



# Fermi National Accelerator Laboratory

FERMILAB-Conf-95/192-E

CDF and D0

## Inclusive Jet Production at Tevatron

A.A. Bhatti

For the CDF and D0 Collaborations

*Fermi National Accelerator Laboratory  
P.O. Box 500, Batavia, Illinois 60510*

*Rockefeller University  
1230 York Avenue, New York, New York 10021*

July 1995

Published Proceedings for the *10th Topical Workshop on Proton-Antiproton Collider Physics*,  
Fermilab, Batavia, Illinois, May 9-13, 1995

## Disclaimer

*This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.*

## Inclusive Jet Production at Tevatron

Anwar Ahmad Bhatti <sup>1</sup>  
Department of Physics  
The Rockefeller University  
1230 York Ave New York USA

### Abstract

The CDF and DØ Collaborations have measured the inclusive jet cross section using 1992-93 collider data at  $\sqrt{s} = 1800$  GeV. The DØ measurement is higher than NLO QCD predictions, though within systematic uncertainties. The CDF measurement is in very good agreement with NLO QCD predictions for transverse energies ( $E_T$ ) below 200 GeV. However it is systemically higher than NLO QCD predictions for  $E_T$  above 200 GeV. The CDF measurement of two-jet mass and total transverse energy spectra also show a similar excess above QCD predictions at higher  $E_T$ .

## 1 Introduction

The measurement of the inclusive jet cross section provides a conceptually very simple, but still fundamental test of QCD. The next-to-leading order  $\mathcal{O}(\alpha_s^3)$  calculations [1, 2, 3] have small theoretical uncertainty. The predicted cross section is not very sensitive to the choice of the renormalization/factorization scales except at very low  $E_T$  ( $E_T < 50$  GeV). However there is a large ( $\approx 30\%$ ) uncertainty due to different choices of parton distribution function (PDF) and a precise measurement of the inclusive jet cross section can provide a useful tool to differentiate between them. Deviations from the standard model due to quark or gluon substructure are likely to be observed in large angle parton scattering, making studies of high  $E_T$  jets an attractive method of searching for hints of new physics [4, 5].

Jet production at the Tevatron is dominated by gluon-gluon scattering at low  $E_T$  whereas at high  $E_T$  the main contribution comes from quark-quark scattering. The gluon-quark scattering is  $\approx 25\%$  of the inclusive jet cross

---

<sup>1</sup>Representing CDF and DØ collaborations

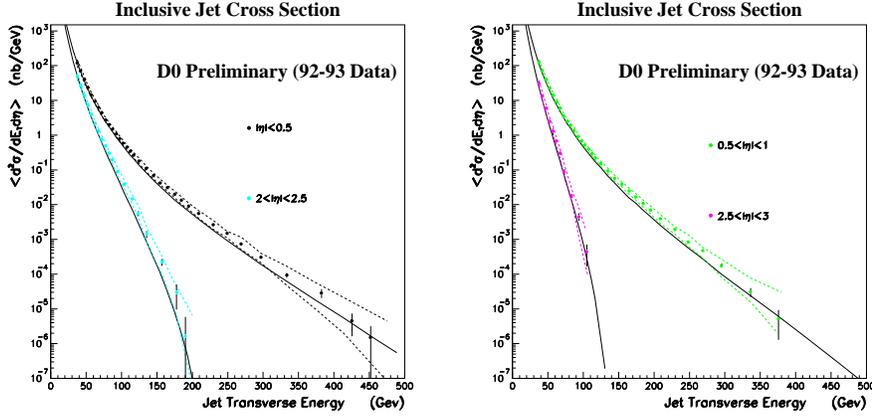


Figure 1: Inclusive jet cross section measured with DØ detector in four different  $\eta$  regions. The bars are statistical errors and the band is the uncertainty from the energy scale corrections. The EKS predictions using CTEQ2M parton distribution functions are shown in solid lines.

section at low  $E_T$ , going up to 50% at 150 GeV and decreasing to 20% at 350 GeV.

The quark distributions derived from  $F_2$ ,  $F_3$  measured in Deep Inelastic Scattering (DIS) experiments[6, 7, 8] are known to a few percent, especially in the  $0.01 > x > 0.5$  range. The new HERA[9] data along with fixed target DIS experiment constrains the gluon distribution at low  $x$  whereas the fixed target direct photon experiments [10, 11] cover the range  $0.3 \leq x \leq 0.5$ . The inclusive jet production at  $\sqrt{s} = 1800$  GeV covers the range  $0.017 \leq x \leq 0.45$  and can be used to test these partons distribution functions.

## 2 DØ Inclusive Jet Cross Section

Based on a  $13pb^{-1}$  data sample collected during the 1992-93 run, the DØ collaborations has measured inclusive jet cross section for three cone sizes and for four pseudo-rapidity ranges. The DØ detector is described elsewhere[12]. It has a uranium-liquid argon calorimeter with full coverage for a pseudo-rapidity range  $|\eta| < 4.1$ , for detection of final state jets. The calorimeters

are azimuthally symmetric and have electromagnetic and hadronic resolution of  $15\%/\sqrt{E}$  and  $50\%/\sqrt{E}$ , respectively. The jets are reconstructed with a fixed cone algorithm. The  $E_T$  of the jet is calculated as a sum of  $E_{T_i}$ 's deposited in each tower  $i$  inside the cone and the position  $(\eta_0, \phi_0)$  is obtained from the  $x, y, z$  components of the energy in each tower:

$$\begin{aligned}
E_x &= \sum_i E_{x_i} & E_y &= \sum_i E_{y_i} & E_z &= \sum_i E_{z_i} \\
\tan \phi_0 &= \frac{E_y}{E_x} & \cos \theta_0 &= \frac{E_z}{\sqrt{E_x^2 + E_y^2 + E_z^2}} & \eta_0 &= -\ln \tan \frac{\theta}{2} \\
E_T &= \sum_i \sqrt{E_{x_i}^2 + E_{y_i}^2}
\end{aligned}$$

The noise and background is removed by requiring that  $0.05 < \text{EMF} < 0.95$ ,  $\text{HCF} > 0.1$  and  $\text{CHF} < 0.4$  where EMF and CHF are the fraction of transverse energy deposited in electromagnetic and hadronic modules of calorimeters. HCF is the ratio of  $E_T$  of second most energetic cell to most energetic cell in a jet. Moreover  $E_T/E_T^{\text{Jet1}}$  is required to be less than 0.7 to remove electronic noise and cosmic showers. The overall efficiency of these cuts is greater than 90% and the noise rejection is greater than 98%. The jet energy scale is determined by  $\gamma$  - *jet* balancing. The electromagnetic energy scale was calibrated using LEP results on  $Z$  boson mass and  $D\bar{O}$  measurement on  $Z \rightarrow e^+e^-$ . The fractional jet  $E_T$  resolution is approximately  $85\%/\sqrt{E_T}$ . The jet  $E_T$  spectrum is corrected for resolution smearing by assuming a hypothetical unsmearred cross section which is a function of  $E_T$  and  $\eta$ . This function was smeared with the measured  $E_T$  resolution and fit to the data. The data were corrected by the ratio of the hypothetical cross section to the smeared cross section. The uncertainty on the cross sections due to energy scale corrections and unsmearing procedure is  $\approx 35\%$ . Other uncertainties are acceptance corrections and background removal and contribute about 7%. The luminosity calculation has an uncertainty of  $\approx 12\%$ . The corrected cross section for the four  $\eta$  ranges is compared with  $\alpha_s^3$  predictions[1] using CTEQ2M[13] parton distribution functions in Fig 1. There is good qualitative agreement between theory and experiment. Although theory predictions are systematically below the experimental results, they are well within the uncertainty band (dotted lines).

Figure 2 shows the inclusive jet cross section for cone size ( $R$ ) 0.5 divided by the cross section for  $R = 0.7$  in the central region ( $-1 < \eta < 1$ ). The cross section for  $R = 0.3$  divided by the cross section for  $R = 0.7$  is also shown. By taking the ratio, the luminosity uncertainty is eliminated and

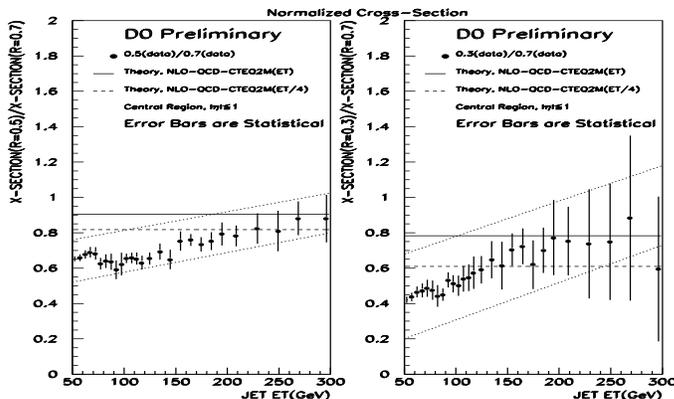


Figure 2: Ratio of the inclusive jet cross sections (0.5/0.7) and (0.3/0.7), respectively, compared to Jetrad theory predictions

the energy scale uncertainty is minimized. The data are compared with NLO QCD predictions [3] for two renormalization scale  $\mu = E_T$  and  $E_T/4$ . As expected the cross section decreases with the jet cone size. The theory prediction[3] are constant as a function of  $E_T$  whereas the data shows a small slope. Naively, one would have expected a small slope in theory ratio because the jet becomes more collimated as the  $E_T$  of the jet increases. It should be noted that the data have not been unsmearred and this may be the cause of apparent disagreement between data and the theory. Further studies of the systematic effects are underway.

### 3 CDF Inclusive Jet Cross Section

CDF collected  $19.3 \text{ pb}^{-1}$  of data during the 1992-93 collider run. The CDF detector has been described elsewhere[14]. CDF used four triggers with  $E_T$  thresholds of 20, 50, 70 and 100 GeV with pre-scale factors of 500, 20, 6 and 1 respectively, for jet studies. These four triggers along with minimum bias events are used to measure the inclusive jet cross section in the  $E_T$  range 15-440 GeV in the central region ( $0.1 < |\eta| < 0.7$ ). The data are corrected for trigger efficiency. The cosmic rays, main ring splash and other

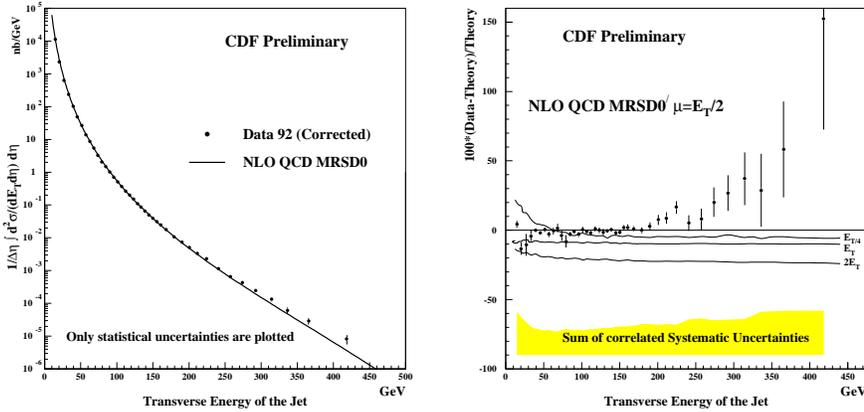


Figure 3: Comparison of Jet Cross Section with NLO QCD predictions

detector backgrounds are rejected by requiring that the out-of-time energy in the hadron calorimeter is less than 8 GeV and  $\cancel{E}_T / \sum E_T < 6.0$  where  $\cancel{E}_T$  is the missing transverse energy and  $\sum E_T$  is the total transverse energy in the event. The jets are reconstructed using a fixed cone algorithm [15] which is similar to the one used in the NLO theory [1, 3], with cone size,  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ . The data are corrected for detector effects using an unsmearing procedure [16]. The *measured* jet transverse energy is parameterized as a function of  $E_T^{true}$ . The  $E_T^{true}$  is defined as the sum of  $E_T$  of all particles in a cone  $R$  around the jet direction. We call this parameterization the response function. The detector Monte Carlo calorimeter response was tuned using pion and electron test beam data from 10-223 GeV. Isolated tracks from collider data are used for lower momenta. A very large sample of di-jet events was generated and fragmented using the Feynman-Field fragmentation model which was tuned to CDF data. These simulated data were used to evaluate the response functions. A hypothetical cross section as a function of  $E_T$  is smeared with resolution functions and fit to the data. The data are corrected by the ratio of the best fit hypothetical cross section to the smeared cross section. The corrected cross section, shown in Fig.3(a), is compared with the NLO QCD predictions using MRSD0' [17] parton distributions and renormalization/factorization scale  $\mu = E_T/2$ . There is an impressive agreement between data and NLO QCD predictions over seven orders of magnitude. However the data deviate from the theory predictions

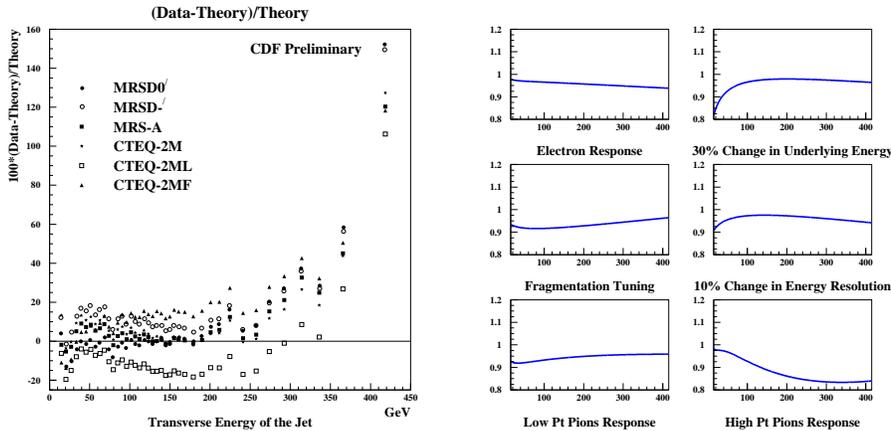


Figure 4: (a) Comparison of Jet Cross Section with NLO QCD predictions using different sets of parton distribution functions. (b) Some of the systematic uncertainties associated with the Inclusive Jet Cross Section as a function of  $E_T$ .

for  $E_T$  above 200 GeV as seen in the linear comparison of theory and data in Fig.3(b). The CDF measurement from 1988-89 data shows a similar excess at high  $E_T$ , though it is statistically less significant[19].

The possible explanations of excess in jet production at high  $E_T$  include

- Input parameters in the theory
- Corrections to the NLO QCD predictions
- Jet energy scale and jet fragmentation functions

The NLO QCD has a very weak dependence on the choice of renormalization and factorization scales. For the sake of simplicity, these scales( $\mu$ ) are generally set equal. The predicted cross sections for  $\mu = E_T/4$ ,  $E_T$  and  $2E_T$  divided by cross section for  $\mu = E_T/2$  are shown in Fig.3(b). Apart from normalization, the theory has a very small dependence on choice of  $\mu$  scale except at very low  $E_T$ .

Although the modern parton distribution functions (PDF) are derived from the same experimental data, they differ because of the choice of the shape of the gluon distribution at very low  $x$  and other assumptions in the fitting procedure. The CDF inclusive jet cross section is compared to NLO

QCD predictions using various sets of partons distribution functions [17, 13] in Fig. 4. Theory predictions using different PDF differ from each other in normalization by about 30%. Their shape is also similar except for  $E_T$  below 80 GeV. After normalizing theory to the data below 150 GeV, the predictions from all the PDF's shown underestimate the cross section. However, one should keep in mind that this comparison does not show the possible variations coming from systematic and statistical uncertainties of the input data to the parton distributions. This is important for the gluon distribution which at high  $x$  is mainly constrained by direct photon experiments[18]. The direct photon experiments have relatively large uncertainties as compared to DIS experiments at high  $x$ .

The NNL and higher order calculations of inclusive jet production are not available yet. These correction may be able to explain the discrepancy between the data and theory at high  $E_T$ . It has been suggested that at high  $E_T$ , we are very close to edge of phase space as the parton density functions are steeply falling. This leads to corrections to the cross section at high  $x$ . No such corrections have been evaluated for inclusive jet production so far. These corrections have been calculated to the Drell-Yan process and are about 10% to NLO cross sections at  $\tau = M_{e^+e^-}/\sqrt{s} = 720/1800 = 0.4$ . As the soft gluon radiation is claimed to be universal, the corrections to inclusive jet production are expected to be similar in magnitude[20].

The systematic uncertainties arising from underlying event subtraction, fragmentation functions, modeling of jet energy resolution and calorimeter energy calibration to pions and electrons are shown in Fig. 4(b). These plots show the change in cross section when the parameters are increased by  $1\sigma$  from their nominal value. These systematic uncertainties are completely correlated. The sum in quadrature of these contributions along with a few other systematic uncertainties as a function of  $E_T$  is shown in Fig. 3(b) as the shaded region at the bottom of the plot.

CDF is looking for any experimental effect which may cause the excess at high  $E_T$ . The jet fragmentation, calorimeter energy scale at high  $E_T$  and shape of the response functions at high  $E_T$  are particularly under study.

## 4 Two-jet mass Distribution

The CDF collaboration has measured the two-jet mass spectrum using  $\sim 70pb^{-1}$  from run 1A and 1B[21]. The two-jet mass is defined as

$$M_{JJ} = \sqrt{\{(E_1 + E_2)^2 - (\mathbf{P}_1 + \mathbf{P}_2)^2\}}$$

where  $(E_{(1,2)}, \mathbf{P}_{(1,2)})$  are the 4-vectors of two leading jets in the events. Only the events in which two highest  $E_T$  jets are in the pseudo-rapidity  $|\eta| < 2.0$  are used. The events are required to have  $|\cos \theta^*| = |\tanh(\eta_1 - \eta_2)/2| < 2/3$  where  $\eta_{1,2}$  are the pseudo-rapidities of two leading jets in the event. The  $\cos \theta^*$  and pseudorapidity cuts define the detector acceptance. The data is not corrected for these cuts, instead these cuts are applied to the theory predictions. The jet energies have been corrected for the non-uniformity in energy response of the CDF detector. However they have not been corrected for smearing. The two-jet mass spectrum is shown in Fig.5(a). The solid line is a best-fit parameterization of the measured spectrum. The data are well described by a smooth curve. The boxes are the leading-order QCD predictions using PYTHIA Monte Carlo. The jets produced by the PYTHIA Monte Carlo have been smeared using CDF detector simulation and analyzed in the same manner as the CDF data. The fractional difference between the data and the theory is shown in Fig.5(b). The PYTHIA predictions have been normalized to the data in the  $E_T$  range 120-320 GeV. The error bars show only the statistical errors and the systematic uncertainties are under study. The CDF data have more events than theory prediction for two-jet mass  $M_{JJ} > 400$  GeV. This analysis differs from the inclusive jet analysis in the previous section in two major aspects. First the theory is smeared whereas in the inclusive jet analysis the data are un-smeared. Thus the two-jet mass analysis does not suffer from any possible biases in unsmearing procedure. Second, PYTHIA/JETSET Monte Carlo is based on string fragmentation model. In inclusive jet analysis independent fragmentation model tuned to CDF data is used. An excess at high  $E_T$  in both these independent analyses is observed.

## 5 $\Sigma E_T$ Spectrum

The Fully corrected  $\Sigma E_T$  spectrum, as measured by the CDF collaboration is shown in Fig.6. For this study, the  $\Sigma E_T$  is defined as the sum of the

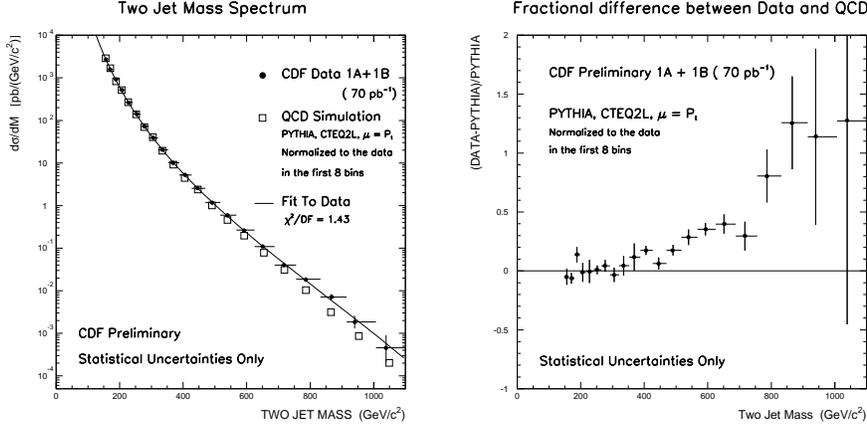


Figure 5: Comparison of Two-jet with PYTHIA predictions

transverse energy of all the jets in the events with  $E_T$  above 20 GeV. The events which have  $\cancel{E}_T / \sum E_T$  greater than 6 or have more than 2000 GeV of energy deposited are rejected. The events are required to be within 60 cm of the center of the detector. A  $\sum E_T$  cut of 320 GeV is applied to maintain full efficiency. The events with multiple interactions (vertices) are not removed. The study of data sets with different instantaneous luminosity, show that it is unlikely to get a jet with  $E_T > 20$  GeV from a second minimum bias interaction. After all these cuts, 26096 events are left.

The measured cross section needs to be corrected for detector effects so that it can be compared to LO/NLO QCD predictions from exact calculations. The detector resolution as a function of  $\sum E_T$  is determined using HERWIG Monte Carlo program and a CDF detector simulation. The measured spectrum is parameterized as

$$A \times \exp(-P_1 \times \sum E_T) \times \{P_2 - P_3 \times \sum E_T + P_4 \times (\sum E_T)^2\}.$$

The parameterization is smeared with resolution functions using a Monte Carlo technique. The ratio  $R$  of the parameterized data to the smeared data is used to correct the measured spectrum. The  $R$  can be thought of as the ratio (smeared/smeared<sup>2</sup>). This ratio  $R$  varies from 1.05 at  $\sum E_T = 320$  GeV to 1.18 at  $\sum E_T = 1120$  GeV, an increase of 13% over 800 GeV. This shows that the smearing changes the normalization of  $\sum E_T$  spectrum but does not change the shape significantly. The biggest systematic uncertainty comes from our knowledge of the calorimeter energy scale. Conservatively, a

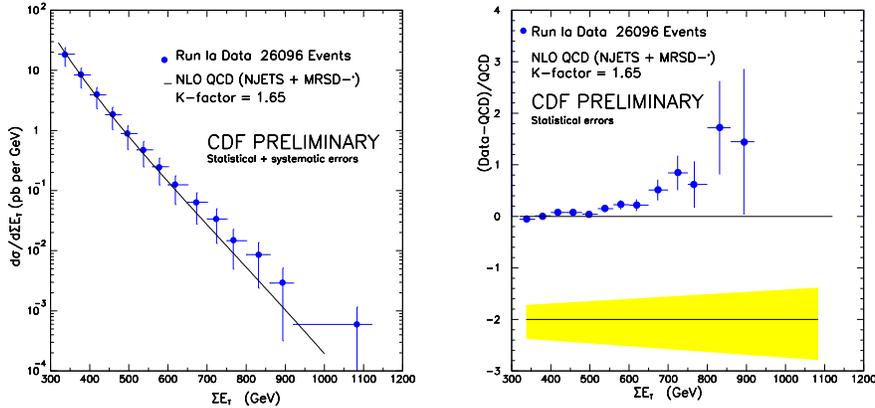


Figure 6: Comparison  $\Sigma E_T$  with Jet Rad predictions

5% systematic uncertainty is assigned to the calorimeter energy scale which translates into a +30/-40% uncertainty in cross section at 320 GeV going up to +45/-75% at 1100 GeV. Other sources to the systematic uncertainty include the shape of the resolution function, luminosity (3.8%) and the uncertainty on the correction factor  $R$  giving a total systematic uncertainty going from about  $\sim +30/ - 40\%$  at 320 GeV going up to  $\sim 50/ - 80\%$  at 1100 GeV, shown as the shaded region at the bottom of Fig. 6(b).

The fully corrected  $\Sigma E_T$  spectrum is compared to  $\alpha_s^3$  QCD calculation[3] in Fig. 6. This is a next-to-leading order  $2 \rightarrow 2$  calculation. The parton distributions used are MRSD-' with scale  $\mu = \Sigma E_T/2$ . For theory prediction, all the jet with  $E_T > 20$  GeV in the  $|\eta| < 3.5$  are summed to calculate the total transverse energy in the event. The QCD curve is normalized to the data in the 320-480 GeV region by multiplying the theory by 1.65. The data points are systematically higher than the QCD predictions above 500 GeV as can be seen in a linear comparison of data and theory in Fig. 6(b).

## 6 Conclusions

The corrected inclusive jet cross section measured by the DØ collaboration, though systematically higher, is in good qualitative agreement with NLO QCD calculation. The CDF measurement is in excellent agreement with NLO QCD prediction below 200 GeV. Above 200 GeV the measured cross

section begins to deviate from NLO predictions with an excess of 20-50% in 260-360 GeV range. CDF observes a similar excess in the dijet mass spectrum over Pythia, a LO QCD Monte Carlo, for  $M_{JJ}$  above 400 GeV.  $\sum E_T$  spectrum also shows an excess over  $\alpha_s^3$  predictions at  $\sum E_T$  above 500 GeV. It is possible that the high  $E_T$  excess in these three measurements has a common explanation either as a experimental artifact or lack of theoretical understanding. Both CDF and DØ are studying the systematic uncertainties especially the calorimeter energy scale and jet fragmentation.

## References

- [1] S. Ellis, Z. Kunszt, and D. Soper, Phys. Rev. Lett. **62** 2188 (1989), Phys. Rev. Lett. **64** 2121 (1990) .
- [2] F. Aversa, P. Chiappetta, M. Greco, P. Guillet, Phys. Lett. B **210**, 225 (1988), **211**, 465 (1988); Nucl. Phys. **B327**, 105 (1989)
- [3] Giele *et al.*, Nucl. Phys. **B403** (1993)
- [4] E. Eichten, K. Lane, and M. Peskin, Phys. Rev. Lett. **50**, 811 (1983).
- [5] Walter Giele, Next-to-leading order PQCD Calculations, in this proceedings.
- [6] BCDMS Collaboration, A. C. Benvenuti *et al.* Phys. Lett. **B223**(1989) 485.
- [7] Quinta, Nevis Preprint 277,(1992).
- [8] Amaudruz, *et al.*, Phys. Lett. B295 (1992) 159.
- [9] ZEUS Collaboration M. Derrick *et al.* DESY-94-192 (1994); H1 Collaboration I. Abt *et al.*, Phys. Lett. **B321** (1994) 161.
- [10] WA70 Collaboration M. Bosenini *et al.*, Z. Phys. **C38** (1988) 371.
- [11] UA6 Collaboration, G. Sozzi *et el.*, Phys. Lett. **B317** 243-249 (1993)
- [12] The DØ Collaboration, *Nucl. Instr. and Methods* **A338** (1994) 185.
- [13] James Bott *et al.*, Phys. Lett. **B304** (1993) 159.

- [14] CDF Collaboration, F. Abe *et al.*, Nucl. Instrum. Methods **A271**, 387 (1988); CDF Collaboration, Nucl. Instrum. Methods **A268**,75 (1988)
- [15] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **45** 1448 (1992).
- [16] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **70** 1376 (1992) .
- [17] A.D. Martin, R.G. Roberts and W.J. Stirling, Phys. Rev. **D50** (1994) 6734.
- [18] A.D. Martin, W.J. Stirling Pinning down the Glue in the Proton RAL-95-021, HEP-PH-9502336
- [19] CDF Collaboration, F. Abe *et al.* Phys. Rev. Lett. **68** (1992) 1104.
- [20] G. Sterman, Theory of soft gluon resummation, in this proceedings.
- [21] R. Harris, Search for New Particles Decaying to Dijets,  $b\bar{b}$ , and  $t\bar{t}$  at CDF, in these proceedings.