Scaling Violation through Squark and Light Gluino Production

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Abstract

In the light gluino scenario, squarks in the 100 GeV mass region can be copiously produced at the Tevatron without a second heavy particle. Their subsequent dijet decay into quark plus gluino leads to non-scaling structure in the inclusive jet $X_T$ distribution. The expected behavior is similar to recent observations.

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Recent anomalies in the production of jets in $p\bar{p}$ annihilation have stimulated significant interest as a possible sign of physics beyond the standard model. A case in point is the inclusive jet transverse energy cross section which was reported by CDF as exhibiting a dip at low $E_T$ and a rise at high $E_T$ relative to the standard model predictions. $^1$. This behavior was cited as a possible indication of quark substructure or of various other non-standard-model effects $^2$. Among these latter was the suggestion that the jet $E_T$ distribution could be due, in the light gluino scenario, to extra jet activity from production of gluino pairs and to the expected slower running of $\alpha_s$ $^3, ^4$. In addition to these two effects, the possible production of a squark in association with a light gluino could explain one of the several possible bumps visible in the CDF data. (For a discussion of other indications of a light gluino see $^5$ and for a discussion of direct phenomenological signals in future searches see $^6$). On the other hand it was also found possible $^7$ to fit the data, apart from the low ($< 50$ GeV) $E_T$ values, by readjusting the gluon distribution function in the proton in a way still consistent with other data or by changing the renormalization scheme $^8$. Thus, whether or not new physics is contained in the Fermilab data must await further analysis. It is significant that the angular distributions of the jets in various dijet mass bins are consistent with that expected from the standard model $^9$. This would seem to rule out many non-standard-model explanations of the data. However, it has been shown that the light gluino hypothesis would lead to dijet angular distributions in practice indistinguishable from the standard model expectations except in dijet mass bins containing an up squark or down squark $^{10, 11}$. This is due to the fact that the structure of light gluino production amplitudes is quite similar to that of other light partons dominated by massless particle exchanges in the $t$ and $s$ channels. However a squark, once produced, will, in the light gluino case, decay into dijets with an isotropic angular distribution in its rest frame.

The light gluino hypothesis, therefore, remains viable only if the valence squarks are below about 150 GeV or above 650 GeV since currently analyzed data does not constrain the lower or higher mass regions $^{12, 4, 11}$. The possible bump at about 550 GeV seen by CDF and discussed in the light gluino case in $^{12}$ might, therefore, be a statistical fluctuation. This interpretation is supported by the failure of the later analysis $^{13, 14}$ to confirm a bump in this region. On the other hand the angular distributions have not been
published in the vicinity of a possible particle near 100 GeV suggested by the $E_T$ data. \[3\]. Furthermore $D0$ has not published data spanning the relevant low $E_T$ region. Assuming it is relatively less attractive to have squarks above 650 GeV, the study of jet angular distributions in the 100 GeV to 150 GeV dijet mass region could therefore be crucial to the light gluino hypothesis.

The parton distribution functions in the standard model must presently be treated as theoretically arbitrary functions; the primary constraints are from data on deep inelastic scattering and from direct photon production. This freedom eliminates the necessity of, although not the possibility of, new physics in explaining the Fermilab results for the jet transverse energy cross sections at high $E_T$. It does not at present, however, allow for an understanding of the behavior below 50 GeV $E_T$. In addition, it is possible to study suitably defined scaling distributions whose ratio at two different Fermilab energies is relatively insensitive to modifications of the parton distributions. Such a quantity is the scaled inclusive jet transverse energy cross section, which is predicted to have the form

$$s \frac{d\sigma}{dX_T} = \alpha_s(\mu)^2 F(X_T, \frac{\Lambda}{\sqrt{s}}, \frac{m}{\sqrt{s}})$$ \hspace{1cm} (1)$$

with

$$X_T = \frac{2E_T}{\sqrt{s}}.$$ \hspace{1cm} (2)$$

Here $\mu$ is conventionally taken to be $E_T/2$, $\Lambda$ is the QCD dimensional transmutation parameter, and $m$ represents any particle mass appearing in the theory. Since the lowest order cross sections in QCD are proportional to $\alpha_s^2$, this has been factored out, although it also could be written as a function of the first two arguments of the scaling function $F$. If all masses in the theory are negligible compared to $\sqrt{s}$, $F$ depends on $s$ only through its second argument coming from scaling deviations in the parton distribution functions and from logarithmic scaling violations due to higher order terms in $\alpha_s$ both of which effects are expected to be small. The ratio of the scaling distribution at two different (high) energies is therefore expected to be approximately constant in $X_T$ (for $X_T \gtrsim 0.05$) independent of small modifications of the parton distribution functions. The CDF collaboration \[15\] has presented preliminary results for the ratio

$$r(X_T) = \frac{s\sigma/dX_T}{s\sigma/dX_T} \quad (\sqrt{s} = 630)$$

$$r(X_T) = \frac{s\sigma/dX_T}{s\sigma/dX_T} \quad (\sqrt{s} = 1800)$$ \hspace{1cm} (3)$$

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In the standard model $r(X_T)$ departs from unity due to the running of the coupling constant in (1) and due to logarithmic scaling violations in the parton distribution functions. This leads to a predicted value for $r$ near 1.8 approximately independent of $X_T$. The data show a systematic tendency to be below this prediction. In the light gluino case $\alpha_s$ runs more slowly than in the standard model leading to a value for $r$ near 1.6 again approximately constant if the squarks are too high in mass to be copiously produced.

The current data for the ratio of the transverse energy distributions at two energies are preliminary. Nevertheless, the reported structure in $r(X_T)$, if not ultimately attributable to systematic errors, is a tantalizing indication of the existence of strongly interacting particles whose masses are not negligible compared to 630 GeV and which lead to a strong effect from the third argument in the $F$ of (1). Weakly interacting particles, such as the $W$ and $Z$ bosons, do not have a sufficiently high production cross section compared to QCD jet production to affect the $r$ parameter significantly. Similarly the top quark or the prevalent supersymmetry hypothesis with pair produced heavy squarks and gluinos have production cross sections too low to be helpful in the current context. In addition, such squarks are not expected to have prominent dijet decay modes.

On the other hand, in the light gluino scenario, which can be obtained in the context of the constrained supergravity related SUSY breaking model by setting the universal gaugino mass $m_{1/2}$ to zero, a single heavy squark can be produced in association with a light gluino leading to greatly enhanced squark production cross sections as discussed in [12, 3]. In the light gluino case, but not in the standard SUSY picture, a squark will have a predominantly dijet decay into quark plus gluino. Such a squark would produce a dip in the $r$ ratio (before smearing due to experimental resolution and hadronization) at approximately $X_T = m(GeV)/1800$ followed by a peak at $m(GeV)/630$. There is in fact some indication in the data for such a low $X_T$ dip followed by a peak at roughly three times higher $X_T$. In the current work we adopt the light gluino hypothesis and consider as in [12, 3, 11] the lowest order standard model processes together with the effect of sparticle production processes

\begin{align*}
GG &\rightarrow \tilde{G}\tilde{G} \quad (4) \\
Q\bar{Q} &\rightarrow \tilde{G}\tilde{G} \quad (5) \\
QG &\rightarrow Q\tilde{G}\tilde{G}. \quad (6)
\end{align*}
Processes (4) and (5), while increasing the jet activity by some 6% do not have a significant effect on the $r$ ratio. The possibility of a squark intermediate state in process (6) leads however to structure in $r$ as discussed above. The effect is shown in Fig. 1 for a squark mass of 135 GeV. The structure shown in the $r$ parameter theory as a function of $X_T$ is due to an intermediate squark in the process of (6). One could, as in [4, 10], use the expected gluino distribution functions in the proton to produce single squarks via the quark-gluino fusion reaction $Q\tilde{G} \rightarrow \tilde{Q}$. If the gluinos are dynamically generated from the gluons in the proton, such a treatment is an approximation (for a forward going, narrow width squark) to the full $2 \rightarrow 3$ process in (6) above.

In lowest order QCD, the squark width is predicted to be

$$\Gamma_{\tilde{Q}} = 2M_{\tilde{Q}}\alpha_s/3$$  (7)

This width would be increased somewhat by electroweak decays of the squark and by QCD corrections to the hadronic decays. In the theoretical curve (solid line) in Fig. 1 we have assumed a width 30% greater than (6). The width could be increased further to simulate crudely the effect of experimental resolution and hadronization smearing, but we prefer to leave a more detailed consideration of such effects to a later paper. Since the peaks, if they exist, sit on a steeply falling background, the effect of resolution would be to move the observed peak upward. Given the preliminary nature of the data and uncertainties in the actual amount of smearing present in the data we would not consider any squark mass between 100 GeV and 140 GeV as counter-indicated at present. The possible bump in the data near $X_T \sim 0.28$ could be fit by a squark of mass 180 GeV but such a mass might be ruled out by dijet angular distribution considerations [10, 11]. A consistent treatment of standard model processes and corrections to processes (4) and (5) at order $\alpha_s^3$ would also reduce the peaks somewhat by lifting the value of the non-resonant backgrounds although, in the absence of peaks, such corrections would not appreciably affect the $r$ ratio. Such refinements are left to a later more detailed paper which will be justified if the observed departure from standard model expectations survives a continued experimental study of possible systematic errors. In particular we suspect that the low data point near $X_T = .07$ might be due to a smearing effect in the 630 GeV data from regions of low $E_T$ where $\alpha_s$ becomes large and the parton distribution functions may not be well behaved.
Our main conclusion at this point is that the light gluino hypothesis together with valence squarks in the 100 GeV to 140 GeV region are in qualitative agreement with current experimental indications. A precise fit must await further understanding of systematic uncertainties in both the experiment and the theory. It seems unlikely that the current magnitude of the observed structure could be fit in any model involving pair production of two heavy particles with coupling strength $\alpha_s$ or less or in any model with additional gauge bosons in the electroweak sector.

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Figure 1: CDF data on the $X_T$ distribution compared to a) the standard model prediction (dashed line), b) light gluino with decoupled (effectively infinitely massive) squarks (dot-dashed line), and c) light gluino plus 135 GeV valence squarks (solid line).