Inclusive Jet E_T Distributions and Light Gluinos

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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. [S0031-9007(96)00982-9]

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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/τ 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 Fermilab 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 are a steeply falling function of E_T and are most conveniently discussed in terms of the function

$$r(E_T) = \frac{d\sigma^{\mathrm{data}}/dE_T}{d\sigma^{\mathrm{QCD}}/dE_T}\,. \tag{1}$$

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 (PDFs) adopted, on the value of α_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 1994–1995 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 [6] 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 [7], the CDF and D0 data are consistent at the 1σ level and both show a systematic excess of data over theory. According to [6], the CDF results cannot be reconciled with standard QCD by modifying the PDFs while retaining consistency with constraints from deep-inelastic scattering. Recently, however, two papers [8] have appeared which, contrary to the results of [6], succeed in tailoring the PDFs so as to reconcile deep-inelastic and the high transverse momentum Fermilab data with the standard model. Other authors have searched for alternative standard QCD effects such as parton double scattering within the proton [9]. Nevertheless, the data remain interesting as a possible observation of effects beyond the standard model and could be evidence for quark substructure or the existence of hitherto unknown partons. An example of a non-SUSY explanation outside the standard model is given by [10].

However, according to the philosophy discussed earlier, 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 1 TeV 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 [11].

In this Letter, 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 0.1 GeV 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 also use 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

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

where the standard QCD and SUSY coefficients are

$$b_3^{\rm QCD} = -11 + 2n_f/3\,, \tag{3}$$

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

Here n_f is taken to be the number of quarks below mass Q (5 or 6 depending on Q), n_s is 0 or 1 depending on whether Q is below or above the (assumed degenerate) squark mass, and n_g is 0 or 1 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 α_s at some reference value, say, M_Z, α_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 α_s throughout the E_T range of the Fermilab experiments. The lowest order parton level subprocesses are

$$GG \to \tilde{G}\tilde{G}\,, \tag{5}$$

$$q\bar{q} \to \tilde{G}\tilde{G}\,. \tag{6}$$

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 [12])

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

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

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 $2 \to 2$ subprocesses is easy to estimate by looking at the 90° 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° 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 PDFs and including effect (1), we define the lowest order gluino pair production and standard QCD contributions to the $p\overline{p}$ inclusive jet distributions dividing out the overall factor of α_s^2; that is,

$$\frac{d\tilde{\sigma}}{dE_T} = \frac{1}{\alpha_s^2}\frac{d\sigma}{dE_T}\,. \tag{9}$$

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

$$r_\sigma = \frac{d\tilde{\sigma}^{\rm SUSY}/dE_T}{d\tilde{\sigma}^{\rm QCD}/dE_T} + 1\,. \tag{10}$$

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:

$$r_\alpha(Q_1, Q_2) = \left(\frac{\alpha_s^{\rm SUSY}(Q_1)}{\alpha_s^{\rm QCD}(Q_2)}\right)^2. \tag{11}$$

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

$$r(E_T) = r_\sigma r_\alpha\,. \tag{12}$$

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_α. 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_α. 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_σ we use the CTEQ3L [13] parton distributions, although the theoretical results which use the PDFs 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 PDFs only in the denominator, and hence is somewhat sensitive to this choice. Similarly, the theoretical ratios r_σ and r_α 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 subprocess

$$qG \to \tilde{q}\tilde{G}\,, \tag{13}$$

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. Because of gluino exchange in the u channel, the cross section is strongly peaked at low energies and forward direction for the primary produced gluino [14]. 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)–(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_σ, while the dot-dashed line beginning near 0.8 and rising above 1.1 shows that of r_α. Both curves are shown in the case $M_{\tilde{Q}} = 106$ GeV only. In this case, the r value peaks near 52 GeV and rises rapidly above 200 GeV due primarily to effect (1). In the case of a squark of mass 460 GeV, the r value peaks at 223 GeV and rises less rapidly above the peak. In this case, the rapid rise due to effect (1) would begin at $E_T = 920$ GeV. Below 200 GeV the theoretical curves are insensitive to the squark mass, except in the peak region. The curve corresponding to the 106 GeV mean valence squark mass includes the supergravity related degeneracy breaking into four peaks with the predicted overall splitting of about 20 GeV. The data however do not have sufficient resolution to convincingly resolve these peaks if, indeed, they are preserved after hadronization. The splitting at a mean squark mass of

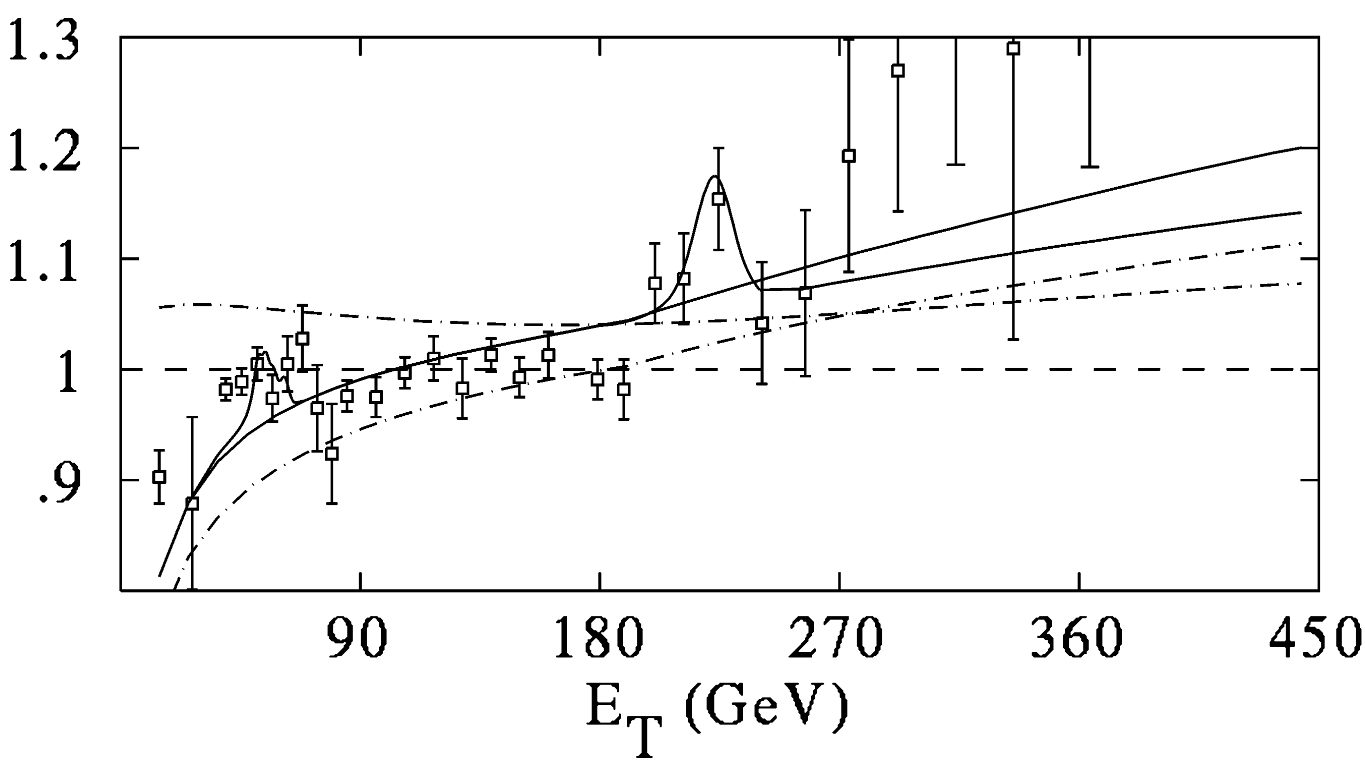

FIG. 1. Light gluino predictions for the inclusive jet E_T. The upper and lower dash-dotted curves give the predictions for r_σ and r_α, respectively, with a squark mass of 106 GeV. The solid curves give the combined prediction for r with an assumed mean squark mass of 460 GeV (lower curve at high E_T) 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 [4] are superimposed.

460 GeV, predicted to be only about 3 GeV overall, is neglected in the theoretical curve shown. It does not seem possible within this scheme to have valence squark spartners at both 106 and 460 GeV. 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 225 GeV E_T region. The D0 Collaboration has not as yet reported results in the region $E_T < 50$ GeV 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 500 GeV region with a two jet decay would also lead to an enhancement at this mass in the dijet spectrum measured at the Tevatron [14]. The CDF dijet data do not rule out a squark in the region below 200 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. 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 or by choices of PDFs. For instance, the next-to-leading order corrections are known to increase the standard QCD cross sections by about 10% [6] 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 PDFs 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. The $2 \longrightarrow 2$ processes of Eqs. (5) and (6) do not lead to jet angular distributions markedly different from those of the standard model processes. On the other hand, in the bump regions (if any survive), we predict a flatter jet angular distribution in the rest frame of the pair [14].

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