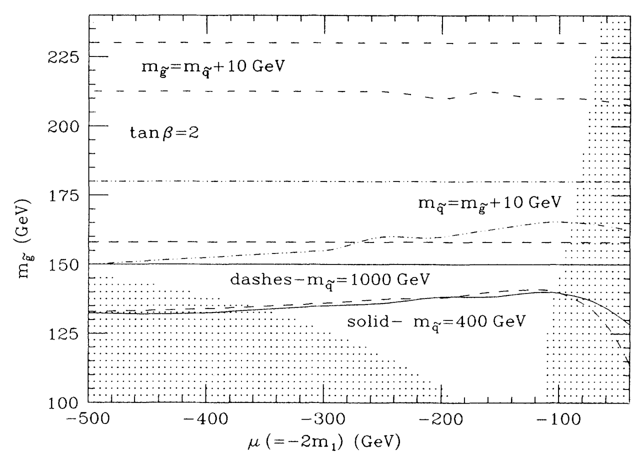

FIG. 1. The variation of the gluino mass bound obtained from our analysis as a function of the supersymmetric Higgsino mass $\mu = -2m_1$ for $\tan\beta = 2$, and for the various choices of squark mass shown. The limits from direct decays to a massless LSP, as obtained by the CDF experiment, are shown as horizontal lines. The various curves show the dependence of the bound obtained from the cascade analysis on μ. Other parameters are as fixed in the text. The region excluded by LEP Z^0 data is shaded with dots. These data also exclude the region -50 GeV $< \mu < 500$ GeV for the whole range of $m_{\tilde{g}}$ in this figure.

of the CDF bound by $\sim 10-30$ GeV for values of SUSY parameters not yet excluded by LEP.

(b) For the cases where $m_{\tilde{q}} \gg m_{\tilde{g}}$, we find a minimum gluino mass of about 135 GeV, where the constraints from LEP and CDF meet, at $\mu \sim -350$ GeV.

(c) Again for $m_{\tilde{q}} \gg m_{\tilde{g}}$, we see a large diminution of the CDF bound at small values of $|\mu|$, within the LEP excluded region. In this region, the radiative decay $\tilde{g} \to g\tilde{Z}_2$ becomes very important because $\tilde{Z}_2$ contains a substantial h-Higgsino component (which couples to the top family via a Yukawa coupling). The $\tilde{Z}_2$ then decays via $\tilde{Z}_2 \to \tilde{Z}_1 f\bar{f}$ where f's are allowed fermions. As a result, only a small fraction of events pass the $\not{E}_T$ cut. This diminution increases with squark mass because the radiative decay amplitude is enhanced relative to the tree amplitude by $\ln(m_{\tilde{q}}/m_{\tilde{g}})$.

(d) The diminution of the gluino mass bound is greater for $m_{\tilde{q}} = 1$ TeV than for $m_{\tilde{q}} = 400$ GeV even though the event kinematics (which determine detection efficiency) and the branching fractions for various gluino decays are essentially the same for large values of $|\mu|$. This is because the gluino pair production cross section falls slightly less steeply with increasing $m_{\tilde{g}}$ in the $m_{\tilde{q}} = 1$ TeV case. As a result, a greater reduction of $m_{\tilde{g}}$ is needed in order to match the cross section from SUSYSM with that given by the direct decay Monte Carlo program.

(e) In the case where $m_{\tilde{g}} = m_{\tilde{q}} + 10$ GeV, all three production processes $p\bar{p} \to \tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}$ contribute to the $\not{E}_T$ cross section. Here, the gluino decays with equal likelihood into $\tilde{g} \to q\tilde{q}_L$ or $q\tilde{q}_R$. The $\tilde{q}_R$ does not couple to charginos; it maintains a large branching fraction to the $\tilde{Z}_1$, which is in between a photino and pure U(1) gaugino, with mass $m_{\tilde{Z}_1} \simeq 30$ GeV, over a whole range of μ shown in Fig. 1. Thus, only the decays of $\tilde{q}_L$ produced directly or via $\tilde{g} \to q\tilde{q}_L$ significantly diminish the CDF expected bound. Since the LSP gaugino content and mass change little over the range of μ shown, the bound diminution shows little variation. For $\mu \to 0$, the Higgsino content of $\tilde{Z}_1$ rapidly increases, resulting in a diminished branching of $\tilde{q}_R \to q\tilde{Z}_1$, and a much smaller mass bound. However, this takes place well into the LEP excluded region. Finally, we note that the diminution of the bound due to the mass of LSP is not very significant because the $\tilde{Z}_1$ is never very heavy for the case under consideration [14].

(f) Finally, we consider the case where $m_{\tilde{q}} = m_{\tilde{q}} + 10$ GeV. In this case, $\tilde{q} \to q\tilde{Z}_i$ and $\tilde{q}_L \to q\tilde{W}_i$ as well as $\tilde{q} \to q\tilde{g}$. The latter is strongly suppressed by phase space and is only important for $\tilde{d}_R$ which has small U(1) couplings. As $|\mu|$ increases, the lighter charginos and neutralinos become more gauginolike, resulting in enhanced cascade decays of $\tilde{g}$ and $\tilde{q}_L$ and a greater diminution from the CDF bound. For this case, the diminution of the gluino bound may be as large as 30 GeV.

The boundary of the region of the $m_{\tilde{g}}$ vs $m_{\tilde{q}}$ plane preliminarily excluded by the CDF analysis [9,10] is shown by the solid contour in Fig. 2. Since it is assumed that squarks and gluinos can only decay directly to the LSP, and since the sparticle production cross sections are fixed by QCD in terms of $m_{\tilde{q}}$ and $m_{\tilde{g}}$, this excluded region

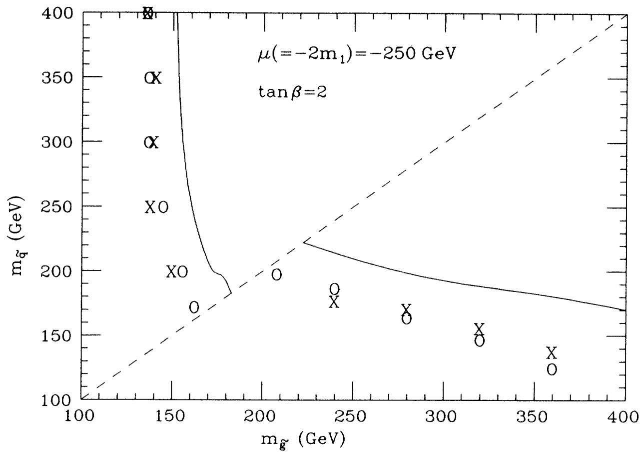

FIG. 2. The CDF sparticle mass limits are shown as the solid contour in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane for $\mu = -250$ GeV, with other parameters as in Fig. 1. The X's and O's show the corresponding results when complete cascade decays are included, for two different normalization schemes described in the text.

does not depend on any other SUSY parameters if the LSP mass is small. To illustrate the modification of the CDF bound due to cascade decays, we have fixed the other parameters at typical values away from the LEP excluded region: $\mu = -250$ GeV, $\tan\beta = 2$, $m_{H^+} = 500$ GeV, and $m_t = 150$ GeV. The O's mark the cascade bound obtained by equating the cut cross section from the Monte Carlo program with only direct decays at $(m_{\tilde{g}}, m_{\tilde{q}}) = (150, 400)$ GeV (for $m_{\tilde{g}} < m_{\tilde{q}}$) or $(m_{\tilde{g}}, m_{\tilde{q}}) = (400, 170)$ GeV (for $m_{\tilde{q}} < m_{\tilde{g}}$) to the same cross section obtained using SUSYSM. The X's denote the cascade bound obtained by a slightly different procedure: here we fixed the heavier of $m_{\tilde{q}}$ or $m_{\tilde{g}}$ to the same value in both direct and cascade Monte Carlo programs, and searched for sparticle masses that gave matching between SUSYSM cut cross sections and direct decay cross sections fixed at CDF mass limits. The X's and O's do not quite coincide because our parton-level Monte Carlo program does not exactly reproduce the CDF contour. The mismatch between the X's and O's gives an estimate of the error introduced by simplifications in our procedure. We see though that the bounds from the two procedures coincide to within a few GeV and that the diminution significantly exceeds this difference.

If $m_{\tilde{g}} \gg m_{\tilde{q}}$, renormalization-group evolution drives $m_{\tilde{q}}^2$ to negative values before the unification scale [15], unless there exist new large Yukawa couplings. In spite of this, we have illustrated the modification of the squark mass bound when $m_{\tilde{g}} > m_{\tilde{q}}$. The diminution of the squark mass bound increases as $m_{\tilde{g}}$ increases in Fig. 2. This is mainly due to the fact that the LSP mass increases with $m_{\tilde{g}}$; the masses of the two $\tilde{Z}_1$'s absorb much of the energy of the squark-pair events, and hence few events pass the $\not{E}_T > 100$ GeV cut. In fact, for $m_{\tilde{g}} = 400$ GeV, $m_{\tilde{Z}_1} \simeq 50$ GeV, and the bound on $m_{\tilde{q}}$ disappears.

We now turn our attention to the region of parameter space excluded by measurements at LEP. Constraints which exclude regions of the μ vs $m_{\tilde{g}}$ plane include [2,3,10] the following.

(i) $m_{\tilde{Z}_1} < m_{\tilde{W}_-}$, so that the chargino is not the LSP.

(ii) $m_{\tilde{W}_-} > 45$ GeV.

(iii) The SUSY contribution to the Z^0 width is less than 63 MeV. This constraint excludes much the same parameter space as (ii).

(iv) The SUSY contribution to the invisible width of Z^0, which comes from $Z^0 \to \tilde{Z}_1, \tilde{Z}_1$, is smaller than 11.2 MeV at 95% C.L. [16-18]. This mainly excludes the region near $|\mu| \simeq 0$.

(v) We have assumed that the branching fraction for decays of Z^0 to visible neutralinos is smaller than 5×10^{-5}. The published results of the LEP experiments which are based on a sample of about 20 000 Z's exclude [19] such branchings at the level of a few $\times10^{-4}$. Since then, the sample of Z^0's has increased by almost an order of magnitude. Assuming SM backgrounds are still negligible, an estimate of 5×10^{-5} as the limit for this branching fraction should be conservative, especially if one combines the results of the various experiments.

The region of the $\mu - m_{\tilde{g}}$ plane excluded by these constraints is shown in Fig. 3 for $\tan\beta = 1.6$, 2, 3, 4, and 10 [20]. We see that for $\tan\beta > 3$ almost the whole range of gluino masses that is being explored at the Tevatron is already excluded by LEP measurements. It should, of course, be stressed that this is only within the framework of the MSSM, so that it is still crucial that gluinos be independently searched for at hadron collider experiments. The smallest value shown in Fig. 3 is of $\tan\beta = 1.6$. This is because smaller values of $\tan\beta$ yield a light Higgs scalar that would have been seen at LEP [2,10]. Hence, at present only Tevatron experiments can exclude the region $1.6 < \tan\beta < 3$ for $m_{\tilde{g}}$ up to ~ 150 GeV. This is why we did not vary $\tan\beta$ in Figs. 1 and 2.

It should, however, be stressed that in order to translate the bounds on the Higgs-boson mass to a limit on $\tan\beta$, one has to make use of tree-level mass relations for the Higgs sector of the MSSM. Recent calculations [21,22] have shown that if the top quark is heavy, radiative corrections involving the top-quark Yukawa coupling can substantially alter the light-Higgs-boson mass from its tree-level value so that the constraints on $\tan\beta$ may not be valid. It has been explicitly demonstrated [21] that both scalar-pseudoscalar Higgs-boson pair production and the Bjorken process may be unobservable at LEP if $m_t \gtrsim 160$ GeV even if $\tan\beta$ is close to unity. In this case, the invisible width constraint becomes ineffective since the coupling of Z to identical neutralinos vanishes. We have checked, however, that except for a small region near $m_{\tilde{g}} \simeq 0$, the excluded region is virtually identical to that for $\tan\beta = 1.6$, i.e. the decay $Z \to \tilde{Z}_1 \tilde{Z}_2$ effectively also excludes very small values of μ.

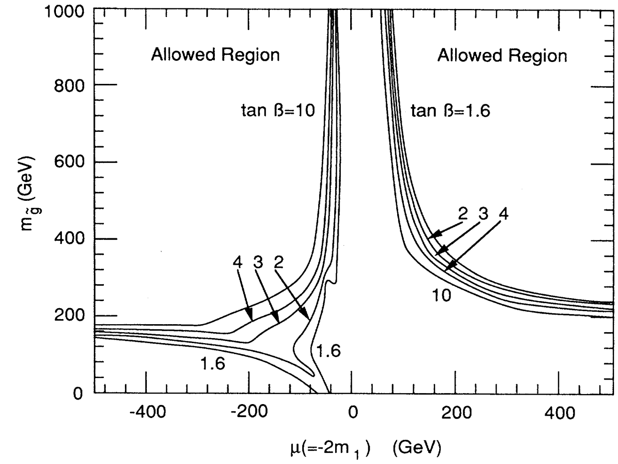

FIG. 3. The regions of the μ vs $m_{\tilde{g}}$ plane excluded by the LEP constraints described in the text, for various values of $\tan\beta$.

To summarize, we have examined how the new CDF bound on squark and gluino masses is altered when the various cascade decays of sparticles through loop and tree diagrams as predicted by the MSSM are incorporated into the analysis. We find a gluino as light as 135 GeV is allowed for $\tan\beta = 2$ if squarks are heavy. This, along with the other LEP constraints, translates to a bound of 18.8 GeV on the LSP mass [23]. For other squark masses, the CDF gluino mass bound is typically reduced by 10–30 GeV in the regions of parameter space not yet excluded by LEP data. The squark mass is typically reduced by ~ 15–20 GeV, unless the LSP is very massive, in which case there could be no bound at all.

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