

Large Transverse Momentum Jet Production and the Gluon Distribution inside the Proton

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The CDF experiment has reported an excess of high- p_t jets compared to previous next-to-leading order QCD expectations. Before attributing this to new physics effects, we investigate whether these high- p_t jets can be explained by a modified gluon distribution inside the proton. We find enough flexibility in a global QCD analysis including the CDF inclusive jet data to provide a (25–35)% increase in the jet cross sections at the highest p_t of the experiment. Two possible sets of parton distributions are presented, and the effects of these on other existing data sets are presented. Further theoretical and experimental work needed to clarify unresolved issues is outlined. [S0031-9007(96)00655-2]

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Jet production in hadron collisions at the Fermilab Tevatron is an important process which presently provides the highest energy for studying hard scattering dynamics. Quark substructure or other new short distance physics would, if present, change the cross section for high- p_t jet production [1]. Such a deviation compared to next-to-leading order (NLO) perturbative quantum chromodynamics (QCD) calculations, based on commonly used parton distributions, has been reported by the CDF experiment [2] in the range $200 < p_t < 420$ GeV from 20 pb^{-1} of data. These data are shown in Fig. 1, indicating a clear 40% excess at $p_t = 350$ GeV compared to the NLO calculation [3]. The points are (Data-NLO QCD)/NLO QCD plotted versus the scaling variable $x_t = 2p_t/\sqrt{s}$. The theory is calculated with CTEQ3M parton distributions [4] and $\mu = p_t/2$. In order to determine whether this enhancement constitutes a signal for *new physics*, it is crucial to investigate possible explanations within the standard model.

One well-known uncertainty concerns the dependence of perturbative calculations on the choices of the renormalization and factorization scales. However, for inclusive jet cross sections, this dependence is quite small (10%) and is largely independent of p_t [3]. Similarly, changes in the strong coupling α_s resulting from variations of Λ_{QCD} mainly affect the normalization. Another source of uncertainty is the effect of summing large perturbative logarithms that may be important at large x_t and have been shown to be significant for high-mass lepton-pair production [5]. A corresponding study for jet cross sections has not yet been carried out. In addition, the long-standing disagreement between NLO QCD and the jet x_t scaling result from CDF [6] points to a potential inadequacy in the NLO calculations, or a possible mismatch between the theoretical and experimental jet definitions. However, it is not clear whether this effect, even if it is real, will extend to the x_t region under consideration.

Finally, there are the parton distributions which play a crucial role in determining the perturbative QCD “predictions” of the jet cross section. For the x_t range in question, the quark distributions are well determined by the precise data from deep inelastic lepton-nucleon scattering (DIS). The gluon distribution is small in this region, but its contribution to the cross section is still substantial—of the order of (25–40)%. The DIS data do not constrain the gluon much at large x , that role being usually played by direct photon production data in most modern global analyses [4]. In light of current theoretical and experimental uncertainties on direct photon production, it remains an open question whether the usual gluon

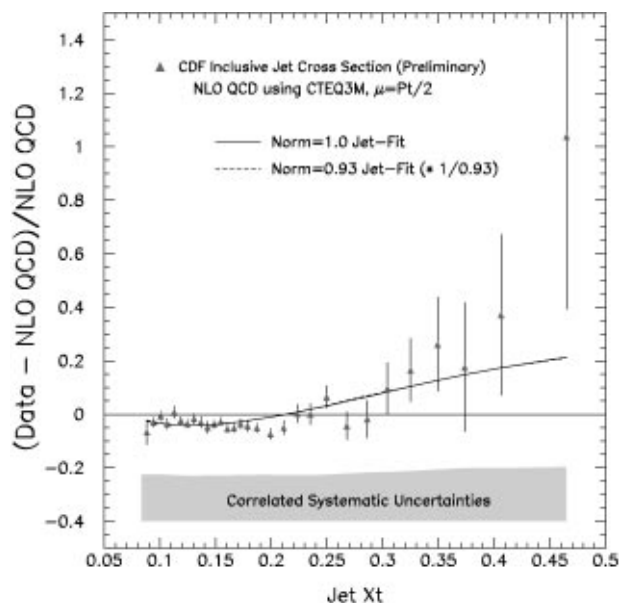


FIG. 1. The preliminary CDF jet data are compared to a NLO QCD calculation using the conventional CTEQ3M parton distributions (points), and the new parton distributions fit to the jet data (solid and dashed lines that lie on top of each other).

distributions can be modified in the relevant x region to accommodate the observed high- p_t jets. The purpose of this paper is to report on a quantitative study addressed to this particular question.

Global QCD analysis incorporating CDF jet data.—We have carried out a global QCD analysis [4] incorporating for the first time the CDF inclusive jet data. Our analysis includes the data with $p_t > 75$ GeV due to a number of potential theoretical and experimental problems relating to low- p_t jets. These include (1) possible problems in the match between theory and experimental jet definitions, such as fragmentation products outside the jet cone, (2) definitions of the “underlying event” coming from the proton-antiproton remnants, (3) scale uncertainty of NLO QCD calculations which becomes non-negligible at low p_t , and (4) k_t broadening (discussed later for direct photons).

We will describe two sample parton distribution sets [7] which illustrate two slightly different ways to enhance the theoretical cross section for the highest p_t jets by (25–35)%. The first, designated as the norm = 1.0 jet fit, fixes the CDF jet data normalization at the nominal value. However, without fixing the normalization of the jet data, the global analysis prefers a relative downward shift of the CDF data with respect to theory. The second example, the norm = 0.93 jet fit, is chosen to represent this possibility. Both solutions give good fits to the other data sets included in the global analysis.

Figure 1 includes two curves corresponding to NLO QCD calculations using parton distributions from the two new fits along with the CDF jet data: the solid line for the norm = 1.0 jet fit and the dashed line for the norm = 0.93 jet fit (divided by 0.93). The two new fits lie virtually on top of each other. The total χ^2 for the 1147 deep inelastic scattering (DIS), Drell-Yan, direct photon, and CDF jet data points in the norm = 1.0(0.93) jet fit is 1160(1130), clearly quite good. Both of the new fits remove much of the excess of the large p_t jet data, with a $\chi^2/N = 1.36$, which is quite acceptable considering this ignores the systematic uncertainties in the jet data. The quadratic sum of eight different CDF systematic uncertainties is shown as a shaded band below the data points. While the size of the band appears independent of jet p_t , individual uncertainties are not; they must be folded in for a proper analysis of errors. But for our purposes of determining if the jet data can be accommodated within QCD uncertainties, the proper procedure is to only fit the jets with statistical uncertainties and give this data set more weight in the global fit, then look closely at the other data sets in the fit to see if discrepancies arise. This does not imply that one obtains the best estimate of the true parton distributions in nature; it does prove that viable parton sets exist.

The gluon distributions from the two new fits are compared with that of CTEQ3M in Fig. 2 at $\mu = 150$ GeV, which corresponds to the middle of the high- p_t data range with $\mu = p_t/2$. In Fig. 2(a), $x^2G(x)$ is plotted against log x . [Since $x^2f(x)d \ln x = xf(x)dx$ is the momentum

fraction within dx , each curve in this plot directly depicts the distribution of momentum fraction carried by the gluon.] In Fig. 2(b), the ratio of the jet-fit gluons to that of CTEQ3M is shown over the $x > 0.1$ range. For the norm = 1.0 fit, we see a significantly increased $G(x)$ in the large- x region, with a compensating decrease in the medium- x region, and little change in the lower- x range. For the norm = 0.93 fit, $G(x)$ is uniformly shifted down from the norm = 1.0 fit in the range $0.05 < x$, with a compensating increase in the small- x region. This shows that the jet data used in the fit constrain the *shape* of $G(x)$ in the region $0.08 < x < 0.45$. Also shown in Fig. 2(b) is the ratio for $\mu = 5$ GeV, which is relevant for discussing comparisons with direct photon data later.

Comparisons to deep-inelastic scattering and direct photon data.—Deep-inelastic scattering data are indirectly sensitive to the gluon distribution through NLO corrections and scaling violations. But at large- x the effects on F_2 due to a modified gluon distribution can be easily compensated by small changes in the quark distributions and in Λ_{QCD} . A detailed look at the shifts in F_2 for the various DIS experiments shows no changes of more than 2% between CTEQ3 and the jet-fit results for all values of x and Q^2 .

Fixed target direct photon data have usually been regarded as the main source of constraint on the gluon distribution at large x . However, the constraint is weakened if the theoretical uncertainties unrelated to parton distributions are significant. The two most significant theoretical uncertainties for fixed target direct photons are the factorization scale dependence and the possible k_t broadening

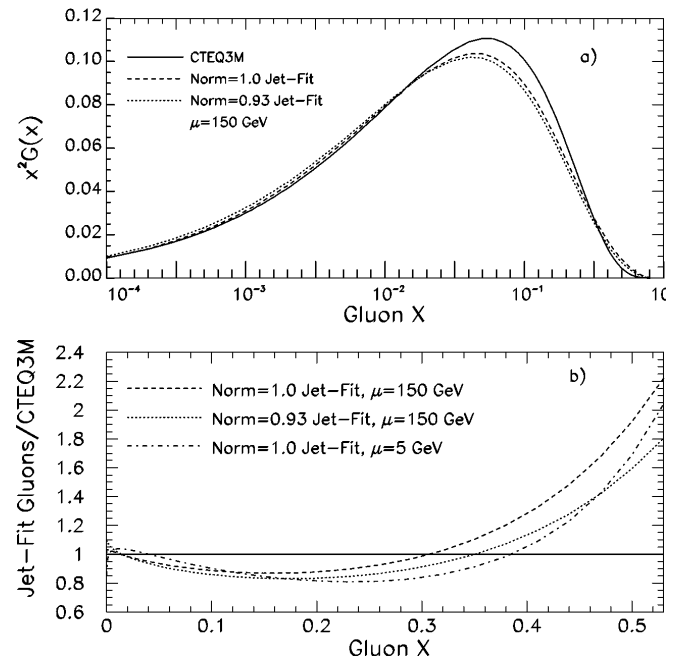


FIG. 2. (a) The gluon distributions at $\mu = 150$ GeV from the norm = 1.0 and the norm = 0.93 jet fits are compared to that of CTEQ3M; (b) the ratio of the two jet-fit gluons to CTEQ3M (see text).

effect. The latter is suggested by a recent global study of all direct photon data [8]; it involves the likelihood that NLO QCD does not contain enough of the k_t of the initial state gluon radiation, thus leading to an underestimate of low- p_t photon cross sections. Since the publication of Ref. [8], there have been two developments which further support the basic idea of k_t broadening in direct photon production: (1) A new calculation of collider direct photon production incorporating NLO QCD hard scattering plus initial state parton showers [9] shows good agreement with the shape of the CDF direct photon data [10]. (2) The preliminary, high-statistics, E706 direct photon data [11] (the most precise measurement yet at fixed target energies) also show a very significant excess of photons compared with NLO QCD calculations.

In Fig. 3(a), the WA70 direct photon data are compared to NLO QCD for a variety of scales, using conventional ABFOW parton distributions [12]. The change in theoretical value in going from optimized μ (used by ABFOW and MRS) to $\mu = p_t$ is about 50%. Next, to show the effect due to a possible k_t broadening, we also include in Fig. 3(a) a curve corresponding to a scale choice of $\mu = p_t$ plus an average k_t broadening of 0.9 GeV using the algorithm of reference [13]. The number 0.9 GeV comes from the WA70 analysis of their diphoton measurement [14]. We see that the broadening correction is also about 50%, and brings the $\mu = p_t$ curve into agreement with the data.

One might expect the fixed target data to rule out the jet-fit gluons because, naively, the differences between the

jet-fit and conventional gluons at a typical $\mu = 150$ GeV might be significantly amplified at the low μ value of the fixed-target experiments. But this is not the case: The crossing point between the jet-fit and CTEQ3M gluons occurs around $x \approx 0.4$ at $\mu = 5$ GeV, as shown in Fig. 2(b). The comparison of the jet-fit results with the WA70 direct photon data is shown in Fig. 3(b). In the solid and dashed curves we have used a scale of $\mu = p_t/2$ with no k_t corrections. In the dotted curve we used $\mu = p_t$ and a k_t broadening of 0.9 GeV. All three curves are consistent with the WA70 data, which have a 10% normalization uncertainty. These results clearly demonstrate that given the uncertainties with scale choice and k_t broadening the new gluon distributions are fully consistent with the WA70 data. As mentioned above, similar results hold for other fixed target direct photon data sets.

UA2 inclusive jet data.—Of considerable interest to our study of high- x_t jets is the earlier UA2 inclusive jet cross section [15] measurement. The data have high statistics, are in the same x range as the CDF measurement, and cover a similar rapidity range. Although the two experiments are at different scales set by the respective p_t ranges, the QCD evolution between the two is not significant, hence they essentially probe the same parton distributions. There are some important differences however. For the same x_t , the UA2 jets are at lower p_t , and may be subject to the additional low- p_t uncertainties that were discussed above. In addition, the UA2 data are based on a jet finding algorithm that less closely follows the infrared-safe “Snowmass” algorithm [16], in fact, the UA2 publication itself expresses caution concerning comparisons with NLO QCD. In our NLO theory calculations for CDF we use the Snowmass algorithm with $R = 0.7$ at the parton level, while we model the UA2 algorithm with the modified Snowmass algorithm [17] with $R = R_{\text{sep}} = 1.37$.

Figure 4 shows the CDF and UA2 jet data compared to these NLO QCD calculations using CTEQ3M parton distributions, and $\mu = p_t/2$. The CDF data points have statistical uncertainties only, while the UA2 points include statistical and p_t -dependent systematic uncertainties (this is the way the two different groups present their data). There is an additional 32% normalization uncertainty in the UA2 measurement, while the CDF correlated systematic uncertainty band is shown at the bottom of the plot. The UA2 data are systematically larger than the theory (but within the normalization uncertainty), but in general there is no distinct shape difference as is seen in the CDF data. If one ignores experimental uncertainties, the two experiments appear to disagree with each other. But clearly the correlated systematic uncertainties must be understood before conclusions can be drawn.

In conclusion, if the excess of high- p_t jets at CDF persists, it will be one of the most important challenges for QCD. This paper has considered in detail only one possible conventional theoretical source, parton

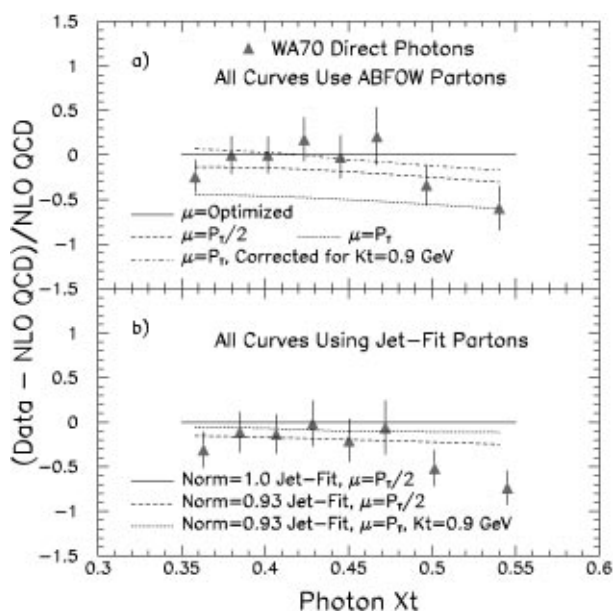


FIG. 3. The WA70 direct photon data are compared to NLO QCD calculations using conventional, ABFOW parton distributions in (a). Different choices of scale are shown as well as the effect of adding additional k_t broadening to the theory. In (b) the WA70 direct photon data are compared to NLO QCD calculations using the two sets of jet-fit gluons (see text).

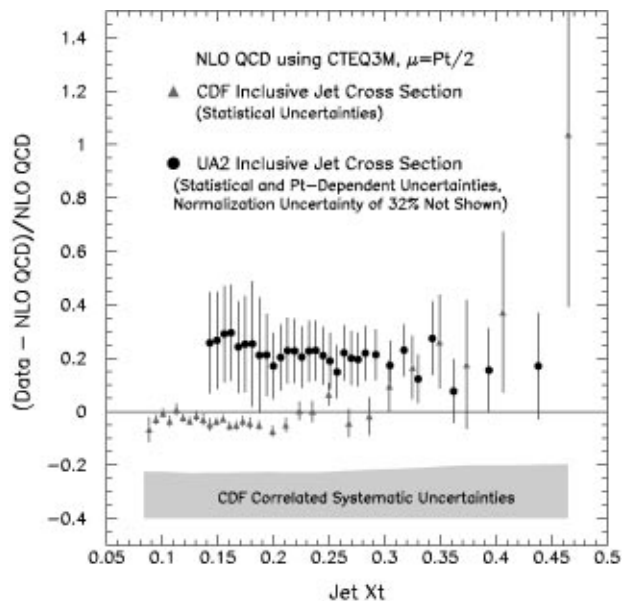


FIG. 4. The CDF and UA2 jet production measurements are compared to NLO QCD calculations (see text).

distributions, especially the gluon distribution. Beyond the obvious need for an independent, robust, method of measuring high- x gluons, we list five potential studies or calculations that are needed to understand the excess: (1) measuring the dijet angular distribution as an independent QCD test that differentiates between parton distributions and new interactions, (2) incorporating the correlated systematic uncertainties from CDF and UA2 jet measurements into the global analysis to determine if they are compatible, (3) confirming and understanding the jet x_t scaling result from CDF with a new lower energy run at Fermilab, (4) performing the large- x resummation for jet production as has been done for the Drell-Yan process to see if the excess can be so explained, and (5) performing a p_t resummation of soft gluons in the direct photon calculation to reduce the uncertainties due to the scale dependence and k_t broadening, hence sharpening the constraints on the gluon distribution due to these two complementary processes. Before one can claim there is *new physics* in the CDF jet excess, it is likely that all five of these future studies will be necessary.

Note added.—A recent paper from the GMRS group [18] has stated it is impossible to obtain parton distributions in agreement with the CDF jet data. Their attempt to modify the quark distributions to fit the jet data results

in a χ^2 of 20703 for 128 BCDMS data points. In contrast, the two jet fits presented in this paper give rise to a χ^2 of 173 and 175, respectively, for 168 BCDMS data points. It appears the reason that GMRS were not able to find satisfactory solutions like ours is that they did not allow sufficient flexibility in the gluon distribution shape.

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