Constraints on light gluinos from Fermilab Tevatron dijet data

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The effects of light, long-lived gluinos on $2\to 2$ processes at hadron colliders are examined. Such particles can mediate single squark resonant production via $q\tilde{g}\to\tilde{q}\to q\tilde{g}$ which would significantly modify the dijet data sample. We find that squark masses in the range $130< m_{\tilde{q}}<694,595,573$ GeV are excluded for gluino masses of 0.4,1.3,5.0 GeV from existing UA2 and Fermilab Tevatron data on dijet bump searches and angular distributions. Run II of the Tevatron has the capability of excluding this scenario for squark masses up to $\sim$1 TeV. [S0556-2821(97)02021-3]

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Supersymmetry is a compelling candidate for physics beyond the standard model (SM) and has engrossed both the theoretical and experimental communities. Most of the attention has been focused on the minimal version of supersymmetry (MSSM); however, many other incarnations of supersymmetry could exist. In most cases these nonminimal models can significantly alter supersymmetric phenomenology and the associated search strategies, and hence all consequences of such models must be examined before regions of supersymmetric parameter space can be positively excluded. Here, we examine one such nonminimal case: the light gluino scenario. In some models it is natural [1] for gluinos to be much lighter than, e.g., squarks, if they acquire their masses radiatively. While several experiments presently cast doubt on the existence of the low-mass gluino window ($m_{\tilde{g}}\lesssim 5$ GeV), it has yet to be conclusively ruled out (or verified). In fact, the experimental bounds on this possibility are surprisingly spotty and controversial as evidenced by the continual debate in the literature [2]. It is thus imperative to examine all implications of this hypothesis in order to quell this dispute. In this work, we investigate an additional data sample which provides strong constraints on the light gluino scenario, namely $2\to 2$ processes at high-energy hadron colliders.

The window for a very light gluino was pointed out [3] many years ago and its effects have since been analyzed in a variety of processes. A resurgence of interest in this scenario surfaced with the relatively recent observation [4] that an apparent discrepancy between the value of α_s measured from jet production at SLAC Large Detector (SLD) and CERN e^+e^- collider LEP and that discerned from low-energy data is resolved by the slower running of α_s in the presence of light gluinos. However, recent compilations [5] of various determinations of α_s no longer show evidence of such a discrepancy, within the errors, but also claim that the precision of each individual measurement is such that any anomalous effect up to the $\sim$5% level may not be perceived. The most noticeable consequence of this model is that the standard signals for gluino and squark production are modified in the presence of light gluinos. The bounds on the gluino mass, $m_{\tilde{g}}>144-224$ GeV from the Fermilab Tevatron [6] (with the range being due to the assumed relative sizes of the squark and gluino masses), are invalidated in this case as they depend on the fact that the $\tilde{g}$ is short lived and decays with the characteristic missing energy signature. Thus to be light, gluinos must be long lived and appear to hadronize as jets. Since they are unable to appear as free particles, light gluinos will indeed form hadrons, with the bound states having longer lifetimes, and fragment in such a way as to mimic jets in a high-energy detector [7]. If kinematically allowed, the gluino hadrons will eventually decay into a final state containing jets $+\chi_1^0$, where χ_1^0 is the lightest neutralino. The crucial ingredient for detection is then the ability of the final state χ_1^0 to pass the detector's missing energy cuts, which depends, amongst other things, on how the $\tilde{g}$ hadron fragments. It has been estimated [8] that for $m_{\tilde{g}}\gtrsim 5$ GeV the $\tilde{g}$ would have been detected at UA1. However, as the gluino mass decreases, the missing energy signal disappears altogether. Standard squark searches are also nullified in this model as now the primary decay is $\tilde{q}\to q\tilde{g}$, which again, escapes searches based on missing energy. In this case, the squark mass bounds are reduced to $m_{\tilde{q}}>M_Z/2$, with the mass constraint being extended to 50–60 GeV from precision electroweak measurements at SLC and LEP [9]. We expect LEP II to strengthen the squark mass bound to $\gtrsim$80–85 GeV.

We now discuss the results from a variety of light gluino searches. At present, the least controversial bound on light gluinos is from a search by CUSB [10] for radiative Υ decays into bound states of gluinos. They exclude the mass range $\sim$1.5–3.5 GeV (regardless of the gluino lifetime), where the lower limit is approximate due to questions [11] concerning the validity of perturbative QCD in this regime. ARGUS [12] looked for secondary vertices from $\chi_b\to g\tilde{g}\tilde{g}$ with a subsequent decay of the gluino bound states and constrained a small region in the gluino-mass–lifetime parameter space; these results, however, also suffer [2] from per-

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turbative QCD uncertainties as well as those from fragmentation effects. Beam dump experiments [13] have looked for secondary vertices from the decay of $\tilde{g}$ hadrons and appear to disfavor light gluinos for restricted regions of the gluino lifetime, but these results depend on (i) assumptions on the production cross sections of the gluino hadrons, (ii) the value of the squark mass, (iii) the interactions of the lightest color-singlet supersymmetric particle χ_1^0 with the detector, and (iv) $\tilde{g}$ fragmentation effects and decay models. Searches for new neutral particles at Fermilab exclude [14] $2<m_{\tilde{g}}<4$ GeV for $\tilde{g}$ lifetimes in excess of 10^{-7} s. Jet angular distributions of decays of the Z into four jets and precision measurements of the QCD structure constants $C_{A,F}$ and T_F have been shown to be particularly sensitive to the existence of light gluinos [15], but critically depend [16] on currently uncalculated higher-order QCD corrections and hence no firm conclusions can presently be drawn. The Z boson can decay into two gluinos, however the branching fraction is small [17] ($B\sim 0.06\%$), and would be hidden underneath ordinary QCD events. The detection of light gluinos at the DESY ep collider HERA, through their effect on deep-inelastic structure functions [18] or via their production in the 3+1 jet photoproduction cross section [19], have also been shown to be difficult.

In this study, we examine the effects of light, long-lived gluinos on dijet production in hadronic collisions. One would expect the influence of light $\tilde{g}$'s to be large in such processes since they contribute at leading order in perturbation theory. It has been shown [20], however, that competing effects tend to suppress their impact on the single-jet inclusive E_T spectrum. Nonetheless, we find that the influence of resonant squark production from the subprocess $q\tilde{g}\to\tilde{q}\to q\tilde{g}$ should not be neglected as it greatly modifies the dijet mass spectrum and places strong constraints on the light gluino window. Our conclusions avoid some of the aforementioned difficulties in constraining this scenario, as nonperturbative QCD effects are negligible at the energies considered here and our results are insensitive to a long $\tilde{g}$ lifetime. The essential ingredients of this model for our analysis are (i) the evolution of α_s is modified by the inclusion of light gluinos in the QCD β function, (ii) long-lived gluinos in the final state hadronize as jets, and (iii) light gluinos contribute a non-negligible partonic content of the proton. This introduces several new 2→2 parton scattering processes, as well as modifying the Altarelli-Parisi evolution of the parton densities. Global fits of structure functions which include a light gluino distribution have been performed [18], and it has been found that the next-to-leading-order (NLO) $\tilde{g}$ parton distributions are roughly three (five) times larger than that of the strange quark at large (small) x for very light gluinos, $m_{\tilde{g}}\lesssim 1.5$ GeV, and carry $\sim 5\%$ of the proton's momentum fraction at large Q^2 for $m_{\tilde{g}}=5$ GeV.

We now proceed with our calculations. All 2→2 subprocesses have been evaluated; they naturally fall into three categories, (i) those of the SM, $qq\to qq$, $q\bar{q}\to q\bar{q},gg$, $qg\to qg$, and $gg\to q\bar{q},gg$, (ii) all SM initiated 2→2 processes with final-state gluinos, $q\bar{q},gg\to\tilde{g}\tilde{g}$, and (iii) all gluino-initiated processes $q\tilde{g}\to q\tilde{g}$, $g\tilde{g}\to g\tilde{g}$, and $\tilde{g}\tilde{g}\to gg,\tilde{g}\,\tilde{g}$. Note that resonant squark production appears in the latter set. Higher-order 2→3 processes, including the new reactions [21] which produce $\tilde{q}$+jet and thus yield three-jet final states once the squark decays, have not been included. The mass of the light gluino has also been neglected in the evaluation of the subprocess cross sections as the results should not be sensitive to $m_{\tilde{g}}$ at the energy scales considered here. The parton distributions (PDs) [18] of Rückl and Vogt have been used for $m_{\tilde{g}}\lesssim 1.5$ GeV and those of Roberts and Stirling for $m_{\tilde{g}}=5$ GeV. These values of the gluino mass avoid all of the experimental constraints detailed above. The change in the evolution of α_s has been taken into account by fixing $\alpha_s(M_Z)$ to the world average value [2] and then running it to the relevant scale using the appropriate two-loop β functions. We note that the three-loop light $\tilde{g}$ β functions have only recently been determined [22].

In principle there is an ambiguity associated with a heavy parton in the initial state that subsequently appears also in the final state, such as the gluino in the present calculation. This arises from the treatment of the gluino as an independent initial-stage parton or as one that is generated by an initial-state gluon which splits into a gluino pair. Stated another way, in addition to the $q\tilde{g}\to q\tilde{g}$ process where the $\tilde{g}$ is associated with a PD, there is also the process $qg\to\tilde{g}\tilde{g}q$ where the initial g splits to $2\tilde{g}$ one of which scatters with the q. This situation has been addressed in the literature for the case of heavy quarks, such as c or b, and the treatment applied there should be applicable here as well [23]. The result of these considerations is that in the limit where the scale $\mu^2=p_T^2(M^2)$ is far greater than $m_{\tilde{g}}^2$, as is the case in the present analysis due to the cuts we apply, the treatment of the $\tilde{g}$ as an independent initial-state parton described by a PD provides a very accurate result for the cross section which improves as the above condition is better and better satisfied.

In evaluating the squark resonance contribution to the cross section, we have used the narrow width approximation, which is valid for $\Gamma/m\lesssim 0.1$ and hence is reliable in this case. We have included a 10% contribution to the squark width for potential nondijet decays, i.e., $\Gamma_{\tilde{q}}=1.1\times\Gamma(\tilde{q}\to q\tilde{g})$. This is conservative as dijet decays will be by far the dominant mode. The 10% figure should cover the additional weak decays $\tilde{q}\to q\chi_{1-4}^0$ and $\tilde{q}\to q\chi_{1,2}^{\pm}$, whichever are kinematically allowed, as they are expected to have small branching fractions of order $\lesssim$1–2 % each and hence are suppressed compared to the dijet mode. However, QCD corrections to the squark decay width are large [24], and may modify our estimate of the nondijet decay fraction. If we alternatively assume an arbitrary value for this quantity in the 0–30 % range the resulting limits that we have obtained below are only modified by a few GeV at either end of the allowed ranges. We note that monojet signals from squark production in this scenario have been previously analyzed [25]. We have also assumed that there are five degenerate squarks, with equal masses for the left- and right-handed states. Our results are not dependent on this assumption, however, as the contribution of each squark flavor to the resonance peak is weighted by the corresponding quark's parton density. Hence this supposition does not simply result in an overall multiplicative factor to the cross section. In fact, the charm and bottom squarks have essentially negligible contributions to the resonance peak.

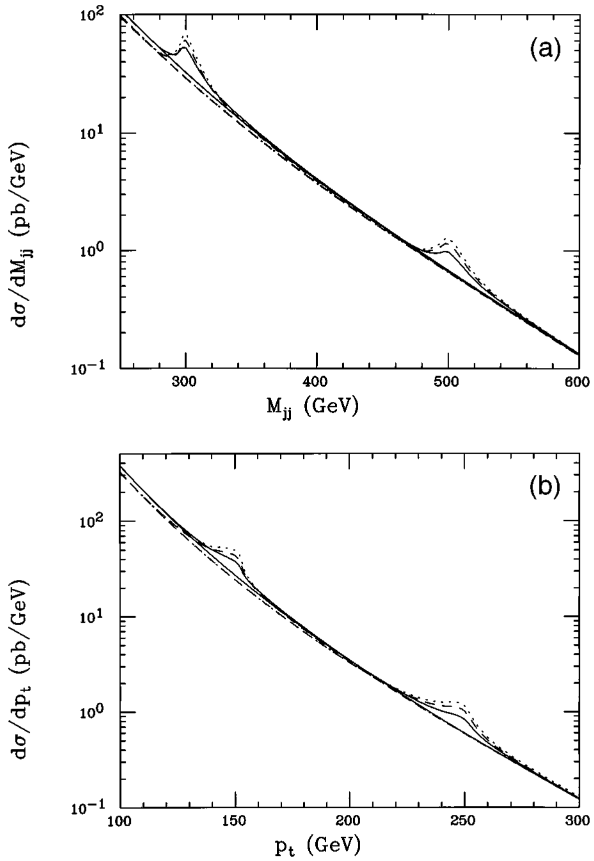

FIG. 1. The (a) dijet invariant mass and (b) single-jet inclusive p_T distributions for the $2\to 2$ processes described in the text for the two cases $m_{\tilde{q}}=300$ and 500 GeV. The gluino mass is taken to be 0.4, 1.3, and 5.0 GeV corresponding to the dotted, dashed, and solid curves, respectively.

Experimentally, the dijet system consists of the two jets with the highest transverse momentum in the event. In all cases, except where noted, we apply the cuts used by the Collider Detector at Fermilab (CDF) Collaboration [26] in their dijet analyses. This corresponds to $p_{T_j}>20$ GeV, $|\eta_{1,2}|<2$, where $\eta_{1,2}$ are the pseudorapidities of the two leading jets, and $|\cos\theta^*|\leq 2/3$, with θ^* being the parton-parton scattering angle in the center-of-mass frame. Following CDF, we evaluate these processes at the scale $\mu=p_T$. In Fig. 1 we display the dijet invariant mass and single-jet inclusive p_T distributions for the cases of $m_{\tilde{q}}=300$ and 500 GeV, taking $m_{\tilde{g}}=0.4$, 1.3, and 5 GeV corresponding to the dotted, dashed, and solid curves, respectively. In the case of the p_T distributions, we assume $|\eta_{1,2}|<0.5$, $\mu=p_T/2$, and no angular cuts are applied. We see that the resonance peaks stand out for all values of the gluino mass. Note the degradation of the cross section as the $\tilde{g}$ mass increases.

We now evaluate the dijet resonance cross section and compare it to searches for dijet mass peaks from the single production of new particles performed by hadron collider experiments [26–28]. Figure 2 presents the single-squark production cross section in the dijet channel as a function of the squark mass for various values of $m_{\tilde{g}}$. Also displayed in the figure (dotted curve) is the upper limit on the production of dijet resonances at (a) UA2 [27] at 90% C.L., as well as

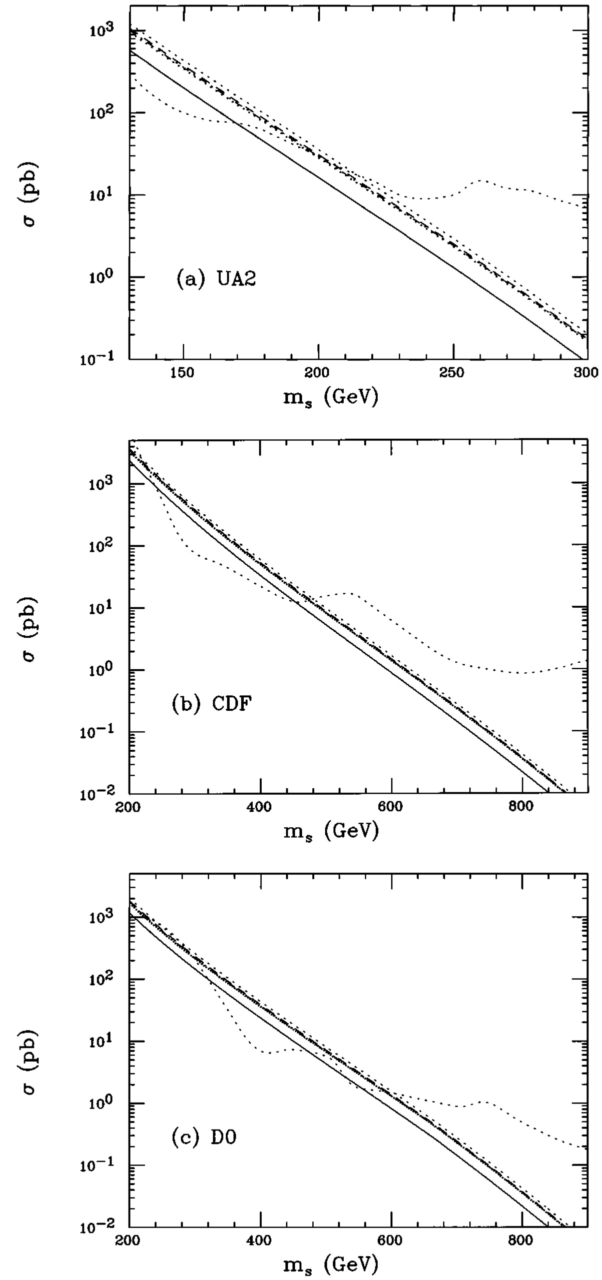

FIG. 2. Comparison of the single-squark production cross section in the dijet channel as a function of the squark mass with $m_{\tilde{g}}=0.4$, 0.7, 1.1, 1.3, and 5.0 GeV (straight curves, dotted, dashed, dash-dotted, square-dotted, and solid from top to bottom, respectively) with the upper bound for the production of new dijet mass resonances from (a) UA2 at 90% C.L., (b) CDF, and (c) D0 at 95% C.L. (dotted curves).

both (b) CDF [26] and (c) D0 [28] at the 95% C.L. In the D0 case the applied cuts are somewhat different than those employed by CDF: $|\eta_{1,2}|<1$ and $|\eta_1-\eta_2|<1.6$. We see that the three experiments combine to exclude substantial regions of the light gluino parameter space. The ranges of the squark masses which are ruled out for each value of $m_{\tilde{g}}$ are summarized in Table I. We do not expect the bounds to drastically improve as $m_{\tilde{g}}\to 0$ as the squark resonance cross section is not appreciably changing as the gluino mass decreases (once $m_{\tilde{g}}\lesssim 1.5$ GeV) as shown in Fig. 2. A short analysis shows that the cross section for massless gluinos is approxi-

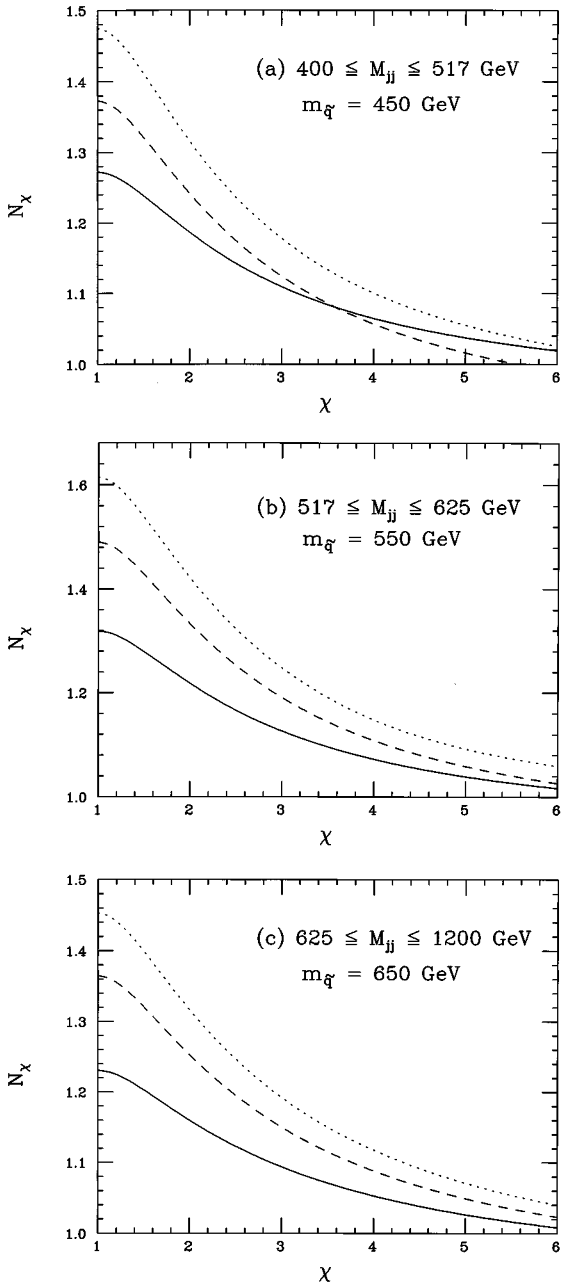

FIG. 3. The ratio $N_\chi \equiv (d\sigma/d\chi|_{\tilde{g}})/(d\sigma/d\chi|_{\rm SM})$ as a function of χ with gluino masses of 0.4, 1.3, and 5 GeV, corresponding to the dotted, dashed, and solid curves, respectively. The dijet invariant mass bins and assumed squark masses are as labeled.

mately 1.3 (1.6) times larger than that for the case of $m_{\tilde{g}} = 0.4$ GeV at low (high) dijet invariant masses.

Dijet angular distributions are a well-known test of QCD and probe of new physics and have recently been measured

TABLE I. The squark mass regions in GeV excluded by the searches for dijet resonances by the UA2 (at 90% C.L.), CDF and D0 (at 95% C.L.) Collaborations for an assumed gluino mass.

$m_{\tilde{g}}$	$m_{\tilde{q}}$ (UA2)	$m_{\tilde{q}}$ (CDF)	$m_{\tilde{q}}$ (D0)
0.4–1.3	130 to 195–220	220–475	310–590
5.0	130–170	240–455	320–460

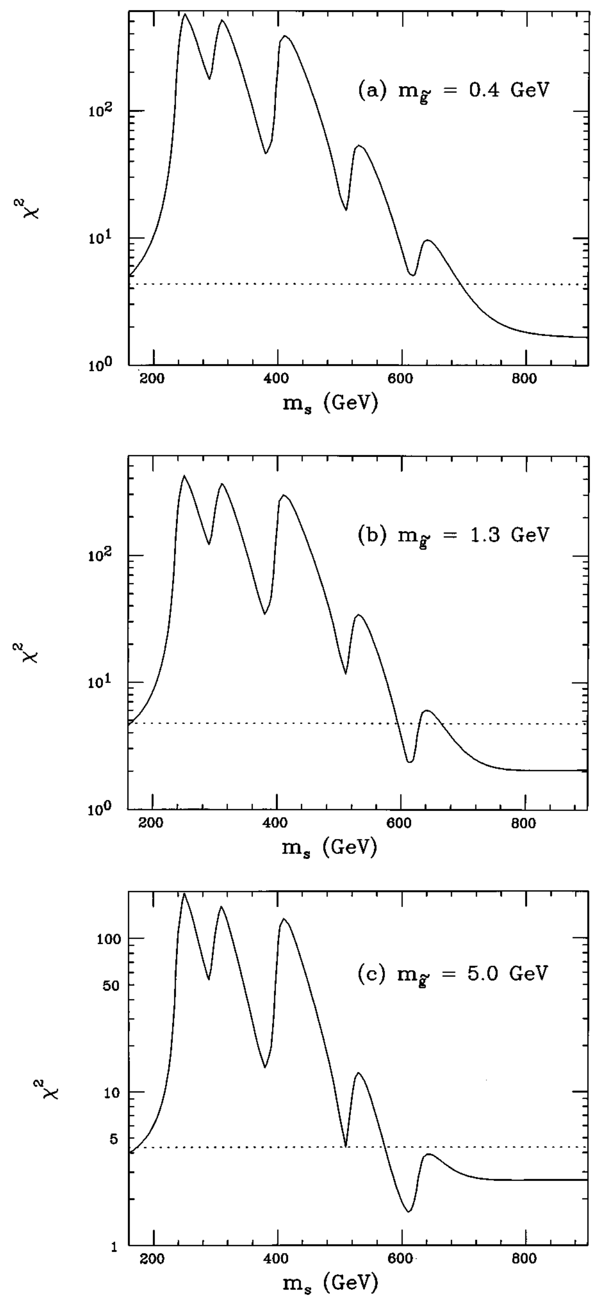

FIG. 4. χ^2 distributions as a function of the squark mass following the analysis described in the text, assuming gluino masses of (a) 0.4 GeV, (b) 1.3 GeV, and (c) 5 GeV. The dotted horizontal line represents the 95% C.L. bound in each case.

at the Tevatron [26,28]. Ordinary QCD processes have large t- and u-channel poles and are thus peaked in the forward direction, whereas, resonant squark production in the light gluino model will have a flat distribution due to the spin-0 nature of the squark. A convenient angular variable to use is $\chi \equiv \exp(|\eta_1 - \eta_2|)$. For the case of $2 \to 2$ parton scattering, this is related to the center-of-mass scattering angle as $\chi = (1 + |\cos\theta^*|)/(1 - |\cos\theta^*|)$. $\chi = 1$ then corresponds to $\cos\theta^* = 90°$. As is well known [29], the advantage of the χ variable is that it removes the apparent singularities associated with the t- and u-channel poles present in QCD. Thus $d\sigma/d\chi$ shows greater sensitivity to new physics which does not possess such poles than does $d\sigma/d\cos\theta^*$. $d\sigma/d\chi$ also has the additional advantage that in its normalized form (as we will use it here) it is quite insensitive to NLO corrections as is emphasized in the CDF analysis [26]. In particular, in their Fig. 1 they directly compare the LO and NLO expectations for this normalized distribution in various dijet mass bins. To show the influence of the production of squark resonances on this distribution we display in Fig. 3 the ratio of $d\sigma/d\chi$ calculated in the light gluino model to that of the SM, i.e., $N_\chi \equiv (d\sigma/d\chi|_{\tilde{g}})/(d\sigma/d\chi|_{\mathrm{SM}})$, for three dijet invariant mass bins (as chosen by CDF [26]) assuming a $\tilde{q}$ resonance lies within each bin. In calculating the SM distributions, we employed the Martin-Roberts-Stirling set A′ (MRSA′) parton densities [30]. In all cases, we see that squark production leads to an enhancement in the distribution at low values of χ compared to the SM. This would result in an increase in the dijet rate near 90°. Comparison with the corresponding figures presented by CDF [26] shows that this rise in $d\sigma/d\chi$ would be easily observable so that squarks with the masses chosen here could be excluded.

We now make this procedure more rigorous in order to determine if the angular distributions can extend the excluded regions listed in Table I. Following the procedure used by CDF [26], we employ the variable $R(\chi) \equiv N(\chi < 2.5)/N(2.5 < \chi < 5)$, which is the ratio of the number of dijet events in the two ranges of χ, for the five mass bins $241 < M_{jj} < 300$, $300 < M_{jj} < 400$, $400 < M_{jj} < 517$, $517 < M_{jj} < 625$, and $625 < M_{jj}$ GeV. As emphasized in the CDF analysis [26], this variable has the advantages that it is not very sensitive to variations in the parton densities, to the choice of renormalization scale (e.g., $\mu = p_T$ versus M_{jj}), or to next-to-leading-order QCD corrections, and that it characterizes the shape of the angular distribution in a mass bin with a single number. This is explicitly demonstrated by the CDF results shown in Fig. 2 of their paper [26]. We have incorporated the systematic errors, as determined by CDF, as well as the statistical errors in our analysis. The systematic errors are highly correlated, and we have reconstructed the full covariance matrix according to the prescription in Ref. [26]. We then calculate $R(\chi)$ in each M_{jj} bin with $m_{\tilde{g}} = 0.4$, 1.3, and 5 GeV for squark masses in the range 160–800 GeV, and perform a fit to the CDF results using their data and correlation matrix. Following the usual χ^2 analysis procedure, we find the minimum value of χ^2 for a given value of $m_{\tilde{g}}$ and then determine the excluded range of $m_{\tilde{q}}$ by examining the χ^2 distribution as a function of the squark mass. For definiteness we perform a LO calculation taking the scale $\mu = p_T$. Our results are presented in Fig. 4 for each assumed value of the gluino mass. Note that the χ^2 minima are generally found in the limit of very large squark masses. In all cases the χ^2 distributions display a similar shape with five peaks which are associated with the five mass bins used by CDF and are due to the fact that the greatest sensitivity to a squark resonance occurs when it coincides in mass with the lower end of a given bin, i.e., when the squark cross section is maximum. To be more specific, when $m_{\tilde{q}}$ is light (<241 GeV) and outside the dijet mass region examined by CDF, the χ^2 is small but increases as the squark mass gets closer to the edge of lowest mass bin and then peaks once the bin is entered. The sensitivity then decreases as $m_{\tilde{q}}$ approaches the high end of the mass bin. As the value of $m_{\tilde{q}}$ rises there is a general loss in sensitivity due to decrease in statistics and the corresponding increase in the size of the errors.

This analysis excludes at the 95% C.L. the $m_{\tilde{q}}$ ranges 151–694, 166–595, and 172–573 GeV for $m_{\tilde{g}} = 0.4$, 1.3, and 5 GeV, respectively. It thus both extends and complements the constraints obtained from the dijet peak searches. Here, we might expect improvements on these constraints for $m_{\tilde{g}} \to 0$ due to the increased enhancement in N_χ at $\chi = 0$. Lastly, as a test of possible scale dependence and/or the influence of NLO contributions, we have repeated the entire R_χ analysis now assuming that $\mu = M$ instead of $\mu = p_T$. We find that the exclusion regions are now given by $\simeq$160–605(598,565) GeV for $m_{\tilde{g}} = 0.4(1.3,5)$ GeV, respectively. This shows that our results are not very scale dependent and are not sensitive to NLO contributions as we expected.

Combining these results with the bounds from the resonance searches excludes squark masses in the range $130 < m_{\tilde{q}} < 694,595,573$ GeV for gluino masses of 0.4,1.3,5.0 GeV.

In summary, we have examined the constraints on models with light gluinos by using both the cross section and angular distribution for dijet events observed at hadron colliders. The critical observation is that a light gluino can act as a partonic component of the proton thus leading to the resonant production $q\tilde{g} \to \tilde{q} \to q\tilde{g}$, provided the $\tilde{q}$ is sufficiently light. From our analysis, it would appear that the survival of the light gluino case requires either a light $\tilde{q}$ in the $\sim$70–130 GeV range, or a heavy $\tilde{q}$ with $m_{\tilde{q}} \gtrsim 600$–700 GeV. From studies of the physics capabilities at run II of the Tevatron [31], we anticipate that this future data will be able to exclude or verify this model for squark masses up to $\sim$1 TeV. High-energy hadron colliders may thus provide the best testing ground for this scenario.

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