Inclusive Jet $E_T$ Distributions and Light Gluinos

L. Clavelli* and I. Terekhov†

Department of Physics and Astronomy
University of Alabama
Tuscaloosa, Alabama 35487
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Abstract

In the light gluino variant of the minimal supersymmetric model gluino pairs can be readily produced in collider experiments even if the squarks are arbitrarily heavy. This enhances the jet transverse energy distributions. In addition the slower running of the strong coupling constant in the presence of light gluinos leads to a further enhancement at higher transverse energies relative to the standard QCD expectations. Finally, the enhanced squark gluino production would lead to a Jacobian peak in the $E_T$ distribution at about $M_{\tilde{Q}}/2$. These effects are of about the right magnitude to explain anomalies observed by the CDF and D0 collaborations.

*e-mail: LCLAVELL@UA1VM.UA.EDU
†e-mail: ITEREKH3@UA1VM.UA.EDU
Of all the proposals for physics beyond the Standard Model, Supersymmetry (SUSY) seems to be the most theoretically well-motivated from the aesthetic point of view due to its moderating of the singular behavior of field theory. In addition there are successful SUSY unification predictions of the weak angle – strong coupling constant correlation and of the \( b/\tau \) mass ratio to top quark mass correlation. Therefore for reasons of economy it is natural to expect that every deviation from the Standard Model should either disappear with better statistics or should find its explanation in terms of SUSY. It is generally accepted that current experiments do not rule out a gluino and photino in the low energy region below \( 5\,\text{GeV} \) \[^1\]. In fact, if the photino mass lies above the gluino mass but not above the mass of the gluino-gluon bound state (glueballino), the region of gluino mass below about \( 1\,\text{GeV} \) is essentially unconstrained by current experiments \[^2\].

Although the existence of these low energy windows has long been known, in the last few years there have been many \[^3\] observances of weak but positive indications of a light gluino from various Standard Model anomalies.

Recently both the \( CDF \) \[^4\] and \( D0 \) \[^5\] collaborations have reported anomalies in the inclusive jet transverse energy distributions at the Tevatron. In these inclusive measurements each event with \( n \) jets satisfying certain rapidity cuts is binned \( n \) times according to the total transverse energy \( E_T \) of each jet. The data as expected is a steeply falling function of \( E_T \) and is most conveniently discussed in terms of the function

\[
r(E_T) = \frac{d\sigma^{DATA}/dE_T}{d\sigma^{QCD}/dE_T}.
\]

(1)

Since the two experiments use slightly different rapidity cuts the data do not in principle have to coincide. In addition \( r \) is unfortunately a mixed experimental-theoretical quantity and depends among other things on the parton distribution functions \((pdf's)\) adopted, on the value of \( \alpha_s \) at some reference scale, say \( M_Z \), and on the QCD scale assumed to be appropriate to these measurements. The experiments use theoretical cross sections proportional to \( \alpha_s(E_T/2)^2 \) in lowest order although theoretical arguments might be made for using the scale \( E_T \) or \( 2E_T \). This assumption can affect the quantitative results for \( r \) but not the qualitative...
experimental observations which can be summarized as follows. CDF [4] observes values of $r$ below unity at low $E_T$ followed by a relatively long region where $r$ seems consistent with unity followed by a region of rapid rise. The D0 preliminary 1994/95 data [5] are consistent with a roughly constant value of $r \approx 1.2 \pm .07$ in the region $50 < E_T < 400$ perhaps rising slightly at high $E_T$ with larger errors. It has been noted [7] that the CDF $r$ values should be renormalized up by at least 4% to be consistent with the lower values of the strong coupling constant preferred by deep inelastic data. If one performs this renormalization and corrects for the slightly different rapidity cuts in the two experiments [6], the CDF and D0 data are consistent at the 1σ level and both show a systematic excess of data over theory. According to [4] the CDF results can not be reconciled with standard QCD by modifying the pdf’s while retaining consistency with constraints from deep inelastic scattering. Although other authors have searched for alternative standard QCD effects such as parton double scattering within the proton [8] the data remain interesting as a possible observation of effects beyond the Standard Model and could be evidence for quark sub-structure or the existence of hitherto unknown partons. An example of a non-SUSY explanation outside the Standard Model is given by [9].

However, according to the philosophy discussed in the introduction, one should first (or at the same time) explore possible SUSY related explanations. In the currently leading theoretical approach to SUSY in which the squarks and gluinos have masses in the several hundred GeV to 1TeV region the production of SUSY particles is orders of magnitude too small to explain the $E_T$ anomaly. In some limited regions of $E_T$ virtual SUSY effects lead at most to deviations of several percent from the standard QCD expectations. [10]

In this note, therefore, we explore the scenario where the gluino lies in the low energy region while the squarks lie in the hundred GeV region. For definiteness we take the gluino mass to be 0.1GeV although our results are not sensitive to the assumed mass. In this light gluino variant of the minimal SUSY model there are three effects which can affect the Fermilab experiments at the level of the observed anomalies.

1.) In the light gluino case the strong coupling constant runs more slowly than in
standard $QCD$. Since in this paper we intend to deal with lowest order QCD cross sections, we use also the one-loop renormalization group equations. We do not expect our results to change qualitatively in higher orders. The one-loop running of the coupling is defined by the renormalization group behavior

$$4\pi \frac{d}{d \ln(Q)} \alpha_s(Q)^{-1} = -2b_3,$$

where the standard $QCD$ and $SUSY$ coefficients are

$$b_3^{QCD} = -11 + 2n_f/3,$$  \hspace{1cm} (3)  

$$b_3^{SUSY} = -11 + 2n_f(1 + n_s/2)/3 + 2n_g.$$  \hspace{1cm} (4)  

Here $n_f$ is taken to be the number of quarks below mass $Q$ (5 or 6 depending on $Q$), $n_s$ is zero or one depending on whether $Q$ is below or above the (assumed degenerate) squark mass, and $n_g$ is zero or one depending on whether $Q$ is below or above the gluino mass. In the light gluino case $n_g$ is always unity for $Q$ in the multi-GeV region. The result is that, given the value of $\alpha_s$ at some reference value, say $M_Z$, $\alpha_s$ lies below the standard $QCD$ expectation at lower values of $Q$ and above at higher values of $Q$. Since the jet cross sections are proportional to second and higher order powers of the strong coupling constant, the light gluino prediction would be for $r$ to be below unity at low values of $E_T$ and rising at high values of $E_T$ in qualitative agreement with the $CDF$ results. The quantitative predictions, which depend on the assumed scale for the parton scattering, are discussed below.

2.) A second important effect in the light gluino case is the appearance of extra jets due to gluino pair production. An extra octet of light elementary particles might a priori be expected to nearly double the QCD jet cross sections. Since gluino pairs can be produced via gluon splitting even without intermediate squarks, these pairs will contribute at lowest (second) order in $\alpha_s$ throughout the $E_T$ range of the Fermilab experiments. The lowest order parton level sub-processes are

$$GG \rightarrow \tilde{G}\tilde{G},$$  \hspace{1cm} (5)  

$$q\bar{q} \rightarrow \tilde{G}\tilde{G}.$$  \hspace{1cm} (6)
The first process is independent of the squark mass while there is some squark mass dependence in the second process due to the possibility of $t$ and $u$ channel squarks. Neglecting the gluino mass the parton level differential cross sections for gluino pair production are (from [11])

$$\frac{d\sigma(gg \to \tilde{G}\tilde{G})}{dt} = \frac{9g_s^4}{64\pi s^2} \left[ \frac{2tu}{s^2} + \frac{u+t}{s} + \frac{u}{t} + \frac{t}{u} \right], \quad (7)$$

$$\frac{d\sigma(q\bar{q} \to \tilde{G}\tilde{G})}{dt} = \frac{g_s^4}{54\pi s^2} \left[ \frac{9(t^2 + u^2)}{2s^2} + \frac{4t^2}{(M^2 - t)^2} + \frac{9u^2}{s(t - M^2)} \right] + (u \leftrightarrow t), \quad (8)$$

where $M$ is the (assumed $L - R$ degenerate) squark mass. The transverse energy of each jet is $E_T = \sqrt{ut/s}$.

The relative importance of these processes to the standard QCD $2 \to 2$ sub-processes is easy to estimate by looking at the 90 degree scattering cross sections ($t = u = -s/2$). Since QCD cross sections fall rapidly with parton CM energy, for any required value of $E_T$ the dominant contributions to the cross section will come from configurations which produce that $E_T$ with minimum parton CM energy. This is the configuration of 90 degree scattering. One can then readily estimate an order of 10% enhancement of the inclusive $E_T$ distributions due to gluino pair production neglecting effect 1. For a quantitative prediction folding in the various pdf’s and including effect 1 we define the lowest order gluino pair production and standard QCD contributions to the $p\bar{p}$ inclusive jet distributions dividing out the overall factor of $\alpha_s^2$. That is

$$\frac{d\tilde{\sigma}}{dE_T} = \frac{1}{\alpha_s^2} \frac{d\sigma}{dE_T} \quad (9)$$

In this quantity dependence on the $\Lambda_{QCD}$ parameter enters in only through the small scaling violations in the pdf’s. We also define

$$r_\sigma = \frac{d\tilde{\sigma}^{SUSY}/dE_T}{d\tilde{\sigma}^{QCD}/dE_T} + 1. \quad (10)$$

Here the SUSY cross sections are those of the above gluino pair production processes and the QCD cross sections are the standard contributions to $2 \to 2$ scattering. To incorporate the effect 1 we need the SUSY to QCD ratio of squared couplings.
\[ r_\alpha(Q_1, Q_2) = \left( \frac{\alpha_s^{\text{SUSY}}(Q_1)}{\alpha_s^{\text{QCD}}(Q_2)} \right)^2. \] \hspace{1cm} (11)

Obviously, in the full supersymmetric theory the SUSY running of $\alpha_s$ applies to all the $2 \to 2$ processes. Therefore, the theoretical prediction for $r$ is

\[ r(E_T) = r_\sigma r_\alpha. \] \hspace{1cm} (12)

It still remains, of course, to choose the scales $Q_1, Q_2$ above. Since the experiments refer to a theory with $Q = E_T/2$, we should certainly use this value in the denominator of $r_\alpha$. If the optimum value of $Q$ is $E_T$ or $2E_T$ as mentioned above this value should be used in the numerator of $r_\alpha$. This is a theoretical point which can only be settled in the context of a full higher order treatment of the inclusive $E_T$ distribution. For definiteness we use $Q_1 = Q_2 = E_T/2$ everywhere. In calculating the reduced cross section ratio $r_\sigma$ we use the CTEQ3L [12] parton distributions although the theoretical results which use the pdf’s in both the numerator and denominator are less sensitive to this choice. The experimentally quoted $r$, on the other hand, depends on the choice of pdf’s only in the denominator and hence is somewhat sensitive to this choice. Similarly, the theoretical ratios $r_\sigma$ and $r_\alpha$ are presumably insensitive to inclusion of higher order effects since these tend to cancel between numerator and denominator.

3.) A final effect that can be discussed in the light gluino case comes from the parton sub-process

\[ qG \to \tilde{q}\tilde{G}, \] \hspace{1cm} (13)

where $q = u, d$.

In the heavy gluino case this cross section is, of course, strongly suppressed by phase space relative to the light gluino case. Due to gluino exchange in the $u$ channel, the cross section is strongly peaked at low energies and forward direction for the primary produced gluino [13]. The squark subsequently decays isotropically in its rest frame into a quark plus gluino. The result is a Jacobian peak in the inclusive $E_T$ distribution at approximately
$M\tilde{Q}/2$. Effect 3 is essentially negligible except in this peak region. The combined predictions of effects 1, 2, and 3 are shown in the solid lines of fig. 1 for two different values of the mean up and down squark masses. The standard QCD prediction $r = 1$ is shown in the dashed line. The dot-dashed line roughly constant near $r = 1.06$ shows the behavior of $r_\sigma$ while the dot-dashed line beginning near 0.8 and rising above 1.1 shows that of $r_\alpha$. Both curves are shown in the case $M\tilde{Q} = 106GeV$ only. In this case the $r$ value peaks near 52GeV and rises rapidly above 200GeV due primarily to effect 1. In the case of a squark of mass 460GeV the $r$ value peaks at 223GeV and rises less rapidly above the peak. In this case the rapid rise due to effect 1 would begin at $E_T = 920GeV$. Below 200GeV the theoretical curves are insensitive to the squark mass except in the peak region. The curve corresponding to the 106GeV mean valence squark mass includes the supergravity related degeneracy breaking into four peaks with the predicted overall splitting of about 20GeV. The data however does not have sufficient resolution to convincingly resolve these peaks if, indeed, they are preserved after hadronization. The splitting at a mean squark mass of 460GeV, predicted to be only about 3GeV overall, is neglected in the theoretical curve shown. It does not seem possible within this scheme to have valence squark spartners at both 106GeV and 460GeV. Therefore within the light gluino SUSY framework, we would expect that one or more of the two peaks should disappear with better statistics. From this point of view it is perhaps significant that the D0 data \[5\] show no enhancement in the 225GeV $E_T$ region. The D0 collaboration has not as yet reported results in the region $E_T < 50GeV$ which would be useful to rule out or confirm a low $E_T$ peak. The normalization and widths of the peaks are, of course, predicted in supersymmetry given a light gluino and a squark of fixed mass. In the heavy gluino theory the squark does not have a prominent two jet decay and hence would lead to a broader peak at lower $E_T$ with a much lower integrated cross section. A squark in the 500GeV region with a two jet decay would also lead to an enhancement at this mass in the dijet spectrum measured at the Tevatron \[13\]. The CDF dijet data do not rule out a squark in the region below 200GeV since here the peak would be largely submerged in the standard QCD background.
In summary we have presented the predictions of the light gluino SUSY theory for the inclusive jet $E_T$ distribution. The predicted enhancement over the standard QCD expectations agrees roughly in shape and magnitude with early results from Fermilab. In particular the theory predicts a dip below $r = 1$ in the low $E_T$ region and a peak near $M_{\tilde{Q}}/2$. Since we present ratios of SUSY to Standard QCD predictions we expect that our results will not be greatly affected by inclusion of higher order perturbative contributions nor by choices of pdf’s. For instance, the next to leading order corrections are known to increase the standard QCD cross sections by about ten percent [7] and can be expected to enhance the SUSY cross sections by a comparable amount leading, therefore, to a much smaller effect on the $r$ ratio. Nevertheless, if the anomaly persists as further data accumulates, it will be of interest to pursue refinements of the theory including higher order contributions and light gluino effects in the pdf’s including the existence of a gluino sea distribution in the proton (which might also have a bearing on the spin deficit observed in polarized deep-inelastic scattering). The current inclusive jet $E_T$ experiments have sufficient sensitivity to establish or rule out the existence of up and down squarks of mass up to at least 600 GeV in association with a light gluino.

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FIG. 1. Light gluino predictions for the inclusive jet $E_T$. The upper and lower dash-dotted curves give the predictions for $r_\sigma$ and $r_\alpha$ respectively with a squark mass of 106 GeV. The solid curves give the combined prediction for $r$ with an assumed mean squark mass of 460 GeV (lower curve at high $E_T$) or 106 GeV (higher curve at high $E_T$). In each case the $r$ value exhibits a narrow peak near $M_{\tilde{Q}}/2$. Data from CDF is superimposed.