



**Fermi National Accelerator Laboratory**

**FERMILAB-Conf-96/225-E**

**CDF**

## **High $E_T$ Jet Cross Sections at CDF**

B. Flaugher

For the CDF Collaboration

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

August 1996

Submitted to the *XIth Topical Workshop on  $p\bar{p}$  Collider Physics*,  
Abano Terme (Padova), Italy, May 26-June 1, 1996

## **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.*

## **Distribution**

*Approved for public release; further dissemination unlimited.*

# HIGH $E_T$ JET CROSS SECTIONS AT CDF

B. FLAUGHER,  
FOR THE CDF COLLABORATION  
*Fermi National Accelerator Laboratory*  
*Batavia, IL 60510 USA*

The inclusive jet cross section for  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV as measured by the CDF collaboration will be presented. Preliminary CDF measurements of the  $\sum E_T$  cross section at  $\sqrt{s}=1.8$  TeV and the central inclusive jet cross section at  $\sqrt{s}=0.630$  TeV will also be shown.

## 1 Introduction

The CDF collaboration has performed a number of measurements involving high  $E_T$  jets. In particular, jet cross section measurements test QCD over a wide range of jet  $E_T$ , 15-440 GeV. At the highest  $E_T$ , this corresponds to a distance scale of  $O(10^{-17})$  cm and thus could provide the opportunity for observing new physics. With small systematic and statistical uncertainties, the CDF inclusive jet cross section measurement provides a powerful test of QCD and the publication of these results early this year has stimulated enormous theoretical activity.

Results primarily based on the Run 1A data sample (19.5  $\text{pb}^{-1}$ ) will be presented along with preliminary results from the Run 1B data sample (87  $\text{pb}^{-1}$ ) and the Run 1C  $\sqrt{s}=0.630$  TeV 600  $\text{nb}^{-1}$  sample. The data are compared with QCD predictions<sup>1</sup> for various sets of parton distribution functions. The inclusive and  $\sum E_T$  cross sections at  $\sqrt{s}=1.8$  TeV are higher than the QCD calculations at high  $E_T$ . Possible explanations for this excess will be discussed.

## 2 Jet identification and Data Samples

The CDF detector has been described in detail elsewhere<sup>2</sup>. The elements important for these analyses are the calorimeters, which measure the jet energies, and the central tracking chamber, which provides calibration information for the low  $P_T$  hadron response. Figure 1 shows a high  $E_T$  jet event in the CDF calorimeter and in the Central tracking chamber.

For the inclusive jet cross section measurement at  $\sqrt{s}=1.8$  TeV the data were collected using several triggers with jet  $E_T$  thresholds of 100, 70, 50 and 20 GeV. Prescales for the lower  $E_T$  triggers were chosen to avoid saturating

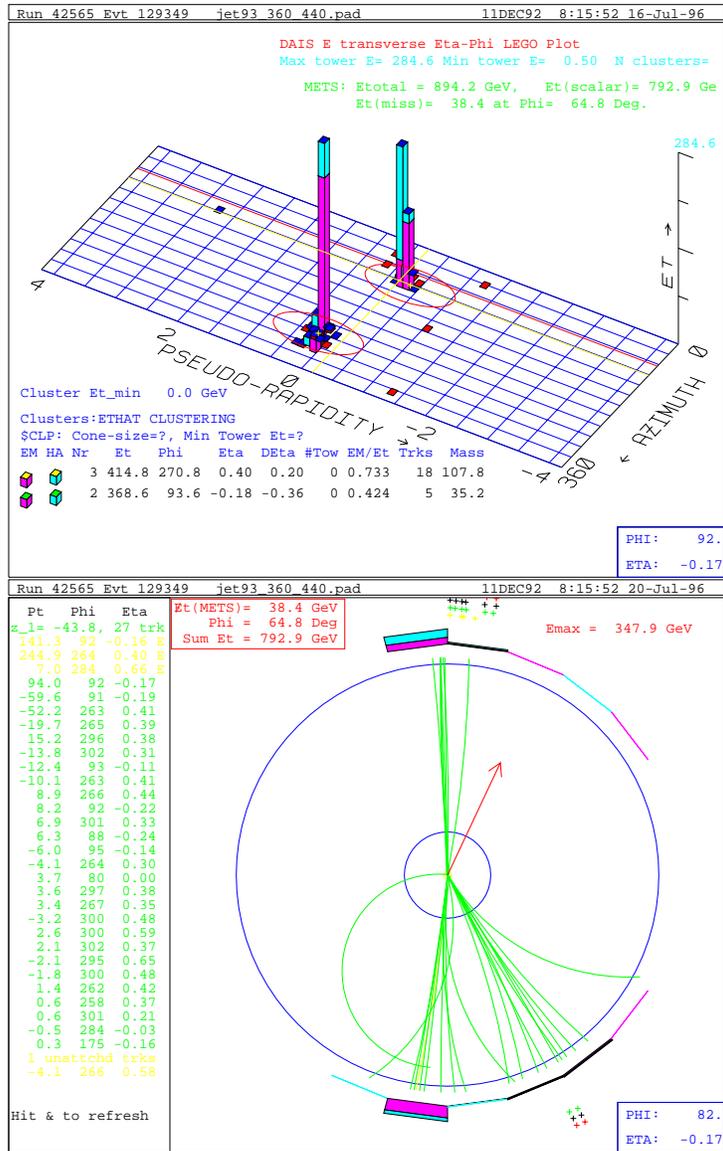


Figure 1: A high Et jet in the CDF detector

the data acquisition bandwidth. In Run 1A the 70, 50 and 20 GeV triggers were prescaled by 6, 20 and 500, respectively. The increased instantaneous luminosity in Run 1B required that these prescales be raised to 8, 40 and 1000, respectively. The  $\sum E_T$  data was collected with a trigger on  $\sum \bar{E}_T > 175$  GeV where the sum is over clusters with  $E_T > 10$  GeV.

The data sample for the  $\sqrt{s}=0.630$  TeV run was collected primarily with a single jet trigger at 15 GeV. The bandwidth capacity and the instantaneous luminosity during this run made it possible to avoid a prescale factor for this trigger.

For both the 1.8 and 0.630 TeV running a large sample of minimum bias (beam crossing trigger without  $E_T$  requirements) data were collected and used for the very low  $E_T$  jet measurements and for trigger efficiency studies.

Jets were reconstructed using a cone algorithm<sup>3</sup> with radius  $R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2} = 0.7$ . Here  $\eta \equiv -\ln[\tan(\theta/2)]$ , where  $\theta$  is the polar angle with respect to the beam line and  $\phi$  is the azimuthal angle around the beam. Figure 1 shows a high  $E_T$  jet event in the calorimeter. The circles around the jets indicate the cone ( $R=0.7$ ) boundary. The QCD calculation used a similar clustering algorithm<sup>1</sup>. If two partons fall inside a cone  $(\Delta\eta^2 + \Delta\phi^2)^{1/2} < 2R$ , they are merged into one "jet". The ambient energy from fragmentation of partons not associated with the hard scattering is subtracted. No correction is applied for the energy falling outside the cone because this effect should be modeled by the NLO QCD calculations.

Cosmic rays and accelerator loss backgrounds were removed with cuts on event energy timing and on missing  $E_T$  significance ( $E_T/\sqrt{\sum E_T} < 6.0$ ) as described in reference<sup>5</sup>. All the events with a jet of  $E_T > 200$  GeV in the Run 1A were scanned and no additional background events were observed. In the Run 1B sample, scanning revealed additional accelerator related backgrounds. These were easily removed by requiring that the total  $E_T$  in the event be less than 1.8 TeV. For the  $\sqrt{s}=0.630$  TeV sample, all events with a jet above 60 GeV were scanned and no backgrounds were found.

### 3 Inclusive Jet Cross Section at CM = 1.8 TeV

Leading Order (LO) predictions for the inclusive jet cross section have existed for many years, but were fraught with large uncertainty due to the choice of renormalization scale<sup>6</sup>. In the late 1980's, new calculations, this time at Next-To-Leading (NLO), were performed<sup>1</sup>. These significantly reduced the uncertainty in the theoretical predictions and challenged experimentalists to reduce both the statistical and systematic uncertainties in their measurements. CDF's recent result on the Run 1a data<sup>7</sup> is shown in Figure 2 and will be

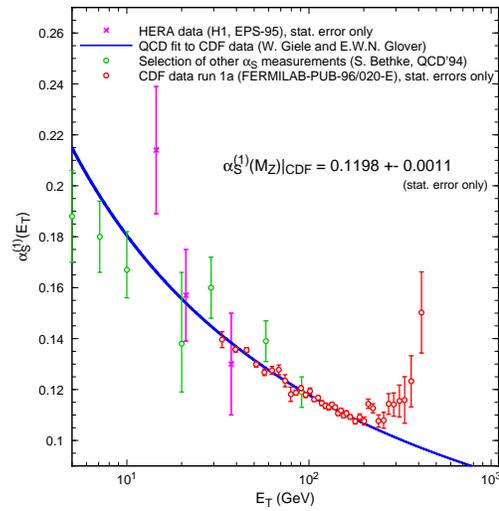
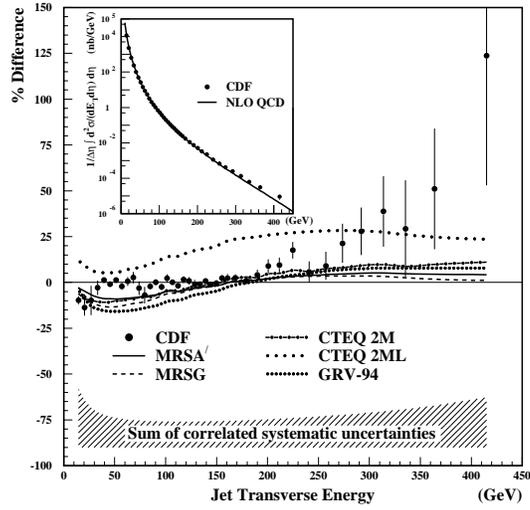


Figure 2: The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0' PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent uncertainties uncorrelated from point to point. The hatched region at the bottom shows the quadratic sum of the correlated ( $E_T$  dependent) systematic uncertainties which are shown individually in Figure 2. NLO QCD predictions using different PDFs are also compared with the one using MRSD0'. Below, this measurement is used to show the running of  $\alpha_s$  (courtesy of W. Giele)

described below. It is the most precise measurement of the inclusive jet cross section to-date and has motivated new theoretical calculations. In addition to testing QCD at the highest energies, and providing a place to search for new physics, it was recently shown that the inclusive cross section measurement of CDF could be used to show the running of the strong coupling constant  $\alpha_s$  over the largest range of  $E_T$  in any single experiment. This result is described in Reference <sup>8</sup> and shown in Figure 2.

The inclusive jet cross section is defined as:

$$\frac{1}{\Delta\eta} \int d\eta \frac{d^2\sigma}{dE_T d\eta} = \frac{1}{\Delta\eta} \frac{1}{L} \frac{N_{jet}}{\Delta E_T}$$

where  $L$  is the integrated luminosity, and  $N$  is the number of jets in a bin of  $\Delta E_T$ . The measured jet  $E_T$  spectrum is corrected for detector and smearing effects caused by finite  $E_T$  resolution with the “unsmearing procedure” described in <sup>9</sup>. A Monte Carlo simulation, based on the ISAJET<sup>10</sup> program and Feynman-Field<sup>11</sup> jet fragmentation tuned to the CDF data, is used to determine detector response functions. A trial true (unsmear) spectrum is smeared with detector effects and compared to the raw data. The parameters of the trial spectrum are iterated to obtain the best match between the smeared trial spectrum and the raw data. The corresponding unsmear curve is hereafter referred to as the “standard curve”, and is used to correct the measured spectrum.

To evaluate systematic uncertainties, the procedure in reference <sup>9</sup> is used. New parameter sets are derived for  $\pm 1$  standard deviation shifts in the unsmearing function for each source of systematic uncertainty. Fig. 3(a-h) shows the percentage change from the standard curve as a function of  $E_T$  for the seven largest systematic uncertainties. The parameters for each uncertainty can be found in reference <sup>7</sup>. They account for the following uncertainties: (a) charged hadron response at high  $P_T$ ; (b) the calorimeter response to low- $P_T$  hadrons; (c)  $\pm 1\%$  on the jet energy for the stability of the calibration of the calorimeter; (d) jet fragmentation functions used in the simulation; (e)  $\pm 30\%$  on the underlying event energy in a jet cone; (f) detector response to electrons and photons and (g) modeling of the detector jet energy resolution. The eighth, an overall normalization uncertainty of  $\pm 3.8\%$ , was derived from the uncertainty in the luminosity measurement<sup>12</sup> ( $\pm 3.5\%$ ) and the efficiency of the acceptance cuts ( $\pm 1.5\%$ ). These eight uncertainties arise from different sources and are not correlated with each other. Additional tests of the unsmearing procedure, including use of the HERWIG Monte Carlo program<sup>13</sup> to model jet fragmentation, were performed and the resulting variations were found to be small.

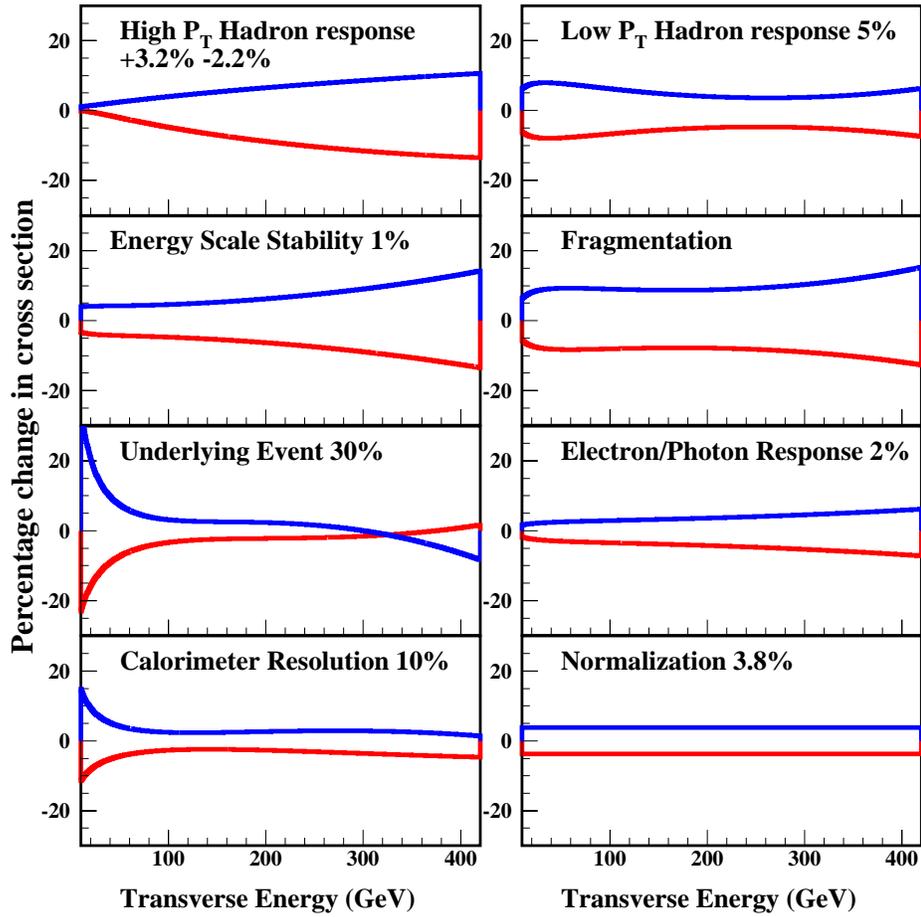


Figure 3: The percentage change in the inclusive jet cross section when various sources of systematic uncertainty are changed by  $\pm 1$ -standard deviation from their nominal values.

In Fig. 2 the corrected cross section is compared with the NLO QCD prediction<sup>1</sup> using MRSD0' PDFs<sup>4</sup>, with renormalization/factorization scale  $\mu = E_T/2$ . These results show excellent agreement in shape and in normalization for  $E_T < 200$  GeV, while the cross section falls by six orders of magnitude. Above 200 GeV, the CDF cross section is significantly higher than the NLO QCD prediction. These data are consistent with our previous measurement<sup>4</sup>, which also shows an excess over NLO QCD for the  $E_T > 280$  GeV region.

To analyze the significance of this excess we use four normalization- independent, shape-dependent statistical tests: signed and unsigned Kolmogorov-Smirnov<sup>15</sup>, Smirnov-Cramèr-VonMises<sup>15</sup>, and Anderson-Darling<sup>16,17</sup>. For this comparison we choose the MRSD0' PDFs which provide the best description of our low  $E_T$  data. The eight sources of systematic uncertainty are treated individually to include the  $E_T$  dependence of each uncertainty. The effect of finite binning and systematic uncertainties are modeled by a Monte Carlo calculation. The statistical tests over the full  $E_T$  range are dominated by the higher precision data at low  $E_T$ ; therefore, we test two ranges. Between 40 and 160 GeV, the agreement between data and theory is  $>80\%$  for all four tests. Above 160 GeV, however, each of the four methods yields a probability of 1% that the excess is due to a fluctuation. We performed the same test with other PDFs. Agreement at low  $E_T$  is reduced for the other PDF's, as is the significance of the excess at high  $E_T$ . The best agreement at high  $E_T$  is with CTEQ2M<sup>18</sup> which gives 8%, but the low  $E_T$  agreement is reduced to 23%.

Figure 4 shows the preliminary inclusive jet cross section from the Run 1b data along with the Run 1a data and with a more modern set of PDFs (CTEQ3M<sup>18</sup>). Although we have not yet performed the significance analysis, two things are clear: the two data sets agree with each other, and CTEQ3M does not profoundly reduce the excess at high  $E_T$ .

In our paper<sup>7</sup> we concluded that the precision of the Run 1A data and its deviation from the standard theoretical predictions (EKS), demanded that the theoretical uncertainties be reevaluated. This reevaluation was viewed as essential before any statements about the presence or absence of new physics explanations could be made. In fact, since the release of the paper there has a great deal of activity on both standard QCD and new physics explanations.

The CTEQ collaboration has included the CDF Run 1a data in their global fitting program and has derived new sets of parton distribution functions. A discussion of these results can be found in reference<sup>19</sup>. In summary, they are able to obtain what is believed to be a reasonable fit to the world data (WA70, DIS, etc. ) including the CDF jet data. A new calculation of the effects of soft gluon resummation<sup>21</sup> has been performed as described in reference<sup>21</sup>. In addition, an unnerving, and interesting paper on the comparison of the DIS

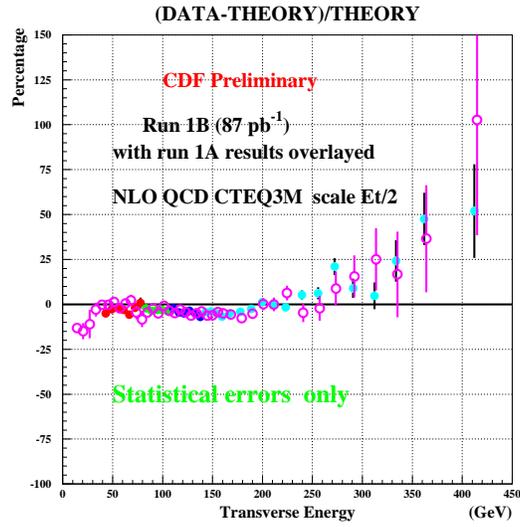


Figure 4: CDF Run 1a and Run 1b data compared to QCD predictions with CTEQ3M.

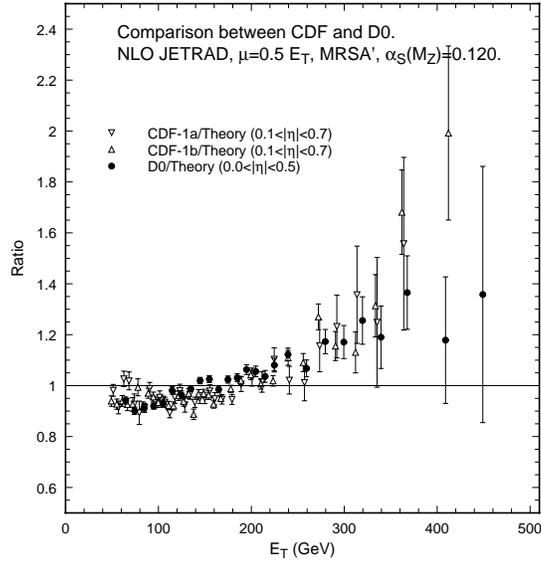


Figure 5: CDF 1a and 1b data compared to JETRAD and D0 data (courtesy of Walter Giele)

and MSbar factorization schemes has also become available<sup>22</sup>.

The D0 collaboration has produced a preliminary measurement of the inclusive jet cross section (see talk at this conference by I. Bertram) and comparisons using JETRAD<sup>1</sup> and EKS<sup>1</sup> show that the two experiments are in good agreement. Figure 5 shows the CDF run 1a, 1b and D0 data compared the the JETRAD Monte Carlo. Only statistical errors are plotted. A similar comparison using the EKS theory prediction can be found in reference<sup>20</sup>.

New physics explanations have also been suggested. These include quark substructure<sup>23</sup>, a slower running of  $\alpha_s$ , and new particles (leptophobic Z')<sup>24</sup>. All of these processes would enhance the cross section at high  $E_T$  and thus would provide better agreement with the data.

#### 4 $\sum E_T$ Cross Section

An alternative test of QCD is to measure the cross section as a function of the  $\sum E_T$  over clusters in each event. This result is correlated with the inclusive jet sample, but could provide additional information about the events. See also the talk by T. Asakawa presented at this conference. For this study two sets of cuts were imposed:

$$\sum E_T \equiv \sum E_T^{jet} > 320 \text{ GeV} , E_T^{jet} > 20 \text{ GeV}$$

and

$$\sum E_T \equiv \sum E_T^{jet} > 400 \text{ GeV} , E_T^{jet} > 100 \text{ GeV}.$$

The jets were allowed to be anywhere within the calorimeter which extends to  $|\eta|=4.2$ . With the higher  $E_T^{jet}$  threshold we expect two jet events to dominate and thus the QCD predictions should be a better approximation.

Individual jet corrections were<sup>25</sup> performed as well as an unsmearing of the  $\sum E_T$  spectrum. The data are compared to two monte Carlo generators, HERWIG and JETRAD (NLO). Figures 6 and 7 show the data compared to QCD predictions for the  $E_T^{jet} > 20 \text{ GeV}$  and the  $E_T^{jet} > 100 \text{ GeV}$  samples on log and linear (data-theory)/theory scales. Note that in both samples an excess at high  $E_T$  is observed. Also, the required normalization factor for the NLO QCD prediction (JETRAD) is significantly reduced when the higher jet  $E_T$  threshold is used.

#### 5 Inclusive Jet Cross Section at C.M. = 0.630 TeV

An alternative way to test QCD is to measure the inclusive jet cross section at widely separated center of mass energies. The hypothesis of "scaling" predicts

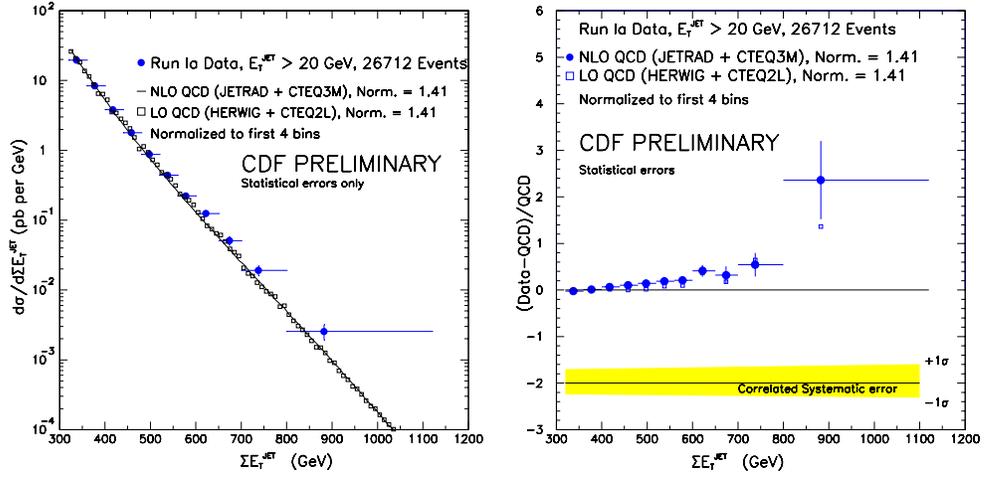


Figure 6:  $\sum E_T$  cross section for jet  $E_T > 20$  GeV

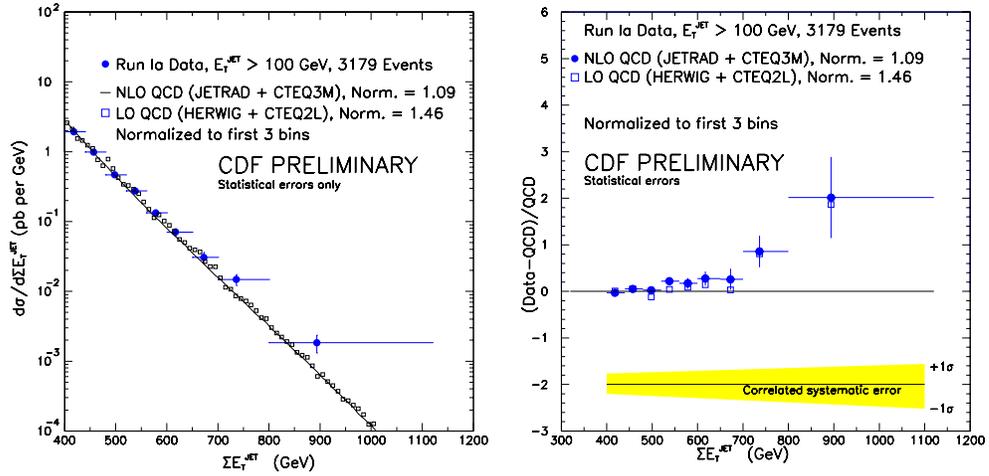


Figure 7:  $\sum E_T$  cross section for jet  $E_T > 100$  GeV

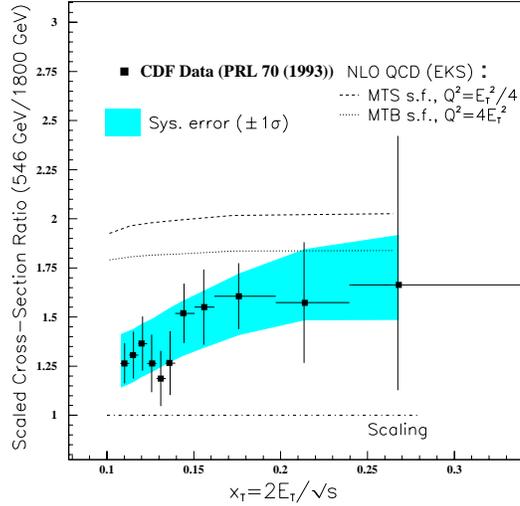


Figure 8: CDF scaling result from 0.546 TeV run of the Tevatron in 1989.

that the scaled jet cross section,  $E_T^4 (Ed^3\sigma/dp^3)$ , will be independent of  $\sqrt{s}$  when plotted as a function of the variable  $x_T = 2E_T/\sqrt{s}$ . However, QCD predictions depend on the energy scale, or  $Q^2$  of the interactions and thus suggest that the cross sections should not "scale". The running of the strong coupling constant and the evolution of the parton distribution functions are manifestations of this energy (or scale) dependence of the predictions. By measuring the scaled jet cross section at two different CM energies in the same experimental apparatus, many systematic uncertainties cancel<sup>9</sup>. CDF's previous measurement of this quantity with a very small data sample ( $7.5 \text{ nb}^{-1}$  collected in 1989) is shown in Figure 8. Scaling was ruled out at the 95% confidence level and a disagreement with the QCD predictions was observed in the low  $E_T$  region.

In Dec. 1995 CDF collected  $600 \text{ nb}^{-1}$  at  $\sqrt{s}=0.630 \text{ TeV}$ . The analysis of this data follows an identical path to the analysis described above for the 1.8 TeV data sample. The data has been corrected and unsmearred and is shown in Figure 9 along with the published 0.546 TeV and 1.8 TeV data.

In order to see the details of the comparison we switch to a linear scale and plot  $(\text{data} - \text{theory})/\text{theory}$ , where the "theory" is calculated at the CM

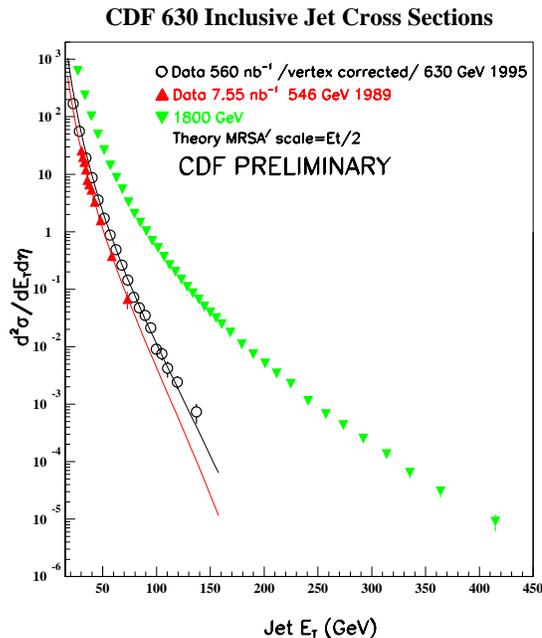


Figure 9: Inclusive jet cross sections as measured by CDF at three different CM energies

energy of the data sample to which it is compared. Figure 10 shows the 0.546 TeV data compared to 0.630 TeV data vs  $\mathbf{x}_T$  with CTEQ3M PDF's. At low  $E_T$ , the 0.630 TeV data is seen to deviate from the QCD prediction in a similar manner to the 0.546 TeV data. Figure 11 also shows the 1.8 TeV data and the 0.630 TeV data on the linear scale, but this time plotted as a function of jet  $E_T$ . The fact that the 0.630 TeV data is lower than the prediction by roughly 20% in a region where the 1.8 TeV data is in good agreement with QCD suggests this disagreement is not a function of jet  $E_T$ . The last plot in Figure 11 shows the CDF 0.630 TeV data compared to data from UA2. The UA2 measurement is only for  $E_T > 45$  GeV, the region where the CDF data is relatively flat. Thus a relative normalization factor could easily bring these measurements into agreement. The CDF 0.546 TeV and 0.630 TeV data provide the only measurement of the jet cross section in the low  $E_T$  ( $< 45$  GeV) region.

## 6 Summary and Conclusions

The CDF measurement<sup>7</sup> is driving the theoretical predictions. The excess of data over theory is seen in both the single jet inclusive and the  $\sum E_T$  cross section measurements, and can not be explained by the experimental uncertainties. Since the paper was released, new results on PDF's, and soft gluon

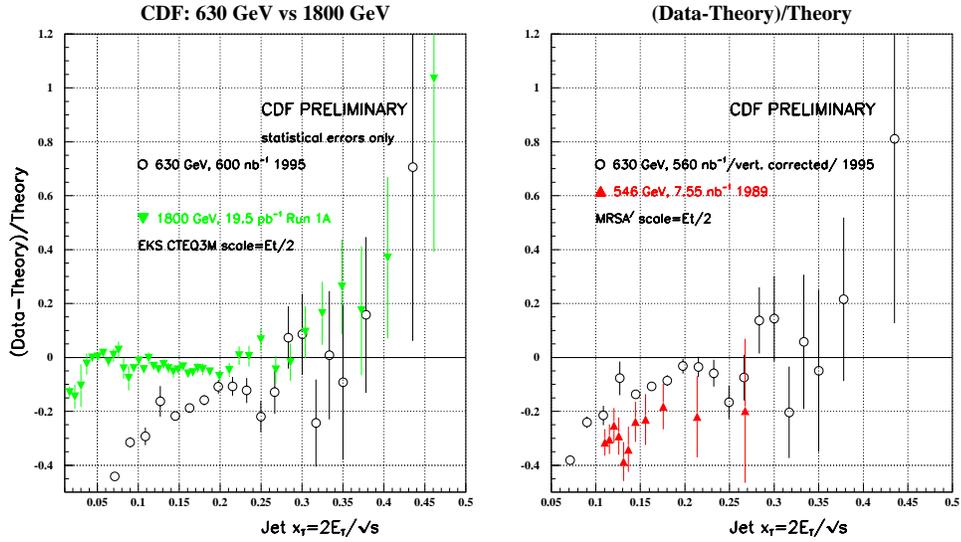


Figure 10: Inclusive jet cross sections at CDF. The 0.630 TeV data is compared to the 1.8 TeV data and to the 0.546 TeV data.

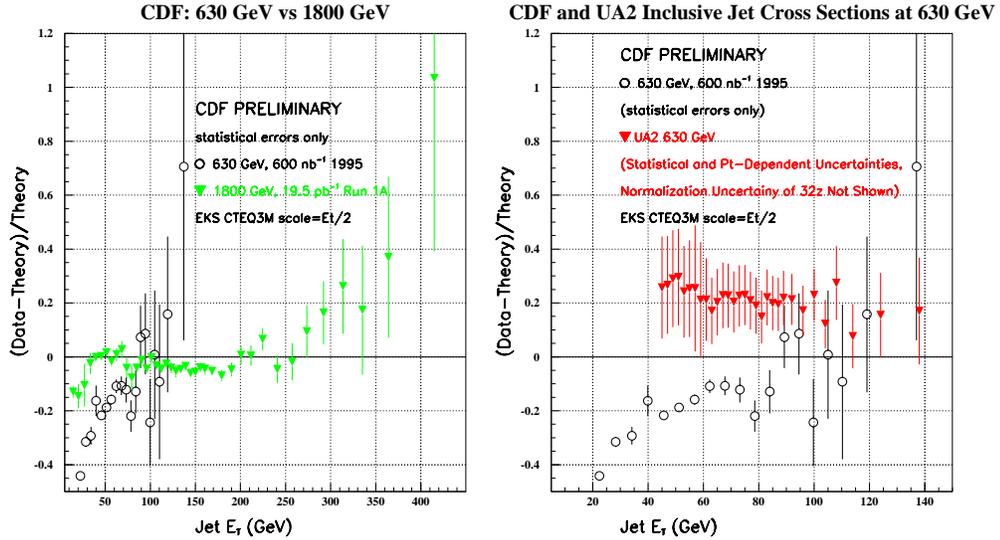


Figure 11: Inclusive jet cross sections at CDF 0.630 TeV and 1.8 TeV vs  $E_T$ , and the comparison to UA2

resummation have been generated, as well as a number of possible new physics explanations. The low CM energy data suggests that there may be another problem with the QCD predictions, however this is still a preliminary result and has not yet been included in any global PDF analysis. If it turns out that these new PDF's, which include (and thus describe) the high  $E_T$  data, are adopted as the best prediction of QCD then we will have a fantastic measurement of the running and perhaps the value of  $\alpha_s$ . However, if it turns out that QCD can not describe the data then we have the possibility of discovering something new.

## References

1. S. Ellis, Z. Kunszt, and D. Soper, Phys. Rev. Lett. **64** 2121(1990). See also F. Aversa, P. Chiappetta, M. Greco, P. Guillet, Phys. Rev. Lett. **65**, 401 (1990); W. T. Giele, E.W.N. Glover and D.A. Kosower, Nucl. Phys. **B403** 633 (1993), and references therein.
2. CDF Collaboration, F. Abe *et al.*, Nucl. Instrum. Methods **A271**, 387 (1988).
3. CDF Collaboration, F. Abe *et al.*, Phys. Rev. **D45** 1448 (1992).
4. CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **68** 1104 (1992).
5. CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **62** 613 (1989).
6. S. Ellis, Z. Kunszt, and D. Soper, in *Proceedings of the 1990 Meeting of the Division of Particles and Fields of the American Physical Society, Houston, 1990*, edited by W.Bonner and H.Miettinen (World Scientific, Singapore, 1990) p. 603.
7. CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **77** 438 (1996).
8. W. T. Giele, E.W.N. Glover and J. Yu, FERMILAB-PUB-127-T, DTP/95/52. hep-ph/9506442 (1995).
9. CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **70** 1376 (1993).
10. F.Paige and S.Protopopescu, Brookhaven Nat. Lab. Report No. BNL-38034 (1986) (unpublished).
11. R.Field and R.Feynman, Nucl. Phys. **B136** 1 (1978).
12. CDF Collaboration, F. Abe *et al.*, FERMILAB-PUB-95-301-E, Submitted to Phys. Rev. D.
13. G. Marchesini and B. R. Webber, Nucl. Phys. **B310**, 461 (1988).
14. A.D. Martin, R.G. Roberts and W.J. Stirling, Phys.Lett. **B306** 145 (1993).
15. See, for example, "Probability and Statistics in Experimental Physics", by Byron Roe, Springer-Verlag, New York, (1992).
16. T.W. Anderson and D.A.Darling, Ann.Math.Stat **23**,193-212 (1952).

17. T.W. Anderson and D.A.Darling, J.Amer.Stat.Assoc. **49**,765-769 (1954).
18. James Botts *et al.*, CTEQ Collaboration, Phys. Lett. **B304** 159 (1993).
19. CTEQ Collaboration, J.Huston *et al.*, Phys. Rev. Lett. **77** 444 (1996).  
See also E.W.N. Glover, A.D.Martin, R.G.Roberts, K.J.Stevenson and W.J.Stirling, DTP-96-22 (1996).
20. H.L.Lai and W.K.Tung, hep-ph/9605269.
21. S.Catani *et. al.*, hep-ph/9604351.
22. M.Klasen and G. Kramer, hep-ph/9605210.
23. E. Eichten, K. Lane, and M. Peskin, Phys. Rev. Lett. **50**, 811 (1983).
24. G.Altarelli *et al.*, hep-ph/9601324, R.Ellis and D.Ross, hep=ph/9604432, R.S.Chivukula, it et al, hep-ph/9603311.
25. CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **47** 4857 (1993).