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# QCD Tests at CDF

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## 1 Introduction

Jet measurements at CDF provide the possibility of exploring new physics beyond the Standard Model and supply a rich testing ground for the properties of QCD. Cross section measurements at the highest available jet $E_T$ are potentially sensitive to the production of new particles or to the presence of quark substructure; deviations from the QCD predictions may signal the onset of new physics. Within the framework of conventional QCD, jet measurements can be used to extract fundamental QCD parameters such as $\alpha_s$. Large datasets with good statistics over a large kinematic range can be combined with the improved theoretical calculations to yield precision tests (at the 10–20 % level) for both next-to-leading order (NLO) QCD matrix-element calculations and Parton Shower (PS) models of QCD. Owing to the sensitivity of jet production on the gluon distribution, these data provide direct constraints on the gluon distribution in the range $10^{-3} \lesssim x \lesssim .5$.

Many QCD analyses are being pursued at CDF. Inclusive, two-jet and multijet differential cross section and angular-distribution measurements test the detailed predictions of perturbative QCD. Photon cross section and angular-distribution measurements provide further tests and additional constraints on the gluon distribution. Studies of heavy flavor production inside jets and in association with photons yield information on gluon splitting and the heavy-flavor content of the proton. Studies of jet production in association with $W$'s and $Z$'s provide complementary tests of QCD and parton distributions. Finally, the diffractive and soft regions are probed by the study of events with rapidity gaps. In this talk, we will concentrate on inclusive single-jet and dijet production, with particular emphasis on the observed excess of events at high $E_T$.

# 2 Jet Measurements

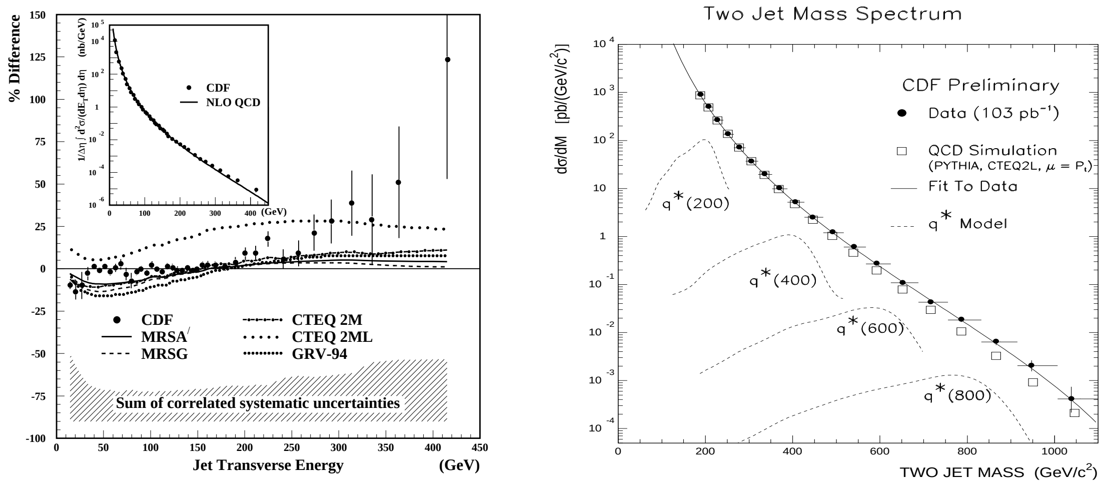
## 2.1 The Inclusive Jet Cross Section

The single-jet inclusive cross section is a probe of new physics at the highest available energies. The measurement provides a stringent test of NLO ($O(\alpha_s^3)$) QCD calculations over a huge dynamic range and can be incorporated into a global parton distribution analysis to provide a direct constraint on the gluon distribution for the $x$ range $10^{-2} \lesssim x \lesssim 0.5$.

The measurement[1] is based on $19.5 pb^{-1}$ of data, recorded by the CDF detector[2] during the 1992-93 (Run 1A) Tevatron $p\bar{p}$ collider run at $\sqrt{s} = 1800$ GeV. The data were collected using triggers with $E_T$ thresholds of 20, 50, 70 and 100 GeV. These triggers were prescaled by factors of 500, 20, 6 and 1 respectively. Minimum bias data were used for the measurement in the jet $E_T$ range 15-25 GeV. Jets were reconstructed using a cone algorithm with a cone-radius $R$ given by $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$. Here, $\eta = \log(\tan(\theta/2))$, where $\theta$ is the polar angle with respect to the beam line and $\phi$ is the azimuthal angle around the beam. Jets were further required to lie in the pseudorapidity interval $0.1 \le |\eta_{jet}| \le 0.7$. The measured $E_T$ spectrum is corrected for detector and smearing effects arising from nonlinearities, energy losses and finite energy resolution via an unsmearing procedure.[3]. A trial true spectrum is smeared by detector effects and compared with the measured spectrum. The procedure is iterated until the best match is obtained.

In Fig. 1a), the corrected cross section is compared with the NLO QCD prediction[4] calculated using MRSD0' parton distributions with a renormalization and factorization scale choice of $\mu = E_T/2$. Other parton distribution choices are also shown. Below $E_T = 200$ GeV, there is excellent agreement with the prediction over the six orders of magnitude of dynamic range spanned by these data. Above 200 GeV, there is an excess of events above the NLO QCD prediction.

The systematic errors on the cross section have been evaluated by varying each of the sources of systematic uncertainty by $\pm 1$ standard deviation and repeating the unsmearing procedure. The shaded band in Fig. 1a) shows the sum in quadrature of these errors. No single source of systematic error can account for the excess at high $E_T$. An attempt to explain the excess as a systematic effect requires the introduction of a large (several sigma) variation in




(a) (b)

Figure 1: A comparison of a) the inclusive jet cross section with the NLO QCD prediction evaluated with MRSD0' parton distributions and b) the dijet mass spectrum with the predictions of PYTHIA and the CDF detector simulation.

least two sources of systematic error in such a way as to obtain a cancellation of effects below 200 GeV and a rising enhancement above 200 GeV.

## 2.2 The Dijet Mass Analysis

This analysis is of interest because it provides an important cross check of the inclusive jet measurement. Of course, it must be remembered that the two measurements are highly correlated since they have many events in common, particularly at high jet $E_T$, where the dijet mass spectrum is dominated by events whose pseudorapidities lie in the central regions of the detector.

The results shown here are based on $103pb^{-1}$ of data collected from Run 1A and 1B. The triggers and the jet reconstruction algorithms are identical to those described for the inclusive jet analysis. The dijet mass is defined as the invariant mass associated with 4-vectors of the two highest $E_T$ jets in the event. The jets are required to satisfy $|\eta_1|, |\eta_2| \leq 2.0$, and the events are required to have $\cos\theta^* \leq 2/3$, where $\theta^*$ is the center-of-mass scattering angle. This analysis differs from that of the inclusive jets in that the jet energies have been corrected for the calorimeter response but no unsmearing corrections are applied to the spectrum.

In Fig 1b), the measured dijet mass spectrum and the predictions of a LO QCD PS Monte Carlo (PYTHIA) together with a full CDF detector simulation are compared with the best fit to the CDF data. (The QCD prediction is normalized to the data in the mass range 150-300 GeV/$c^2$.) Once again, there is a clear excess of events above a dijet mass of 400 GeV/$c^2$. The excess is consistent with that observed for the inclusive jet spectrum. This analysis uses five times more data than the inclusive jet analysis and establishes that the observed excess is not a statistical fluctuation. Furthermore, since no unsmearing corrections are applied to these data, it is clear that the excess cannot be simply a pathology of the unsmearing corrections.

The dijet angular distribution is of particular interest because it is a powerful probe of the jet-production mechanisms and may be sensitive to anomalous jet production arising from new physics. For example, effective models of quark compositeness containing[5] four-Fermi contact interactions predict a rise in the jet cross section at high $E_T$ that resembles the behavior of the CDF data. However, since these models also predict an enhancement in the isotropic contribution to jet production, the dijet angular distribution can be used to discriminate between conventional QCD and this type of new physics. At present, this analysis is underway; however, until the theoretical uncertainties and the experimental systematics are better understood, it is not possible to make a definitive claim about the presence or absence of new physics.

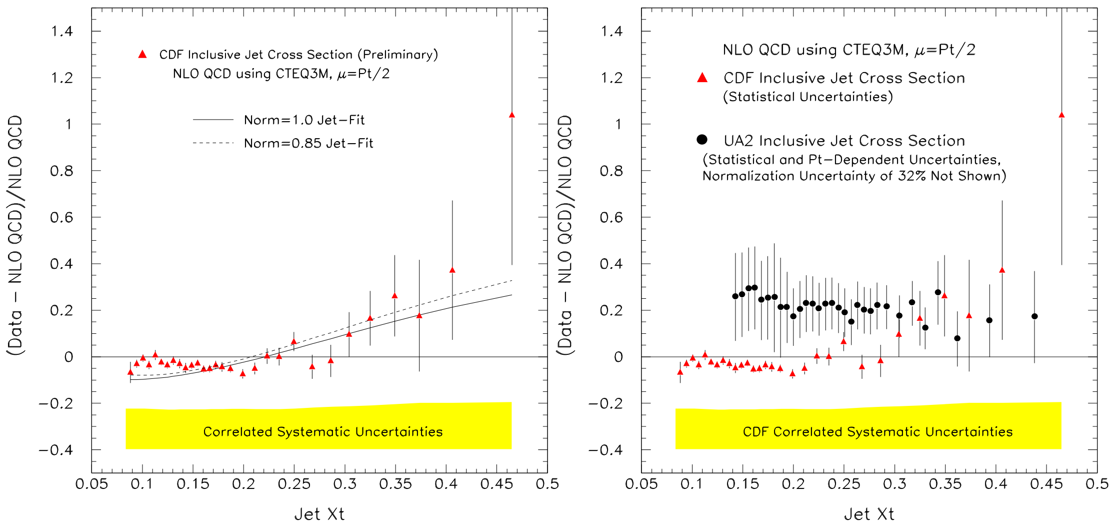
# 3 Possible Explanations for the High-$E_T$ Excess

## 3.1 Sources of Uncertainty on the Cross Section

In this section, we consider the possibility that the explanation for the high $E_T$ excess can be found within the framework of conventional QCD. There are a number of well-known theoretical uncertainties in the perturbative calculations: The dependence on the choices for the renormalization and factorization scale is small, and results in about a 10 % change, with very little dependence in $E_T$.[4,6] Changes in the value of $\alpha_s$ that arise from variations of $\Lambda_{QCD}$[7,8] also affect the overall normalization of the cross section rather than its shape. Another possible uncertainty is the effect of resumming large logarithms of $x_T$. This resummation has a substantial effect on the predictions for Drell-Yan production,[9] but has not yet been carried out for jet production. One hint that this will not be a large correction for CDF jets comes from an examination of the K-factor (ratio of NLO to LO QCD) as a function of the jet $E_T$: Typically, divergent behavior of this quantity can signal the need for resummation. In our case, it is well behaved and flat over the entire CDF $E_T$ range. Finally, there are uncertainties arising from the choice of parton distribution function (PDF). As can be seen in Fig. 1a), a variation in the choice from the commonly available sets of PDF gives about 15% variation in normalization, with small shape differences. However, these changes do not reflect the true uncertainty due to PDF choice, since the parametrizations available through the usual PDF sets are limited. We now look in detail at the possibility that the excess can be explained by a new parton distribution.

## 3.2 A New Gluon Distribution

For a jet $E_T$ in the range 200–400 GeV, the fraction of the jet cross section attributable to quark-quark scattering rises from about 50% to 85%, whereas that attributable to quark-gluon scattering falls from about 40% to 10%. Since the quark distributions are strongly constrained by precise data from deeply inelastic scattering (DIS), one must look to the gluon distribution




(a) (b)

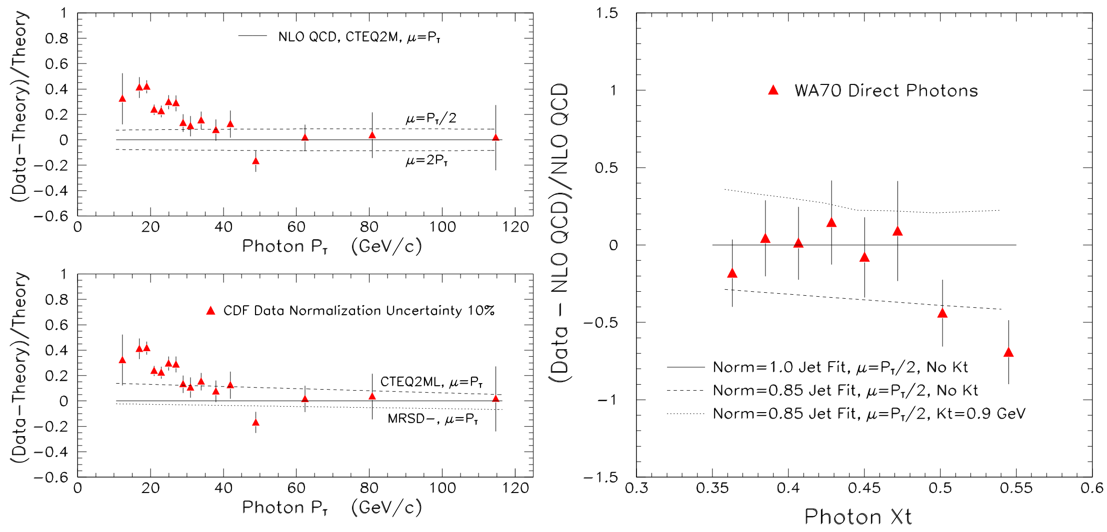
Figure 2: a) A comparison of the CDF jet data to a NLO QCD calculation using CTEQ3M parton distributions (triangles) and a) the new parton distributions fitted to the jet data (solid and dashed lines) and b) the UA2 data (circles) measured over the same $x$ range.

to produce the change required to explain the excess. In fact, in order to produce about a 20% excess at 400 GeV, the gluon distribution needs to be doubled. Now, the strongest constraints on the gluon distribution come from fixed-target direct photon production. (DIS data provide little constraint at large $x_T$.) So, the question becomes: given the present uncertainties on direct photon production, can the gluon distribution be modified in such a way that it explains the high-$E_T$ jet excess without disrupting the agreement between the data and NLO QCD for direct photon production? We now present the results of such an analysis.[10)]

In Fig. 2a), we show the results of incorporating the CDF jet data into a global QCD analysis that includes the collection of data sets used in previous analyses.[7)] Owing to the theoretical and experimental uncertainties associated with the measurement of low $E_T$ jets, the jet data below 75 GeV have not been included in the fit. Two examples of the resulting fits are shown. The "Norm = 1.0 Jet Fit" is a result of fixing the normalization of the CDF jet data at its nominal value, whereas the "Norm = 0.85 Jet Fit" allows the normalization to float to its preferred value. Both of the fits remove much of the large $E_T$ excess, whilst still giving good overall fits to the other data sets in the global analysis. Qualitatively, the new gluon distributions both show an enhancement over the CTEQ3M distribution at large $x$, and owing to the constraints imposed by the momentum sum rule, show a corresponding decrease in the medium-$x$ region.

### 3.3 Direct Photon Data and $k_T$ Smearing Effects

The inclusive photon cross section has been measured at CDF[11)] and other collider and fixed target experiments. At CDF, this measurement provides a precision test of NLO QCD ($O(\alpha_s^3)$) with small systematic errors of around 10%. Since the Compton process contributes a significant




(a) (b)

Figure 3: The inclusive photon cross section measured at a) CDF and b) WA70. The CDF data is compared with the NLO QCD prediction evaluated with different renormalization scale and PDF choices. The WA70 data is compared with the NLO QCD prediction evaluated using the jet-fit gluon distributions with and without a $k_T$ smearing correction.

fraction of the overall production rate, this measurement provides constraints on the gluon distribution in the $x$ range .01–.1.

In Fig. 3a), we see that the CDF data agree well with the predictions of NLO QCD[12)] for $p_T > 40$ GeV. However for low $p_T$, there is a 35% excess in the data that cannot be explained by variations in the choice of renormalization scale or PDF. Recently, it has been observed that similar low-$p_T$ excesses may be observed in other fixed-target and collider direct-photon experiments and that $k_T$ smearing effects may provide an explanation for this behavior.[13)] Here the idea is that multiple soft gluon emissions from the initial state, which are not included in the NLO QCD calculations, induce a smearing correction on the inclusive cross section. New evidence in support of the $k_T$ smearing hypothesis includes the observation of a significant excess above NLO QCD in the preliminary data from E706 and the results of a new calculation[14)] that incorporates the effects of initial state parton showers into the NLO QCD framework.

## 3.4 Compatibility of the New Gluon Distribution with Other Data

As previously mentioned, fixed-target direct photon data have provided the strongest constraints on the large-$x$ gluon distribution in previous global analyses. However, the possibility of significant $k_T$ smearing effects coupled with the relatively large uncertainty due to the choice of renormalization scale means that these constraints may be considerably weakened. In fact, using the WA70 data as an example, it has been demonstrated[10)] that the effects of a change in the renormalization scale from $p_T$ to $p_T/2$ can be compensated by the addition of a $k_T$ smearing correction. In Fig. 3b), we show a comparison of the WA70 data with the NLO QCD predictions evaluated using the jet-fit gluon distributions and a renormalization scale choice of

$\mu = p_T/2$. The effects of a $k_T$ smearing correction (using a value for the mean $k_T$ measured by the WA70 diphoton analysis[15)]) can be seen by comparing the dotted and dashed curves. Given these uncertainties, we see that the new gluon distributions are completely consistent with the WA70 data.

Another data set that is relevant to our discussion is the high statistics UA2 inclusive jet data set, which covers a similar $x$ and rapidity range as the CDF measurement. In Fig. 2b) we compare the two measurements with the NLO QCD predictions. For the calculation of the UA2 cross section, we have modelled their jet algorithm as closely as possible within the context of NLO QCD using a cone of $R = R_{sep} = 1.37$. However, this procedure has a larger than usual theoretical uncertainty of around 20%. The CDF points have statistical errors only, whereas the UA2 points include an additional $E_T$-dependent systematic error. The UA2 measurement also has an additional 32% normalization uncertainty. Taken at face value, the two data sets disagree; the UA2 data do not exhibit the shape changes seen in the CDF data. However, one must bear in mind that UA2 jets are measured at lower $E_T$ and may be subject to additional uncertainties and that both experiments have correlated systematic errors that must be taken into account to evaluate properly whether or not the two data sets are compatible.

# 4 Summary and Conclusions

We have presented results for the inclusive jet cross section and the dijet mass distribution. The inclusive cross section and dijet mass both exhibit significant deviations from the predictions of NLO QCD for jets with $E_T > 200$ GeV, or dijet masses $> 400$ GeV/$c^2$.

We have shown that it is possible, within a global QCD analysis that includes the CDF inclusive jet data, to modify the gluon distribution at high $x$. The resulting increase in the jet cross-section predictions is 25–35 %. Owing to the presence of $k_T$ smearing effects, the direct photon data does not provide as strong a constraint on the gluon distribution as previously thought. A comparison of the CDF and the UA2 jet data, which have a common range in $x$, is plagued by theoretical and experimental uncertainties, and cannot at present confirm the CDF excess or the modified gluon distribution.

Clearly, there is much work to be done. One would like to find additional evidence for the high-$x$ gluon distribution at CDF and other experiments. Preliminary E706 data[16)] shows significant enhancements over the NLO QCD predictions at both low and high $x$. Further study of the apparent discrepancy between the CDF and UA2 is warranted. The inclusion of the correlated systematic errors into the full global analysis will determine if the two data sets are compatible. Particular attention should be paid to the theoretical and experimental uncertainties on low $E_T$ jets and on the accurate modelling of the experimental jet reconstruction algorithms. In this context, a nonperturbative leakage of a small amount of energy from the jet cone has the potential to alter the jet-energy scale and warrants further experimental and theoretical study. Data from LEP and from the upcoming $\sqrt{s} = 630$ GeV Tevatron run may shed some light on this issue. The constraints on the gluon distribution imposed by the direct photon data can be improved by better understanding $k_T$ smearing effects. Although there is some evidence from PS models that QCD radiation can reproduce such effects, quantitative results from a QCD calculation involving a resummation of multiple soft gluon emissions is necessary to confirm or reject the $k_T$ hypothesis. Similarly, a large-$x$ resummation calculation, such as has been performed for the Drell-Yan process, is necessary to rule out the possibility that the CDF excess is caused by an inadequacy of NLO QCD. Finally, one should extend the earlier studies[18] of the various types of new strongly interacting operators that can cause an excess in the jet cross section to consider the effects of such operators on the dijet angular distribution.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