Abstract

We consider the effects of a light gluino on the dijet angular distributions in $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV. We show that the slower running of $\alpha_s$ and the production $q\bar{q}, gg \rightarrow \tilde{g}\tilde{g}$ do not significantly alter the normalized differential cross-sections. On the other hand, single $\tilde{u}, \tilde{d}$ squark production $qg \rightarrow \tilde{q}\tilde{g}$ with subsequent $\tilde{q} \rightarrow q\tilde{g}$ results in dijets whose angular distributions are dramatically different from that in SM. The CDF data on dijet angular distributions with integrated luminosity of $106\text{pb}^{-1}$ exclude $\tilde{u}$ and $\tilde{d}$ squarks in the mass ranges $150 \leq m \leq 650$ and $170 \leq m \leq 620$, respectively. We consider lower energies as well and show that in a future experimental analysis for dijet mass below 240 GeV squarks could be observed or ruled out.
In recent years, many theoretical proposals beyond the Standard Model have been developed; however, Supersymmetry (SUSY) remains one of the best motivated and attractive models. Extensive experimental searches for SUSY have imposed numerous constraints on allowed mass ranges for the super-particles, most of the effort being concentrated within the framework of the Minimal Supersymmetric Standard Model (MSSM). However, theoretical arguments have been made in favor of certain special variants, most notably, the light gluino scenario where gluino and photino are much lighter than squarks and, in fact, are (nearly) massless ($\leq 5\text{GeV}$). The idea acquired a particular interest with the emergence of the discrepancy between the measurements of the strong coupling constant at low energy and at the $M_Z$ scale. The contribution of a neutral colored fermion, such as a light gluino, into the $\beta$-function would slow the $\alpha_s$ running so as to improve the agreement appreciably [1]. Although recent studies have reported a diminished discrepancy [2] and thus necessitate the light gluino to a lesser extent, the possibility remains appealing.

The experimental low mass window for gluino was first pointed out by the UA1 collaboration [3]. A number of other experiments attempted to search for a light gluino as well; these include beam dump experiments [4], searches for new neutral particles [5], and radiative Upsilon decay [6]. Many claimed to have narrowed down the allowed window dramatically. Farrar, however, has provided a critical review of these experiments [7] and indicated that most analyses mentioned therein had to make assumptions on gluino decay modes or rely on non-perturbative effects so their claims had to be weakened. The allowed region in the gluino mass and lifetime space was given. Occasionally, the results of [7] are considered liberal in the literature, but they are particularly interesting due to the possibility of a gluino that is ultra-light ($\leq 1\text{ GeV}$). Such a particle would have to be long-lived, that is, would not decay before interacting hadronically in a detector or beam dump. Possible missing energy from a gluino weak decay would therefore be negligible so the canonical SUSY searches would have been incapable of detecting it.

Clearly, a low mass long-lived gluino implies a dramatically different phenomenology. It is expected to form hadrons such as $R^0$ [7, 8] which in turn result in jets in the detector. Consequently, it may be the jet physics where SUSY with the light gluino is discovered. Remarkably, such phenomenology has
distinct advantages. The principal part of the calculations is perturbative, the resulting cross-sections depend insignificantly on the gluino mass, and many predictions do not depend on the details of gluino fragmentation. In the present work, we will continue to study light gluino implications for collider jet physics.

Last year Fermilab announced the observation of an excess of high transverse energy jet events in $p\bar{p}$ collisions\[9\]. Here the light gluino, mostly due to the effect on the $\alpha_s$ running, was shown to be able to alleviate the discrepancy noticeably\[10, 11\], although not to fully account for it. At the same time, several possible suggestions were made within the framework of standard QCD, mostly regarding parton density functions (pdf's)\[12\]; finally, the CTEQ collaboration has presented a set of updated pdf’s\[13\] with inclusive jet $E_T$ experiments incorporated into the analysis, and the overall consistency of the Standard Model has thereby been restored. The new fits required a significant modification of the gluon pdf and ignoring a fair amount of low $E_T$ data, which may certainly be justified given both theoretical and experimental difficulties in the low energy region\[13\]. However, the agreement with the CDF data, including the low $E_T$ region\[4\] is better with the light gluino than without it\[10\]. Since in addition to ordinary partons a light gluino sea must be present in hadrons\[14, 15\], it would be interesting to incorporate the Tevatron $E_T$ data into developing a set of pdf’s with the light gluino.

Other jet experiments are more sensitive to the low mass gluino. In this scenario, a single squark can be readily produced via $qg \rightarrow \tilde{q} \tilde{g}$; see\[10\] for the cross-section as a function of squark mass. The subsequent decay $\tilde{q} \rightarrow q \tilde{g}$ results in a pair of jets an invariant mass close to $m_{\tilde{q}}$. The jet experiments deal with dijets, which are defined as the pair of jets with the highest $p_T$ in the event subject also to other selection criteria\[13, 14\]. Based on the early CDF dijet mass distribution data sample of 19pb$^{-1}$\[8\], it was possible to exclude $\tilde{u}, \tilde{d}$ squarks between 330 and 440 GeV at 95% CL\[16\]. In a recent similar analysis of\[20\], the excluded region has been extended down to 220 GeV and up to 475 GeV. In the present paper, we address the impact of single squark production on the distribution of dijet cross-section in the center of mass scattering angle $\theta^*$. It should be noted that the work\[21\] studies the dijet angular distributions as well. However, the previous analysis relies on the gluino pdf and considers the $2 \rightarrow 2$ process $q\bar{g} \rightarrow \tilde{q} \rightarrow q\tilde{g}$. Since the gluino

\[2\] The D0 collaboration has not presented its low energy data.
sea is due to the $\tilde{g}\tilde{g}$ vertex, all gluino initiated processes can be conceived of as part of the respective gluon initiated processes, where the gluino momentum is restricted to be parallel to the proton beam. Hereinafter we present a complete treatment of the $2 \rightarrow 3$ process $qg \rightarrow \tilde{q}\tilde{g}q$, where $q = u, d$.  

In the standard QCD, the jet (and dijet) angular distribution is sharply peaked in the forward direction due to the t-channel exchange of a (nearly) massless parton. In SUSY with light gluino, several new effects are added. The modification of $\alpha_s$ running is expected to be relatively unimportant as the pattern of dijet angular distribution is roughly the same for the whole energy range involved. Two more processes of a gluino pair production must also be considered: $q\overline{q}, gg \rightarrow \tilde{g}\tilde{g}$; but again, the situation is not expected to change qualitatively as the resulting picture will be largely determined by the still massless t-channel gluinos. On the other hand, the production of almost any heavy particle which decays somewhat isotropically in its rest frame, such as a squark, flattens the observed jet angular distribution and can be sensed even with a small production cross-section.

Recently, CDF presented the $106\text{pb}^{-1}$ data sample on the dijet angular distribution measurements $^{19}$. Instead of $\cos \theta^*$, a more convenient variable $\chi \equiv (1 + |\cos \theta^*|)/(1 - |\cos \theta^*|)$ was used for differential cross-sections as $d\sigma/d\chi$ is relatively flat for background processes. Here $\cos \theta^*$ is actually defined through the observable jet pseudorapidities as $\tanh \frac{\eta_a - \eta_b}{2}$ and has a meaning of cosine CMS scattering angle only for a pair of jets with balanced $p_T$. New processes with flatter $d\sigma/d\cos \theta^*$ would result in an excess of low $\chi$ ($\approx 1$) events. It is important to note that the normalized cross-section $(1/\sigma_{tot})d\sigma/d\chi$ has little sensitivity to higher order corrections and the scale at which pdf’s and $\alpha_s$ are evaluated $^{19}$.

We evaluate the squared amplitude for $qg \rightarrow \tilde{q}\tilde{g}q$ $^{16}$ and perform a multidimensional Monte-Carlo integration over the phase space. In computing the $\chi$ for an event we select the two highest $p_T$ jets and use the CDF pseudorapidity cuts $|\eta_{a,b}| < 2.17$, as well as constrain the dijet invariant mass to the same mass bins as in $^{19}$. We take the squark width to be $\Gamma(\tilde{q} \rightarrow q\tilde{g}) = 2/3\alpha_s m_{\tilde{q}} \approx \Gamma_{tot}$ thus neglecting non-hadronic modes. We also sum over left/right squark production neglecting the possible mass splitting between these

$^{3}$Using the gluino pdf’s from $^{14}$ we have checked that the dijet cross-sections would be similar to those in $^{20}$. We thank Dr. J. Stirling for furnishing us the code for pdf evaluation.
states. Since there is no interference between diagrams containing $\tilde{q}_L$ and $\tilde{q}_R$, in the case of $M_R - M_L$ mass splitting large relative to the $\tilde{q}$ width one simply divides the cross-sections by 2 to get separate cross-sections. We have taken the gluino mass to be 100 MeV. We employ the CTEQ3L (leading order QCD fit without the Tevatron jet $E_T$ data) pdf’s \cite{17} and evaluate them at half of the transverse energy of the leading jet. The strong coupling constant is evaluated at the same scale using SUSY RGE equations with $\alpha_s(M_Z) = 0.12$. We also evaluate in the lowest order all relevant background $2 \to 2$ processes, including gluino pair production. The latter amount for only 6-10% of the standard processes\cite{10, 11, 20}. The resulting normalized distributions along with the actual data (statistical errors only) are illustrated in Fig. \ref{fig:1} for the dijet mass range of $517 \leq M \leq 625$ GeV and a $m_{\tilde{u}} \approx 550$ GeV squark. As expected, the distribution for SUSY with light gluinos but heavy decoupled squarks is rather close to that for standard QCD, whereas the addition of squark production is distinctly inconsistent with the data. In particular, the excess of dijet events in this mass bin \cite{18} cannot be associated with squarks in the light gluino scenario.

For a more detailed analysis, we use the CDF data on $R_\chi$, which is defined for each mass bin as the ratio of the number of events with $\chi \leq 2.5$ to that with $\chi > 2.5$. The proprietary choice of 2.5 for the “pivot point” was related to the CDF search for the quark compositeness, but it is suitable for our procedure as well. Unlike $d\sigma/d\chi$, the $R_\chi$ data is provided with systematic errors and their correlation (full correlation is suggested in \cite{14} among systematic errors for the five mass bins). We add the systematic error matrix in quadrature to the statistical error matrix (zero correlation) in computing the full covariance matrix $V_{ij}$. We then evaluate

$$\chi^2 = \sum_{i,j=1}^{i,j=5} \Delta R_i \Delta R_j (V^{-1})_{ij}$$

where $\Delta R_i(m_{\tilde{q}}) = R^{SUSY}_i(m_{\tilde{q}}) - R^{data}_i$, for different squark masses. Here $R^{SUSY}_i(m_{\tilde{q}})$ is the value of $R_\chi$ in SUSY with light gluinos including squark effects. Assuming different masses of $\tilde{u}, \tilde{d}$, we perform the $\chi^2$ analysis separately for the two squark flavors corresponding to valence quarks in the proton. We have found that $\tilde{u}$ squarks in the mass range 150 – 650 GeV and $\tilde{d}$ squarks in the range 170 – 620 GeV are incompatible in the $\chi^2$ sense with the CDF data at the 95% CL, in rough agreement with \cite{20}.
Figure 1: Production of a $\tilde{u}$ squark ($m_{\tilde{u}} = 550$ Gev) and angular distributions of dijets with the mass $517 \leq M \leq 625$ GeV. The LO predictions of Standard Model and SUSY with light gluinos and infinitely heavy squarks are also shown.
Although the CDF analysis of their dijet angular distribution data has been primarily oriented toward possible new physics at high energies (∼ 1 Tev), such as quark substructure, lower energies may as well be interesting for analyses such as ours. In the Supergravity SUSY models [21], the light gluino implies low masses of squarks, below a few hundred GeV, if a light stop contributes appreciably into the $R_b$ ratio $^2$. More importantly, the CDF data on jet transverse energy distributions may suggest $\tilde{u}, \tilde{d}$ quarks near $\approx 106$ GeV $^1$. We hope that if the gluino is light, Supersymmetry will be observed at these energies. It is therefore imperative to make predictions about the effects on dijet angular data of squarks in the 50 – 200 GeV range $^4$. Special attention to this low mass region is another major difference between the present and earlier analyses.

In addition to the five published CDF dijet mass bins, we consider two more bins, $60 \leq M \leq 150$ and $150 \leq M \leq 241$ GeV and compute the expected deviation from the standard QCD $\Delta R'_i(m_{\tilde{q}}) = R^{SUSY}_i(m_{\tilde{q}}) - R^{QCD}_i$, where, as above, $i$ distinguishes dijet mass bins. The result is plotted in Fig.2 for the two suggested mass bins along with that for the lowest actual CDF mass bin of $241 \leq M \leq 300$ GeV. We compare $\Delta R'$ to the uncertainty in the measured $R_\chi$ in the $241 \leq M \leq 300$ bin, $\sigma = 0.021$, by plotting the $2\sigma$ level line. Clearly, if the CDF is able to determine $R_\chi$ for dijet masses such as in Fig. 2 with an error of $\lesssim 0.02$, squarks below $\approx 150$ GeV, will be observed or excluded at the 95% CL. In the latter case, at least some Supergravity related models with light gluino will be ruled out even without upgrading the Tevatron energy.

To recapitulate, we have studied the impact of the light gluino on dijet angular distributions at the Tevatron. We have shown that the major effect is associated with the single squark production. The current CDF data with 106 pb$^{-1}$ integrated luminosity are inconsistent with $170 \leq m_{\tilde{q}} \leq 650$ GeV squarks in the light gluino case. The same or better precision data for dijet masses below 240 GeV will allow one to discover the squarks near $\approx 100$ GeV, which may be suggested by the $R_b$ anomaly or by the CDF inclusive jet $E_T$ distributions. Since any SUSY theory can only be attractive if it exists at the electroweak scale, the dijet angular measurements, depending on luminosity, may prove crucial tests for the light gluino hypothesis.

$^4$Note that the Tevatron searches $^2$ assume the missing energy signature of squarks and therefore their results are not applicable to the light gluino scenario.
Figure 2: Predictions for $\Delta R' = R^{SUSY} - R^{QCD}$ for three dijet mass ranges. The dotted line is the projected 2σ level, where $\sigma = 0.021$ is an example taken from the experimental uncertainty in $R_x$ in the lowest published dijet mass bin, $241 \leq M \leq 300$ GeV.
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