JETS AND PARTONS

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October 18, 1996

Abstract

Jet production in high energy hadron-hadron collisions can serve as a probe for new physics. I review recent data from CDF and D0 on the high $E_T$ jet cross section. Reporting on recent work of the CTEQ collaboration, I argue that the apparent excess seen in the CDF data may be due to the gluon distribution function used in the theoretical calculation being too small at large $x$. I discuss data on the dijet angular distribution, which shows no sign of a new physics signal.

Adapted from talks at

XXVIII International Conference on High Energy Physics, Warsaw, July 1996
and at
QCD Euroconference 96, Montpellier, July 1996
In high energy collisions of hadrons one can produce highly collimated jets of particles, with the total transverse momentum of a jet reaching several hundred GeV, as illustrated in Fig. 1. Such jets reflect the underlying parton dynamics.

Figure 1: Sketch of two jet production in a hadron-hadron collision.

One can use measurements of jet cross sections to check in detail how well the perturbative diagrams of QCD describe actual quark and gluon collisions. One can also use the measurements to help determine parton distributions. In particular, there is an opportunity to pin down the comparatively unknown the gluon distribution, since gluon initiated processes are important for moderate values of the jet transverse momentum. As we will see, the data may also be telling us something surprising about the gluon distribution at large $x$.

The most important role that can be played by jet cross sections is to help us to discover a breakdown of the Standard Model at small distances. Suppose that there is some new process that can lead to parton-parton scattering, as illustrated in Fig. 2. Such a new process could be part of a theory that has the Standard Model as its long distance limit. Then the new physics signals accessible at moderately long distances can be characterized as additions $\Delta \mathcal{L}$ to the lagrangian of the Standard Model, for example

$$\Delta \mathcal{L} = \frac{\tilde{g}^2}{\Lambda^2} \bar{\psi} \gamma^\mu \psi \bar{\psi} \gamma_\mu \psi. \quad (1)$$

In contrast to the usual dimension 4 terms in the lagrangian, such a term has dimension 6 and thus a factor of $1/\Lambda^2$, where $\Lambda$ is a large mass characteristic of the short distance scale. Here $\tilde{g}^2$ is a coupling of the new theory.

The effect of such a term $\Delta \mathcal{L}$ in the lagrangian is to change the inclusive cross section $d\sigma/dE_T$ to make a jet with transverse energy $E_T$. One looks for a signal of the form

$$\frac{\text{Data} - \text{Theory}}{\text{Theory}} \propto \frac{\tilde{g}^2 E_T^2}{\Lambda^2}. \quad (2)$$
The “Theory” here is next-to-leading order QCD \[1, 2, 3\], not including a new physics contribution.

Jet cross sections at hadron colliders are a good place to look for traces of $\Delta \mathcal{L}$ because one can go out to very large $E_T$, over 400 GeV at the Fermilab Collider, and still have a measurable Standard Model signal. The one jet inclusive cross section is useful because it is the most inclusive jet cross section, but (as will become clear in this talk) the two jet angular distribution is also very useful.

In order to have reasonably precise Standard Model predictions, one needs to be careful to state the algorithm by which jets are defined. The choice of algorithm is a matter of convention, but the convention must be the same in the theory and in the experiment. In hadron-hadron physics, the definition that has been typically used is the “Snowmass Convention” \[4\], in which a jet consists of all the particles inside a certain cone.

In the theoretical calculation, the jet cross section takes the form

$$
\frac{d\sigma}{dE_T} = \int d\xi_a f_{a/A}(\xi_a) \int d\xi_b f_{b/B}(\xi_b) \times \left\{ \int dk_1 dk_2 \frac{d\sigma(a + b \to 1 + 2)}{dk_1 dk_2} S_2(k_1, k_2; E_T) \\
+ \int dk_1 dk_2 dk_3 \frac{d\sigma(a + b \to 1 + 2 + 3)}{dk_1 dk_2 dk_3} S_3(k_1, k_2, k_3; E_T) \right\} \tag{3}
$$

Here $f_{a/A}(\xi)$ is the parton distribution function giving the probability to find a parton of type $a$ in a hadron of type $A$ carrying momentum fraction $\xi$. The function $d\sigma(a + b \to 1 + \cdots + N)/[dk_1 \cdots dk_N]$ gives the QCD cross section for partons $a$ and $b$ to make $N$ final state partons. Finally the functions $S_N$ contain the algorithm for defining the jet cross section. The calculation will produce a finite answer because the functions $S_N$ are “infrared safe”. E.g.

$$
S_3(k_1^\mu, (1 - \lambda)k_2^\mu, \lambda k_2^\mu; E_T) = S_2(k_1^\mu, k_2^\mu; E_T) \tag{4}
$$
This says that a mother parton will produce the same contribution to the jet cross section whether or not it breaks into two daughter partons moving in the same direction.

The theoretical calculation is strictly an order $\alpha_s^3$ calculation. Monte Carlo event generators can do a good job of modeling the part of the order $\alpha_s^4$, $\alpha_s^5$, $\alpha_s^6$, ... contributions that comes from approximately collinear parton branchings, but because of the property of infrared safety enjoyed by the jet cross section, the approximately collinear integration regions are not particularly important. For this reason, no $\alpha_s^4$, $\alpha_s^5$, $\alpha_s^6$, ... contributions are included. Also because of infrared safety, jet cross sections at high $E_T$ are not sensitive to hadronization. Thus the calculations do not try to correct for hadronization.

The theoretical formula for the one jet inclusive cross section depends on a scale $\mu_{UV}$ that appears in the running coupling and on another scale $\mu_{CO}$ that appears in the parton distribution functions. These scales also appear explicitly in the order $\alpha_s^3$ contributions to the cross section. In Fig. 3, I show the dependence of the calculated cross section on the logarithms of the scales $\mu$, $N_{UV}$ and $N_{CO}$ defined by $\mu_{UV} = (E_T/2) \times 2^{N_{UV}}$, $\mu_{CO} = (E_T/2) \times 2^{N_{CO}}$. The figures are contour graphs with 5% contour lines of $d\sigma/dE_T d\eta$ with arbitrary normalization, with the jet rapidity $\eta$ set equal to zero. We see that both at $E_T = 100$ GeV and at $E_T = 500$ GeV the scale dependence is on the order of 15%. This provides a rough estimate of the likely error in the theory due to leaving out the uncalculated contributions of order $\alpha_s^4$ and higher.

The jet cross section at moderate $E_T$ is sensitive to the gluon distribution,
while at large $E_T$, it is mostly the well measured quark distributions that count. This is illustrated in Fig. 4. Notice, however, that even at the highest values of $E_T$, the contribution from gluons is still not negligible.

Figure 4: Contribution to the Born-level one jet inclusive cross section from gluon-gluon, gluon-quark, and quark-quark collisions.

Let us now look at the data for the one jet inclusive cross section. In Fig. 5, I show the CDF \[5\] and D0 \[6\] cross sections as a function of $E_T$. The range of rapidities included in the two cases is not same, so that the data are not strictly comparable. Nevertheless, one has the impression of good agreement between the two experiments.

In Fig. 6, I show a comparison of these data to theory, taken from the work of the CTEQ Collaboration \[7, 8\]. The comparison uses the CTEQ3M set of parton distributions. The $(\text{Data} - \text{Theory}) / \text{Theory}$ format of the figure allows us to see the quality of the agreement despite the fact that the data falls by seven orders of magnitude in the $E_T$ range shown. The systematic experimental errors are not shown. In the CDF data, the systematic error is about 20%. For the D0 data, the systematic error is larger.

We see from the graph that there is very good agreement between theory and experiment for $50 \text{ GeV} < E_T < 250 \text{ GeV}$. For $250 \text{ GeV} < E_T$, the D0 data is in agreement with the CDF data within the errors. Furthermore, the D0 data is in agreement with the theory within the errors. However, the more precise CDF data shows a systematic rise above the theory as $E_T$ increases. Using an earlier data set than shown above and comparing to MRSD0' partons, the CDF collaboration reports \[5\] that the chance that the high $E_T$ excess is a statistical fluctuation, taking the systematic error into account, is less than 1%. This is just the sort of new physics signal that we were looking for, so it is well worth a careful examination.

We can also compare to QCD theory using the latest CTEQ4M parton
Figure 5: CDF and D0 cross sections $\langle d\sigma/d\eta dE_T \rangle$ averaged over $0.1 < |\eta| < 0.7$ (CDF) and $|\eta| < 0.5$. 
distributions [8]. This set makes use of new data on deeply inelastic scattering from NMC, E665, Zeus and H1. The data included in the fit also includes the CDF and D0 jet data under discussion. The jet data, however, do not have enough statistical power to control the fit. The resulting (Data − Theory) / Theory plot looks much the same as Fig. 6. One can do the same using the latest MRS parton distribution set [9], which uses the new deeply inelastic scattering data but not the jet data. The result is the same.

It seems that the theoretical prediction is robust against changes in the parton distribution, but we may ask more directly whether there could be enough flexibility in the partons to account for the apparent high $E_T$ excess. Note that high $E_T$ corresponds to high momentum fraction $x$ for the colliding partons. $E_T \approx 450$ GeV corresponds to $x \approx 0.5$. The quark distribution at large $x$ is quite accurately pinned down by deeply inelastic scattering. The gluon distribution is not. Since with “standard” partons, events with initial gluons do not account for much of the cross section, one would have to change the gluon distribution quite drastically at large $x$ in order to account for the high $E_T$ excess. The CTEQ Collaboration has tried this [7]. They forced the parton parameterization to change so that the theory cross section goes through the large $E_T$ jet data, while the fit to deeply inelastic scattering and other data remains as good as possible. The result is shown in Fig. 7. In order to obtain this result, the quark distributions remained nearly unchanged, while the gluon distribution function approximately doubled near $x = 0.5$.

We see that with the modified parton distributions the jet data can be accommodated. The question is, does this ruin agreement with other data? The $\chi^2$ for the CTEQ4M set compared to 1297 DIS and Drell-Yan data was 1320. The $\chi^2$ for the special CTEQ4HJ set compared to this same data was
This is not as good, but not really much worse. Since systematic errors are not generally included in these $\chi^2$ values, the change may be regarded as not significant.

What about direct photon production in hadron-hadron collisions? This process gets big contributions from $\text{quark} + \text{gluon} \rightarrow \text{photon} + X$, so it is sensitive to the gluon distribution. Furthermore, experiments at fixed target energies can reach to $x_\gamma \equiv 2P_T/\sqrt{s}$ on the order of 1/2, which probes the gluon distribution with $x \approx 1/2$. In Fig. 8, I show the comparison of theory and experiment for WA70 data [10] using the conventional ABFOW parton distribution set [11]. One sees that the agreement between theory and experiment is none too good. The figure also shows three alternative theory curves based on different scale choices and on the addition of transverse momentum effects that might be expected from multiple gluon emission in the initial state. One sees that in fact the theory is quite unstable. This instability may be attributed to the fact that the transverse momenta involved (< 7 GeV) are not large. In Fig. 8, I show the WA70 data compared to a theoretical calculation using the CTEQ4HJ set. Again, the agreement between theory and experiment is none too good. But it is not much worse than with conventional partons, and one can argue that the agreement is good enough given the theoretical uncertainties.

I conclude that direct photon production results do not, in fact, determine the gluon distribution very well.

Let me mention two issues raised by recent theoretical papers. First, Klasen and Kramer [12] have investigated how the prediction for the high $E_T$ jet cross section depends on whether the fitting of partons and then the subsequent calculation of the jet cross section is done in the $\overline{\text{MS}}$ factorization
Figure 8: Direct photon production. Data from the WA70 experiment is compared to theory using ABFOW partons, taking the scale $\mu$ in $\alpha_s$ and the parton distributions to be fixed by the “principle of minimal sensitivity.” Three other theory curves show the effect of choosing $\mu = P_T$ and $\mu = P_T/2$ instead and of choosing $\mu = P_T$ while adding smearing in the transverse momentum for the incoming partons.

Figure 9: Direct photon production. Data from the WA70 experiment is compared to theory using CTEQ4HJ partons (the “Norm = 1.0 Jet Fit”) and also to the theory using an alternative set of partons that give a good fit to the high $E_T$ jet data (the “Norm = 0.85 Jet Fit”). The scale $\mu$ is set to $P_T/2$, and a theory curve using transverse momentum smearing is also shown.
scheme or in the DIS scheme. They find that the difference is large and that the high $E_T$ excess goes away when the DIS scheme is used. My interpretation of this is that the difference comes in the parton fitting. Since the gluon distribution at large $x$ is poorly constrained by data, the results of the fitting program can be different depending on small differences in the way the fitting is done. Second, in the large $x$ region, where the parton distribution functions are steeply falling, fixed order perturbation theory may be inadequate and one may need a soft gluon summation. This has not yet been done for jet production, but it has been done for top quark production by two groups \cite{13, 14}. The effect appears to be moderately large \cite{14} or small \cite{13} depending on the method of calculation.

We have seen that there is an excess of high $E_T$ jets compared to standard theory, but that this excess has a plausible explanation based on the standard gluon distribution function being too small at large $x$. Fortunately, there is a way to get at the possible new physics signal that is not very sensitive to the parton distributions. One can look at the jet production and examine the angular distribution of the two jets in each event that have the highest $E_T$s. Specifically, consider the cross section

$$\frac{d\sigma}{dM_{jj}d\eta_{jj}d\eta^*}.$$ \hspace{1cm} (5)

Here $M_{jj}$ is the jet-jet mass, $\eta_{jj} = (\eta_1 + \eta_2)/2$ is the rapidity of the jet-jet c.m. system, and $\eta^* = (\eta_1 - \eta_2)/2$ is the rapidity $(-\ln \tan(\Theta^*/2))$ of first jet as viewed in the jet-jet c.m. system. Look at the cross section as a function of $\eta^*$ for a fixed bin of $M_{jj}$ and $\eta_{jj}$. Dividing by the cross section integrated over $\eta^*$ gives the angular distribution. Since the angular distributions in quark-quark collisions, quark-gluon collisions, and gluon-gluon collisions are very similar, the net angular distribution is not very sensitive to the parton distribution functions.

Fortunately, the angular distribution is sensitive to a new physics signal associated with a term $\Delta \mathcal{L}$, such as that in Eq. 1. Vector boson exchange in QCD produces an angular distribution with the behavior

$$\frac{d\sigma}{d\eta^*} \propto \cosh(2\eta^*) \hspace{1cm} \eta^* \gg 1.$$ \hspace{1cm} (6)

A new physics term gives low angular momentum partial waves and thus few events with $\eta^* > 1$.

To look at this question, the CDF group \cite{15} has studied the ratio

$$\mathcal{R} = \int_{0}^{0.46} d\eta^* \frac{d\sigma}{dM_{jj}d\eta^*} \bigg/ \int_{0.46}^{0.80} d\eta^* \frac{d\sigma}{dM_{jj}d\eta^*}. \hspace{1cm} (7)$$

In Fig. 10, I show the CDF result. The data are compared to standard QCD theory (with standard partons) and to standard QCD plus a new physics
Figure 10: Dijet angular ratio as a function of the jet-jet mass. Theory curves show QCD predictions at next-to-leading order (NLO) and also at leading order. Also shown are expectations from including a new physics term with various values for the dimensionful parameter giving its strength. This plot is an earlier version of the CDF plot [15] submitted for publication.
term. The new physics term is similar to that in Eq. (1). Its strength is parameterized by a parameter $\Lambda^+$, which is essentially the $\Lambda$ in Eq. (1) with a conventional choice for $\tilde{g}$ if we choose the sign so that the new physics term interferes constructively with standard QCD. If we choose destructive interference, the new physics signal is parameterized by a parameter $\Lambda^-$. Choosing for the moment positive interference, the CDF single jet inclusive cross section favors $\Lambda^+ \approx 1.6$ TeV. The angular distribution data rule out this value of $\Lambda^+$ at the 95% confidence level [15]. A somewhat larger value of $\Lambda^+$ could still be consistent with both sets of data and QCD plus new physics with standard parton distributions. Choosing destructive interference, the conflict between the angular distribution data and the single jet data, taking standard partons in the theory, is not as strong. I have discussed the CDF data here, but D0 data [16] on the dijet angular distribution also shows no sign of a new physics signal.

I conclude that the angular distribution data disfavor the new physics hypothesis as the explanation of the high $E_T$ excess seen in the single jet cross section. The “more gluons” hypothesis remains as a plausible explanation. It also seems plausible that part of the explanation lies in corrections to the theory from soft gluon summation.

Acknowledgements

This work was supported in part by U.S. Department of Energy grant DE-FG03-96ER40969.

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