Inclusive Jet $E_T$ Distributions and Light Gluinos

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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. These two effects are of about the right magnitude to explain anomalies observed by the CDF and D0 collaborations.
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\( GeV \) [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\( GeV \) 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

\[
    r(E_T) = \frac{d\sigma^{\text{DATA}}/dE_T}{d\sigma^{\text{QCD}}/dE_T}. \tag{1}
\]

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 $r \approx 1.2 \pm 0.07$ 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 $1\sigma$ level and both show a systematic excess of data over theory. According to [7] 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

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

(2)

where the standard QCD and SUSY coefficients are

\[ b_3^{QCD} = -11 + 2n_f/3, \]

(3)

\[ b_3^{SUSY} = -11 + 2n_f(1 + n_s/2)/3 + 2n_g. \]

(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

\[ GG \rightarrow \tilde{G}\tilde{G}, \]

(5)

\[ q\bar{q} \rightarrow \tilde{G}\tilde{G}. \]

(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])

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

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

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 $QCD$ $2 \rightarrow 2$ 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 $2 \rightarrow 2$ scattering. To incorporate the effect 1 we need the $SUSY$ to $QCD$ ratio of squared couplings.
\[ r_\alpha(Q_1, Q_2) = \left( \frac{\alpha_s^{SUSY}(Q_1)}{\alpha_s^{QCD}(Q_2)} \right)^2. \] (11)

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

\[ r(E_T) = r_\sigma r_\alpha. \] (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. The combined predictions of effects 1 and 2 are shown in fig. 1. The standard QCD prediction \( r = 1 \) is shown in the dashed line. The upper dot-dashed line shows the behavior of \( r_\sigma \) while the lower dot-dashed line shows that of \( r_\alpha \). Their combined contribution to \( r \) is shown as solid lines for two different assumptions of the (assumed degenerate) up and down squark masses. The theory shows a slow growth of \( r \) with \( E_T \) with about a 20% enhancement over standard QCD predicted at high \( E_T \). The dip at low \( E_T \) observed by CDF is also predicted although the effect seems to be somewhat exaggerated in the current theory perhaps suggesting additional contributions in the low \( E_T \) region. The D0 collaboration has not as yet reported results in the region \( E_T < 50 GeV \).

3.) A final effect that can be discussed in the light gluino case comes from the parton sub-process
\[ qG \rightarrow \bar{q}\tilde{G}, \]  

(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 \( M_{\tilde{Q}}/2 \). For (assumed degenerate) up and down squarks of mass \( 460 \text{GeV} \) and using the amplitudes of ref. [13] this is shown in fig. 2 superimposed on the \( CDF \) data in the \( 225 \text{GeV} E_T \) region. Here \( r(E_T) \) is extended to include the contribution from squark-gluino final states. The \( D0 \) data [5] show no enhancement in this region. The normalization and width of the peak is, 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 \( 500 \text{GeV} \) 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 \( CDF \) data do not rule out a squark in the region below \( 200 \text{GeV} \) 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. 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). In addition, it is expected that the $SUSY$ partners of the top and bottom quarks might also be significantly lighter than those of the other quarks. In the light gluino case such squarks (as well as valence quark sparticles) could have evaded the limits imposed by current collider experiments due to non-standard decay modes. Pair production of these squarks might then contribute at a low level to the inclusive jet $E_T$ distribution in the low $E_T$ region and could conceivably reduce the theoretical dip in the $r$ parameter which is due to the slower running of $\alpha_s$. This dip is too pronounced in the current model compared to the data although it might also be partially filled in by an up squark in the $100 - 200 GeV$ region produced in conjunction with a light gluino (effect 3). Fig. 2 shows that, with further study, the current experiments have sufficient sensitivity to establish or rule out the existence of up and down squarks of mass up to at least $400 GeV$ in association with a light gluino.

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REFERENCES


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 440$GeV$. The solid curves give the combined prediction for $r$ with an assumed squark mass of 440$GeV$ (lower curve) or 100$GeV$ (upper curve).

Fig. 2: Peak in the inclusive jet transverse energy distribution due to a squark at 460$GeV$ and a light gluino. $CDF$ data from [4] (multiplied by 1.04 as suggested by [7]) is shown superimposed on the theoretical curve.
Fig. 1
Fig. 2