Effect of Cascade Decays on the Fermilab Tevatron Gluino and Squark Mass Bounds

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The CDF (Collider Detector Facility) collaboration has recently announced limits on the masses of squarks and gluinos assuming that they decay directly to a massless lightest supersymmetric particle (LSP). We examine how these mass limits change when realistic squark and gluino decays to all gauginos are incorporated and the LSP mass is given by the minimal supergravity model. The gluino mass limit is diminished by 3–30 GeV as we vary the model parameters over their complete range. The squark mass limit is typically reduced by $\lesssim 10$ GeV if $m(\text{LSP}) \lesssim 20$ GeV.

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The CDF (Collider Detector Facility) experiment[1] at the Fermilab Tevatron $p\bar{p}$ collider has recently announced the lower limits

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

on the masses of gluinos and squarks—the supersymmetric partners of the gluon and quark. Although these limits are based on an analysis of just 25 nb^{-1} of data, they are already considerably better than the previously excluded values,[2,3]

$$\begin{aligned} &m_{\tilde{g}} < 53\ \text{GeV}, \quad m_{\tilde{q}} < 45\ \text{GeV}\ \ (\text{UA1});\\ &15\ \text{GeV} \le m_{\tilde{g}} \le 50\ \text{GeV},\\ &9\ \text{GeV} \le m_{\tilde{q}} \le 45\ \text{GeV}\ \ (\text{UA2}), \end{aligned} \tag{2}$$

obtained by the UA1 and UA2 experiments at the CERN S$p\bar{p}$S collider. It is clear that an analysis of the accumulated CDF data sample ($\int L\,dt \gtrsim 2$ pb^{-1}) should lead to a considerable improvement on the mass limit (1).

The mass bounds (1) and (2) are obtained from the nonobservation of missing-transverse-momentum ($\not{p}_T$) events over the expected background from standard-model sources. In these analyses, it is assumed that the gluinos and squarks always decay via

$$\tilde{g} \to q\bar{q}\tilde{Z}_1, \quad \tilde{q} \to q\tilde{Z}_1, \tag{3}$$

where $\tilde{Z}_1$, the lightest supersymmetric particle (LSP), is assumed to be a massless photino ($\tilde{\gamma}$) which escapes detection.

It has, however, been pointed out[4,5] some time ago that if squarks and gluinos are heavy enough to decay into charginos ($\tilde{W}_i$, $i=-,+$) and neutralinos other than the LSP ($\tilde{Z}_i$, $i=2,3,4$), these decays are likely to dominate the direct decays (3) to the LSP. (Henceforth, we refer to $\tilde{W}_-$ as $\tilde{W}$). The $\tilde{W}_i$ and $\tilde{Z}_i$ then decay into lighter charginos and neutralinos with the decay cascade terminating in the (stable) LSP. In this case, the transverse momentum carried by the LSP is degraded due to the cascade decay, so that the $\not{p}_T$ spectrum from gluino or squark pair production is softer than that expected from direct decays to the LSP. Since the mass bounds (1) and (2) are obtained from the nonobservation of events with large $\not{p}_T$, it is evident that these bounds are sensitive to the assumption (3) for the decays of the supersymmetric particles (SP's).

It was explicitly shown in Ref. 4 that within the framework of minimal supergravity models[6] (which we take as a guide to the SP masses and mixings) the cascade decays do not significantly alter the $\not{p}_T$ spectrum for the range of squark and gluino masses accessible at the CERN collider so that the bound (2) remains essentially unaffected.

The situation for heavier squarks and gluinos that may be produced at the higher-energy Tevatron is quite different as can be seen from the branching fractions for $\tilde{q}$ and $\tilde{g}$ decays that may be found in the literature.[7,8] For example,[7] the branching fraction for the decay $\tilde{g} \to q\bar{q}\tilde{Z}_1$ falls to about 0.5 for $m_{\tilde{g}} = 100$ GeV, while that for $\tilde{u}_L \to u\tilde{Z}_1$ ($\tilde{d}_L \to d\tilde{Z}_1$) is just 0.4 (0.1) for 100-GeV squarks. Since most of the diminution of the branching ratio into the LSP is due to decays into charginos (which do not couple to $\tilde{q}_R$) the LSP mode (3) still dominates $\tilde{q}_R$ decay over a wide range of parameter space. As the Tevatron is expected to probe squark and gluino masses up to ~ 150 GeV,[9] it is extremely important to include the non-LSP decays of $\tilde{q}$ and $\tilde{g}$ in the analysis. We stress that for the mass values being currently probed at the Tevatron, the cascade decay of gluinos and squarks is the rule rather than the exception, unless $|2m_1| \ll M_W$. This is reflected in our results of Fig. 1. A study of how these cascade decays affect the CDF bound (1) forms the subject of this Letter.

Toward this end, we have constructed parton-level Monte Carlo generators to simulate the final state from the pair production of gluinos and squarks, taking into account the CDF experimental cuts and triggers (described below) when (a) the squarks and gluinos are assumed to decay directly to a massless LSP as in (3), and

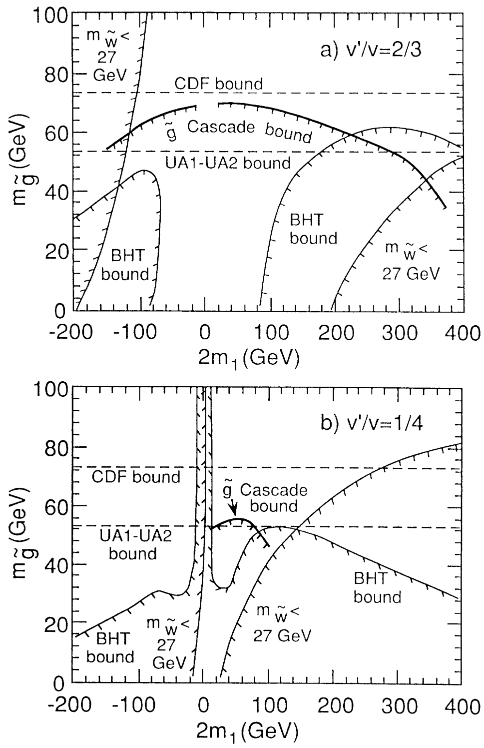

FIG. 1. (a) A plot of the gluino mass bound from CDF as a function of the Higgsino mass $2m_1$, for $v'/v=2/3$. The limit from direct decays to a massless LSP is shown as the dashed horizontal line. The region excluded by $e^+e^- \to \tilde{W}^+\tilde{W}^-$ is shown by the contour at $m_{\tilde{W}}=27$ GeV. The region excluded by the UA1 $m_L>41$ GeV limit applied to decays such as $W\to \tilde{W}\tilde{\gamma}$ is also shown, and is denoted by BHT (Ref. 10). We take $m_{\tilde{q}}=0.5$ TeV. (b) Same as above except $v'/v=1/4$.

(b) the cascade decays of the squarks and gluinos as well as all the SP masses given by the minimal model are incorporated into the generator. We then calculate the modified bound by requiring that the cross section after cuts from the cascade Monte Carlo simulation (b) be equal to the cut cross section from Monte Carlo simulation (a) when $m_{\tilde{g}}$ and $m_{\tilde{q}}$ are set equal to the CDF lower bound (1). For simplicity, we have focused on the two extreme cases $m_{\tilde{g}} \gg m_{\tilde{q}}$ and $m_{\tilde{q}} \gg m_{\tilde{g}}$ for which the limits (1) apply.

The construction of the event generator (b) requires a knowledge of all the allowed decay modes of the gluinos and squarks as well as the decays of the gauginos. The decays of squarks and gluinos have been studied in Refs. 4, 5, 7, and 8 where the relevant formulas may be found. The decays of the $\tilde{W}_i$ and $\tilde{Z}_i$ are discussed in detail in Refs. 7 and 11. For further discussion of these decays we refer the reader to the literature cited above.

In our Monte Carlo simulation of $\not{p}_T$ events from squarks and gluinos, we have attempted to simulate the CDF conditions via the following acceptance criteria:

(1) We coalesce partons within $\Delta R=(\Delta\eta^2+\Delta\phi^2)^{1/2}<0.7$ into single jets. We also require that all the jets satisfy $|\eta_j|<2.5$, 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

$$\not{E}_T > \max\left[40\ \text{GeV}, 2.8\times\left(\sum E_T\right)^{1/2}\right],$$

where $\sum E_T$ is the total scalar transverse energy in the event, including a soft-scattering E_T contribution.

Before turning to a presentation of our results, we briefly describe the model inputs that enter the calculation. The gluino[12] and squark[13] production cross sections are fixed by QCD and supersymmetry in terms of $m_{\tilde{g}}$ and $m_{\tilde{q}}$. Assuming a common gaugino mass at the unification scale, only three other parameters enter the calculation of the SP decays. In the notation of Ref. 7, we take these to be the supersymmetric Higgsino mass ($2m_1$), the ratio of the two Higgs-field vacuum expectation values (v'/v), and the charged-Higgs-boson mass, which we fix at $m_{H^+}=500$ GeV. Results are insensitive to variations in m_{H^+}.

We now turn to the computation of the change in the gluino mass bound (1) due to the cascade decays and the effect of $m_{\tilde{Z}_1}\neq 0$. For the relevant range of gluino masses considered here, the allowed decays are

$$\begin{aligned} &\tilde{g}\to q\bar{q}+(\tilde{W}, \tilde{Z}_2, \text{or } \tilde{Z}_1),\\ &\tilde{W}\to q\bar{q}\tilde{Z}_1 \text{ or } l\nu_l\tilde{Z}_1,\\ &\tilde{Z}_2\to f\bar{f}\tilde{Z}_1 \text{ or } H_l^0\tilde{Z}_1 \quad (f=q,l,\nu). \end{aligned} \tag{4}$$

We veto events containing leptons with $p_T>5$ GeV.

We first compute the cut cross section σ_0 assuming that the gluino always decays to a massless LSP for $m_{\tilde{g}}=73$ GeV, the CDF mass bound (1). We find $\sigma_0=385$ pb, which we take to be the CDF bound for the $\not{E}_T$ cross section with the cuts and triggers as described in the text.[14] Next, for each point in the three-dimensional parameter space $(m_{\tilde{g}}, 2m_1, v'/v)$ we generate gluino pair events incorporating the complete cascade decay of the gluino as well as experimental cuts. We then require that for all points in this parameter space $\sigma(\not{E}_T)<\sigma_0$ which for given values of $(2m_1, v'/v)$ gives us the gluino mass bound.

The dependence of the resulting gluino mass bound on the Higgsino mixing mass ($2m_1$) is shown by the solid line in Fig. 1(a) where we have fixed $v'/v=2/3$ and have taken $m_{\tilde{q}}$ to be large ($m_{\tilde{q}}=500$ GeV). The new bound is closest to the CDF bound at $2m_1\sim 100$ GeV, where it reaches $m_{\tilde{g}}=70$ GeV; at this point the branching fractions are all directly into $\tilde{Z}_1$, so the diminution of the CDF bound by 3 GeV is caused by the nonzero $\tilde{Z}_1$ mass (here, $m_{\tilde{Z}_1}=10$ GeV). Since $m_{\tilde{Z}_1}<10$ GeV for all values of $(2m_1, m_{\tilde{g}})$ considered here, it is clear that any substantial diminution of the CDF bound comes from the cascade decays and not the LSP mass, in accord with Ref. 15.

The largest deviation from the CDF limit occurs at $2m_1 \sim 340$ GeV, where a gluino as light as 44 GeV is allowed due to the large gluino branching into gauginos other than the LSP. The reduction of $\sigma(\not{p}_T)$ is dominantly due to the chargino decays of the gluino that depend on the SU(2) gauge coupling which is larger than the U(1) gauge coupling responsible for the $\tilde{g} \to \tilde{Z}_i$ decays. The percent reduction in the gluino mass limit for values of $m_{\tilde{q}}$ other than $m_{\tilde{q}} = 500$ GeV is comparable to the specific case we have chosen, as long as $m_{\tilde{g}} < m_{\tilde{q}}$.

We also plot the contour in $(2m_1, m_{\tilde{g}})$ space where the lightest chargino has mass equal to 27 GeV; below this mass, charginos would likely have been seen in experiments at the KEK e^+e^- collider TRISTAN,[16] which have already ruled out t quarks and heavy leptons with $m < 27$ GeV.

For very small values of $|2m_1|$ where $\tilde{Z}_1$ is almost a Higgsino, the decay $\tilde{g} \to q\bar{q}\tilde{Z}_1$ is strongly suppressed by the Yukawa coupling of $\tilde{Z}_1$ to the squark mediating the decay. In this case the gluino may decay via (a) $\tilde{g} \to q\bar{q}\tilde{Z}_2$ with the photinolike $\tilde{Z}_2$ decaying[17] via $\tilde{Z}_2 \to \tilde{Z}_1\gamma$, or (b) $\tilde{g} \to \tilde{Z}_1 g$ where this latter decay[18] is mediated by top-family loops (and so depends on m_t via the t-quark Yukawa coupling). If decay (a) dominates, then the $\not{p}_T$ spectrum is greatly diminished[19] and there is no bound on $m_{\tilde{g}}$. If the decay (b) is dominant, the $\not{p}_T$ spectrum is even harder than the spectrum from the decays of Eq. (3). In this case, the bound on $m_{\tilde{g}}$ may be even greater than the CDF bound. The gap in the solid curve near $2m_1 \simeq 0$ denotes the region where these uncertainties could make a significant difference in our analysis.

If the vector-boson decays $W \to \tilde{W}\tilde{Z}_1$ and $Z \to \tilde{W}^+\tilde{W}^-$ or $\tilde{Z}_2\tilde{Z}_1$ are allowed, then additional regions of the parameter space of Fig. 1 may be ruled out.[10] The UA1 limit[20] of $m_L > 41$ GeV on a sequential heavy lepton L can put constraints on the similar W decays to gauginos listed above. The region of $(2m_1, m_{\tilde{g}})$ space ruled out by lack of monojets primarily from the decay $W \to \tilde{W}\tilde{Z}_1$ is also shown in Fig. 1.

To illustrate the dependence of our analysis on variations in v'/v, we show the corresponding situation for $v'/v = 1/4$ in Fig. 1(b). The region of allowed parameter space is much smaller than in Fig. 1(a) because the chargino $\tilde{W}$ becomes lighter as v'/v deviates from unity.[21] This also results in increased branching fractions of the gluino to the gauginos other than the LSP. Hence, in this plot, the gluino mass bound is 20–30 GeV below the CDF result.

We now discuss the analysis of the bound $m_{\tilde{q}} > 74$ GeV which was obtained assuming $m_{\tilde{g}} \gg m_{\tilde{q}}$. In the class of models[6] that we are considering, it is very difficult to realize this limit since (except for D terms) $m_{\tilde{g}} \leq 1.2 m_{\tilde{q}}$. In order to compare with the CDF analysis, we have calculated the squark pair production total cross section assuming $m_{\tilde{g}} = \infty$, for which the bound (1) was obtained. However, the decays of the squarks are fixed by specifying the parameters $m_{\tilde{g}}$, $2m_1$, and v'/v, so that the specification of a squark event entails four parameters as opposed to just three for gluino pair events. Since it is impractical to scan the whole parameter space, and it is unrealistic to expect $m_{\tilde{g}} \gg m_{\tilde{q}}$ in any case, we present results for a selected variety of parameter choices.

We have obtained the modified squark bound by equating the $\not{p}_T$ cross section obtained using generator (a) with six squark flavors (as in Ref. 1) to that from the cascade decay generator (b). In the latter, we have excluded the top-squark contribution because its decays are qualitatively different from the decays of the other squarks. Our results are shown in Table I. For positive $2m_1$, the chargino is in general too heavy to allow substantial $\tilde{q} \to \tilde{W}, \tilde{Z}_2$ decays, and hence the reduction in mass bound is due mainly to the mass of the LSP. The squark mass bound disappears for $m_{\tilde{Z}_1} = 20$–25 GeV. We have mainly focused on negative values of $2m_1$. We have chosen parameters so that the LSP is relatively light and the chargino mass just satisfies the TRISTAN and UA1 bounds discussed above. This maximizes the effect of the cascade decays. We see that the reduction from the CDF bound is generally ~ 10 GeV, which is much smaller than when complete cascade decays are allowed in the gluino case. The reason for this is that $\tilde{q}_R$ does not couple to charginos, and so almost always decays directly to the LSP. The decay $\tilde{q}_R \to q\tilde{Z}_2$, unlike the chargino decay, proceeds via a U(1) coupling and so is small. As a result, over half the squark pairs decay directly to the LSP so that the effect of the cascade decays on the CDF bound is small. We note that the CDF bound would, of course, be further reduced as the LSP mass is increased. The percent reduction in the squark

TABLE I. A tabulation of selected parameters, LSP mass in GeV, allowable decay modes of squarks, and the resulting squark mass limit, also in GeV. We have assumed here $m_{\tilde{g}} = \infty$.

$m_{\tilde{g}}$ (GeV)	$2m_1$	v'/v	m(LSP)	$\tilde{q} \to$	$m_{\tilde{q}} >$
200	200	0.67	28.3	$\tilde{Z}_1$	No limit
200	50	0.67	29.4	$\tilde{Z}_1, \tilde{Z}_2$	No limit
200	−300	0.67	11.2	$\tilde{Z}_1, \tilde{Z}_2, \tilde{W}$	65
400	−130	0.67	12.3	$\tilde{Z}_1, \tilde{W}$	65.5
750	−75	0.67	15.8	$\tilde{Z}_1, \tilde{W}$	65
300	−120	0.25	15.2	$\tilde{Z}_1, \tilde{W}$	64
500	−75	0.25	16.6	$\tilde{Z}_1, \tilde{W}$	64.5
∞	CDF	bound	0	$\tilde{Z}_1$	74

mass limit for values of $m_{\tilde{g}}$ other than $m_{\tilde{g}}=\infty$ is comparable to our chosen case, as long as $m_{\tilde{q}} < m_{\tilde{g}}$, and the LSP mass remains fixed.

In summary, we have studied how the CDF bounds (1) depend on the assumption that squarks and gluinos can only decay to a massless LSP. Our results, with realistic decays as given by the minimal supergravity model, are summarized in Fig. 1 and Table I. The reduction in the gluino limit can be as large as over 30 GeV while the reduction in the squark case is generally smaller than 10 GeV, unless the LSP is very heavy (~20–25 GeV).

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