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Recent Results in High E_T Jet Production

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We present results on high E_T jet measurements from CDF and D0. First we show the inclusive jet cross section and compare it to NLO QCD predictions. Preliminary CDF measurements of the $\sum E_T$ cross section are also shown. In order to place limits on the amount of quark compositeness the data can tolerate, we show the dijet angular distributions. Finally, we discuss the inclusive jet cross section measurement at $\sqrt{s} = 0.63$ TeV and tests of scaling.

1 Introduction

The CDF and D0 collaborations have performed a number of measurements involving high E_T jets. In particular, the inclusive 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. In the absence of new physics, the recent high statistics jet E_T measurements which have relatively small systematic uncertainties provide a powerful test of QCD predictions. The inclusive jet cross section measurements have stimulated enormous theoretical activity aimed at understanding the comparison of the measurements with QCD predictions.

2 Inclusive Jet Cross Sections at 1.8 TeV

The inclusive 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_{jet} is the number of jets in a bin of width, ΔE_T . The CDF measurements are based on two data samples, one with 19.5 pb^{-1} (Run 1a) and the other with 87 pb^{-1} (Run 1b) of data; both use jets with $E_T > 15$ GeV and $0.1 < |\eta| < 0.7$. The D0 measurement is based on 90 pb^{-1} of data and uses jets with $E_T > 60$ GeV and $|\eta| < 0.5$. Jets are reconstructed using a cone algorithm with a cone radius $R = 0.7$ where

$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. In both measurements, cuts on energy imbalance in the detector (missing energy) are used to remove backgrounds, mostly from cosmic rays and calorimeter malfunctions. The data are also corrected for detector effects such as energy scale which is about a 20% correction. Finally the cross sections are corrected for the effects of finite detector resolution. The measured jet resolution is convoluted with a trial “physics curve” and compared to the data. The measured physics curve is that which after convolution compares best (in a χ^2 test) with the data. For further details on the “unsmearing procedure” see ref^{1,7}.

CDF compares the measured spectrum to the EKS³ prediction and D0 compares to the JETRAD⁴ prediction, both of which are NLO QCD calculations. In order to make the comparison to data meaningful, nearby partons in these calculations are clustered to form jets. These jets are formed out of at most two partons in the final state and represent the NLO approximation to the fully hadronic final state measured in the data. The clustering radius differs slightly between the EKS ($R = 0.7$) and JETRAD ($R = 0.91$) predictions. The effect of this is that the amount of energy which falls outside the jet cone is approximated differently in the two calculations. The smaller clustering cone results in a predicted spectrum which falls faster. Another difference between the predictions is the implementation of factorization/renormalization scale, μ . The EKS calculation uses the E_T of the jet and JETRAD uses the E_T of the most energetic jet in the event. The JETRAD choice gives a lower cross section at low E_T .

The corrected spectrum from CDF⁵ is presented in Figure 1. The data are compared to the predictions of EKS³ using the MRSD0' parton distributions and a renormalization/factorization scale, $\mu = E_T/2$. There is qualitative agreement over nine orders of magnitude but comparing the data and theory on a linear scale reveals that the measured cross section is larger than predicted by NLO QCD for jets with E_T above about 200 GeV. The sum in quadrature of the systematic uncertainties are shown by the shaded band at the bottom of the plot. The effect of varying the parton distribution functions (PDFs) is shown relative to MRSD0'. None of the current PDFs give a good description of the data. Also shown is the comparison between NLO QCD using a more modern PDF, CTEQ3M, and the published cross section with 19 pb⁻¹ of data and the preliminary measurement based on 87 pb⁻¹. The data are in statistical agreement and the comparison to theory does not improve significantly with the new PDF.

The systematic uncertainty in this measurement is the sum of eight different component sources. Figure 2 shows the individual contributions ($\pm 1\sigma$). Following the procedure in reference¹ the uncertainty from the following sources

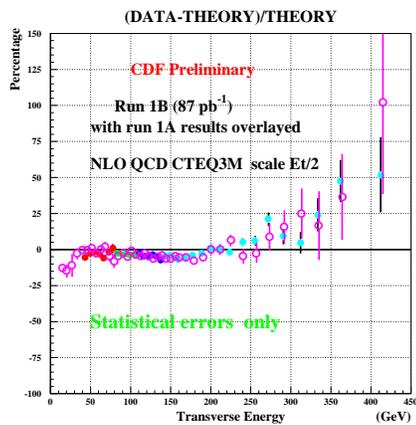
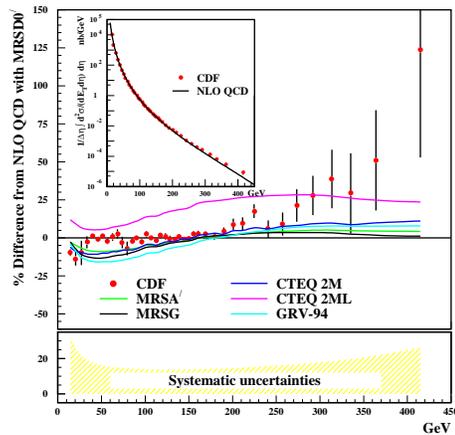


Figure 1: Above, the percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0' PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent uncertainties uncorrelated from point to point. The hatched region at the bottom shows the quadratic sum of the 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, the CDF measurement using 19 pb^{-1} (open circles) and 87 pb^{-1} (filled circles) of data compared to QCD predictions with CTEQ3M.

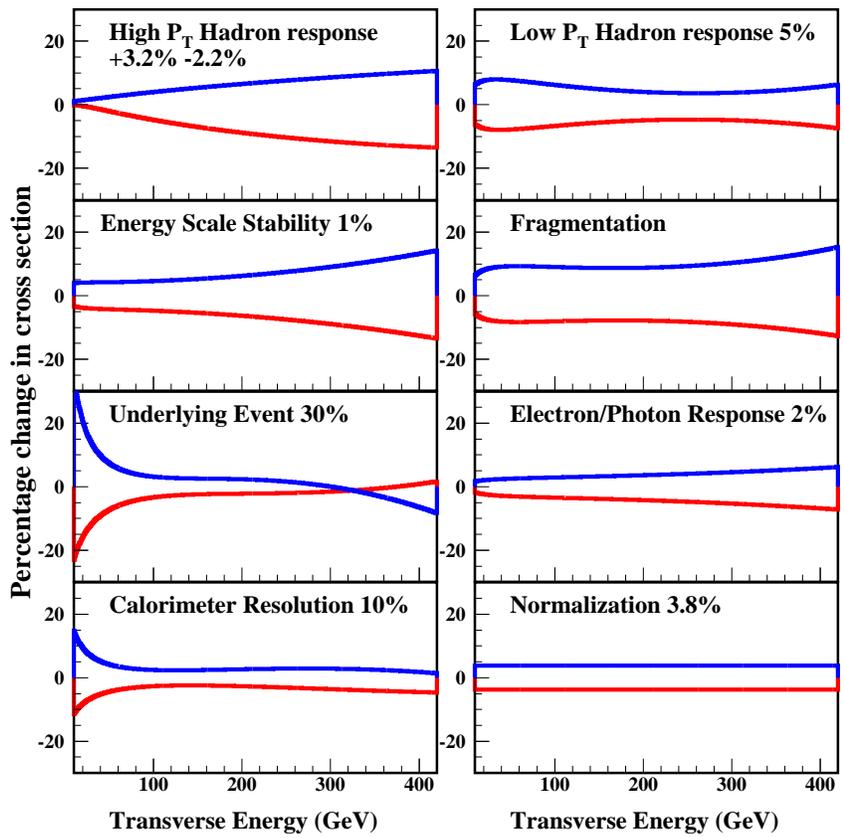


Figure 2: The percentage change in the inclusive jet cross section when various sources of systematic uncertainty are changed by ± 1 -standard deviation from their nominal values.

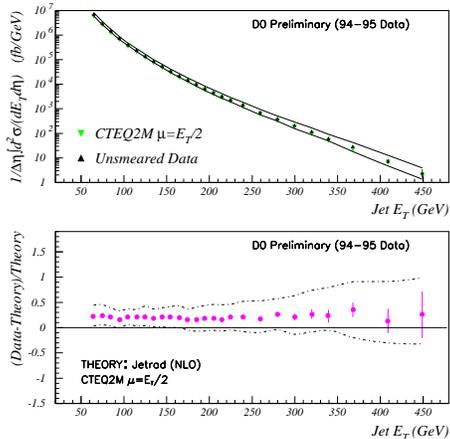


Figure 3: Above, D0 inclusive jet measurement compared to NLO QCD prediction using CTEQ2M PDFs. Below, the percent difference between the D0 inclusive jet cross section (points) and the NLO QCD prediction. The normalization shown is absolute. The error bars represent uncertainties uncorrelated from point to point. The dash-dot lines indicate bands of correlated systematic uncertainty.

were evaluated; (a) charged hadron response at high p_T , (b) 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, (g) modeling of the detector jet energy resolution and (h) uncertainty in the total integrated luminosity. These eight uncertainties arise from different sources and are not correlated with each other. Furthermore, no reasonable combination of these systematic uncertainties can be made to account for the excess observed in the E_T spectrum. The significance of the excess is discussed in ref⁵.

The results from D0² are shown in Figure 3. The data are compared to NLO QCD⁴ using CTEQ2ML PDFs and a renormalization/factorization scale, $\mu = E_T/2$. Again, general agreement is observed over seven orders of magnitude. The comparison of the relative difference between data and theory show that there is $\sim 25\%$ excess at all E_T over QCD predictions, but that this is within the systematic uncertainty of the measurement. The level of the offset has been shown to be sensitive to μ scale and PDFs, but the character of the agreement does not change.

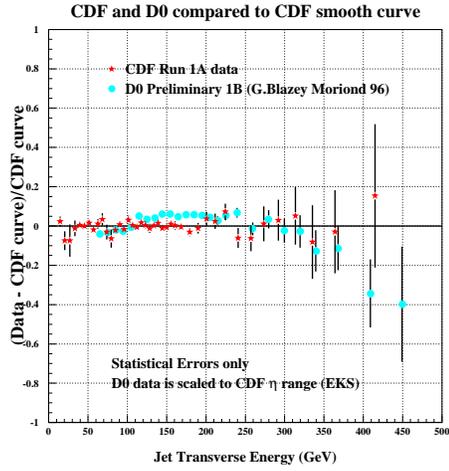


Figure 4: D0 measurement (circles) compared to an analytic fit to the CDF measurement. The D0 data have been scaled to the same η region used at CDF. The CDF data (stars) show that the fit is a good one. Remarkable agreement is observed between the two experiments.

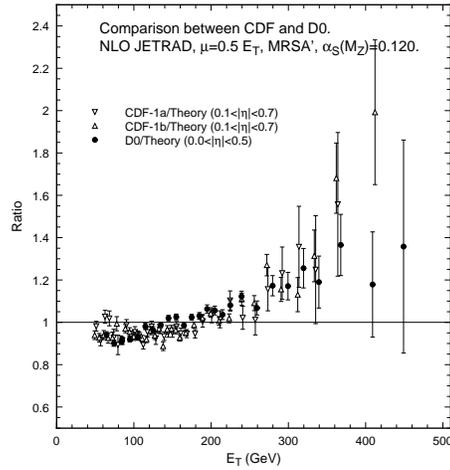


Figure 5: CDF 1a and 1b data compared to Jetrad and D0 data (courtesy of Walter Giele)

A natural question to ask is whether the two measurements are in agreement. The first step in a data to data comparison is to determine the acceptance factor for the different η ranges used in the two experiments. The ratio of the theoretical prediction with $0.1 < |\eta| < 0.7$ to the prediction $|\eta| < 0.5$ was taken as a function of E_T . Figure 4 shows the comparison of the D0 data scaled by this factor to the physics curve measured by CDF. The CDF points show that the physics curve is a good description of the CDF data. The D0 and CDF data are in remarkable agreement; both agree well within the systematic uncertainty of either experiment. An alternative comparison of the CDF and D0 measurements to the calculation of ref. ⁴ is shown in Figure 4. The D0 measurement is in agreement with both the NLO QCD calculation and the CDF data.

3 $\sum E_T$ Cross Section at CDF

An alternative test of QCD is to measure the cross section as a function of the $\sum E_T$ over jets in each event. This result is correlated with the inclusive jet spectrum, but provides a kinematically different comparison. For example, it is possible that the highest $\sum E_T$ events are comprised of events containing many medium energy jets and that the largest jets in the sample contribute to a wide range of $\sum E_T$. For this study at CDF, two data sets were constructed:

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

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 NLO QCD predictions should be a better approximation. The lower threshold sample contains more multijet events.

Individual jet corrections ⁶ were 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.

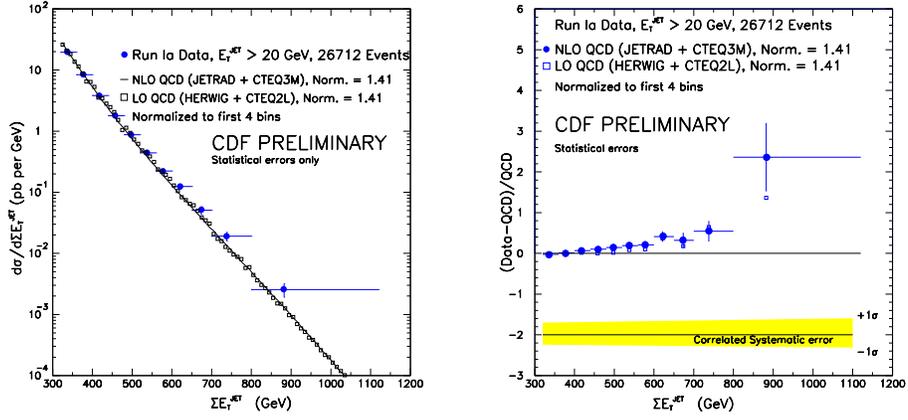


Figure 6: ΣE_T cross section for jet $E_T > 20$ GeV

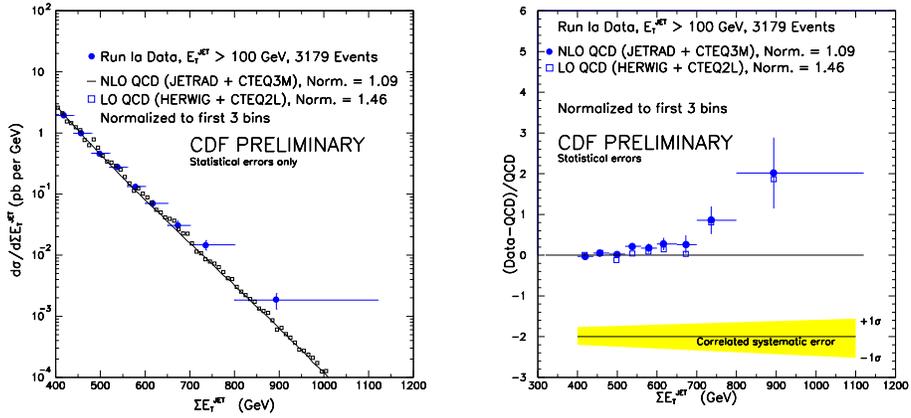


Figure 7: ΣE_T cross section for jet $E_T > 100$ GeV

4 Theoretical Status

In the CDF paper ⁵ we concluded that the precision of the measured spectrum (using 19 pb^{-1}) and its deviation from the standard theoretical predictions (EKS) demanded that the theoretical uncertainties be reevaluated. This reevaluation is essential before any statements about the presence or absence of new physics explanations can be made. Since the release of the paper, there has been a great deal of activity on both standard QCD and new physics explanations.

The CTEQ collaboration has derived new parton distribution functions by including the CDF and D0 data at intermediate energies in their global fitting program (CTEQ4M) ⁷. In addition they have produced a PDF (CTEQHJ) which gives increased weight to the high E_T CDF jet data while still giving a good fit to the rest of the world's data. This PDF is compared to the CDF and D0 measurements in Figure 8. As expected, the excess at high E_T is reduced with the new PDF.

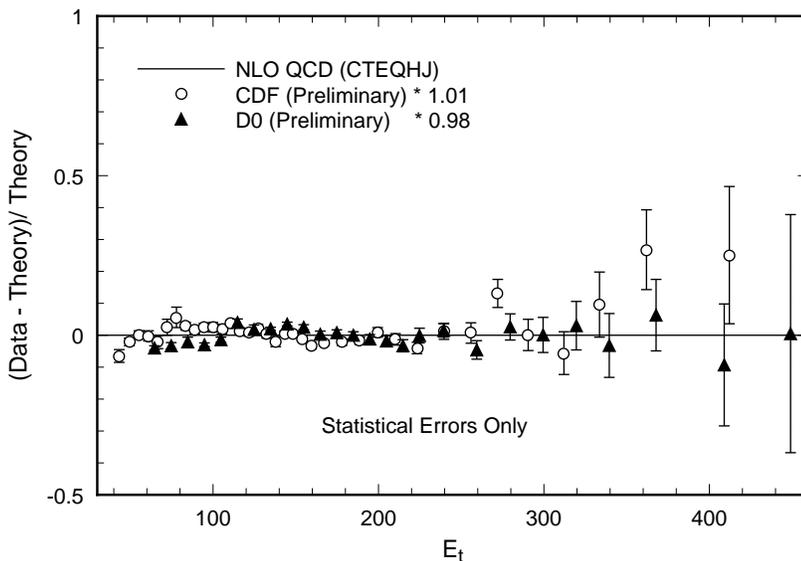


Figure 8: A new CTEQ fit which accomodates the high E_T CDF and D0 data.

In addition, a number of papers have been written pointing out additional theoretical uncertainties in high E_T jet production. A new calculation of the

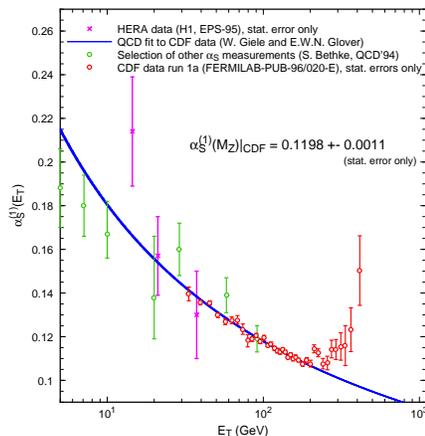


Figure 9: CDF measurement of α_s , and the running of α_s .

effects of soft gluon resummation⁸ has been performed as described in reference⁸. In addition, a comparison of the DIS and MSbar factorization schemes has also become available⁹.

More exotic explanations involving new physics have also been suggested. These include quark substructure¹⁰, a slower running of α_s , and new particles (leptophobic Z')¹¹. All of these processes would enhance the cross section at high E_T and thus would provide better agreement with the data.

Finally, under the assumption that the intermediate jet data are well described by QCD, the CDF measurement has been used to show the running of the strong coupling constant¹², α_s . Figure 9 shows the distribution of α_s as a function of jet E_T . The value of α_s at the Z mass is consistent with the world average and shows the possibility of being the worlds best determination. But first, the systematic uncertainty needs to be evaluated.

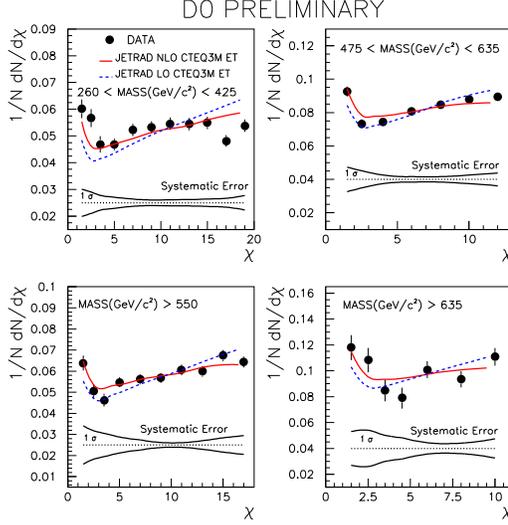


Figure 10: Angular distributions measured at D0 in four dijet mass bins (points). The LO (dashed) and NLO (line) predictions are shown for comparison. Good agreement is observed between data and NLO predictions

5 Dijet Angular Distribution

The dijet angular distribution can provide additional constraints on possible explanations for the high E_T excess observed in the inclusive cross section. The angular distribution is typically expressed in terms of χ where $\chi = (1 + |\cos\theta^*|)/(1 - |\cos\theta^*|)$ and θ^* is the angle between the incoming and outgoing partons in the center-of-mass (CM) frame. The χ variable flattens out the t-channel pole in the QCD prediction making it easier to observe the effects of new physics processes having a more isotropic distribution than QCD, e.g., quark compositeness. Unlike the inclusive spectrum, the angular distribution is insensitive to PDFs and overall energy scale. It is, however, more sensitive to the η dependence of the calorimeter response and resolution.

The dijet angular distribution¹³ for four different dijet mass regions as measured at D0 is shown in Figure 10. The data are compared to LO and NLO QCD using CTEQ3M PDFs and a scale of $\mu = E_T$. Good agreement is found with NLO QCD. Similar results are available for CDF, but here we show a related variable, R_χ , which is used to set limits on the quark compositeness scale, Λ . R_χ is the ratio of the number of events with $\chi < 2.5$ to the number

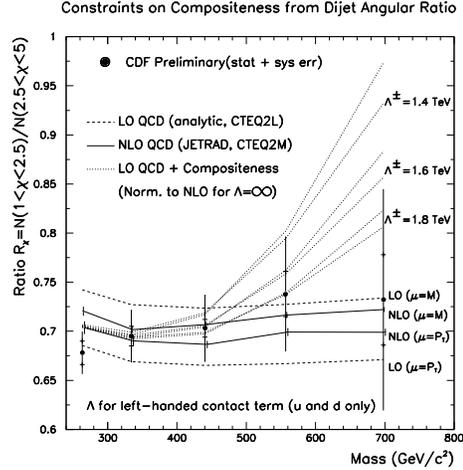


Figure 11: The ratio, R_χ , of the number of events with $\chi < 2.5$ to the number with $2.5 < \chi < 5$ measured at CDF. The LO (dashed), NLO (line) and various compositeness scale predictions are shown for comparison. Again, good agreement is observed between data and NLO predictions.

with $2.5 < \chi < 5$. This distribution is shown in Figure 11 for five slices of dijet mass. Again, we see that the data is in good agreement with NLO QCD. In the case where only u and d quarks are composite, CDF obtains limits of $\Lambda_{ud}^+ \geq 1.6$ TeV and $\Lambda_{ud}^- \geq 1.4$ TeV at 95% C.L. In a model where all quarks are composite, CDF obtains limits of $\Lambda^+ \geq 1.8$ TeV and $\Lambda^- \geq 1.6$ TeV at 95% C.L. The best fit value of Λ for the inclusive jet cross section (using MRSD0' PDFs) was $\Lambda_{ud}^+ = 1.6$ TeV. This best fit value depends critically on the NLO QCD prediction, which in turn is sensitive to the PDF chosen. The lack of an observable isotropic contribution to the angular distribution is therefore critical to our understanding of the high E_T jet data.

6 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 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

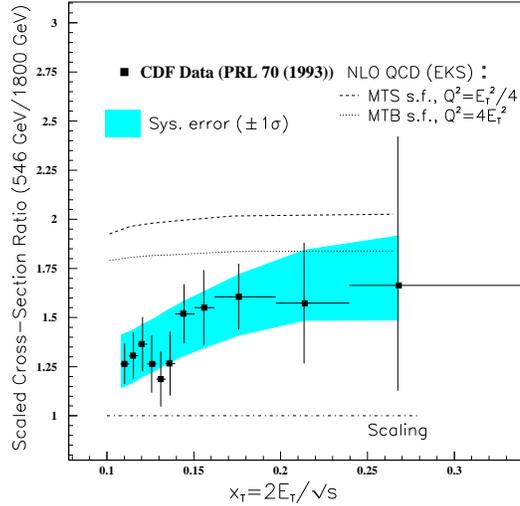


Figure 12: CDF scaling result from 0.546 TeV run of the Tevatron in 1989.

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 cancel¹. CDF's previous measurement of this quantity with a very small data sample (7.5 nb^{-1} collected in 1989) is shown in Figure 12. Scaling was ruled out at the 95% C.L. and a disagreement with the QCD predictions was observed in the low E_T region. In Dec. 1995 CDF collected 600 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 13 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 energy of the data sample to which it is compared. Figure 14 shows the 0.630 TeV data compared to 0.546 TeV and 1.8 TeV data vs 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 15 also shows the 1.8 TeV data and the 0.630 TeV data on the linear scale, but this time

CDF Inclusive Jet Cross Sections

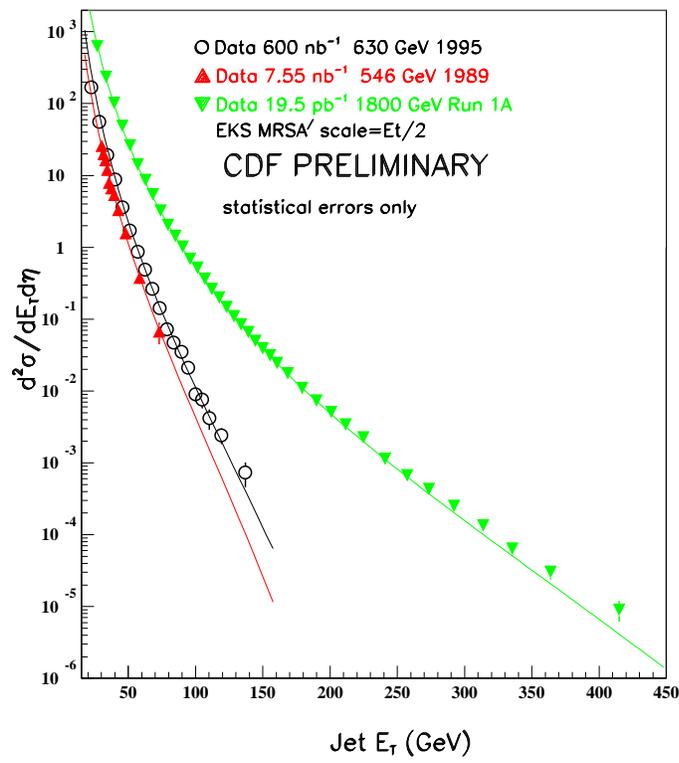


Figure 13: Inclusive jet cross sections as measured by CDF at three different CM energies

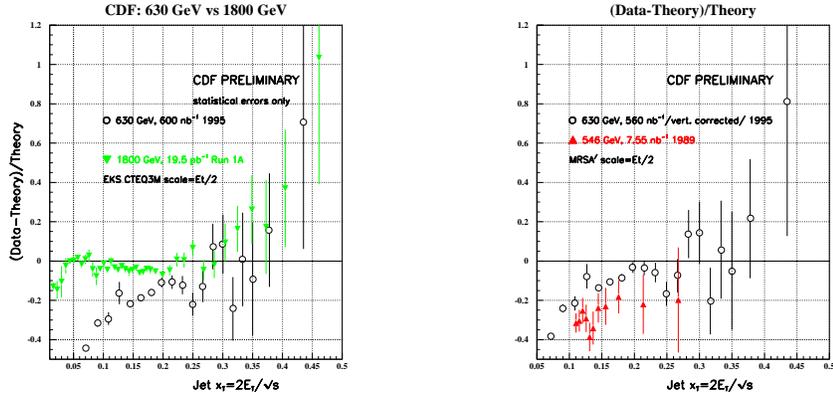


Figure 14: Inclusive jet cross sections at CDF. The 0.630 TeV data is compared to the 1.8 TeV data and to the 0.546 TeV data.

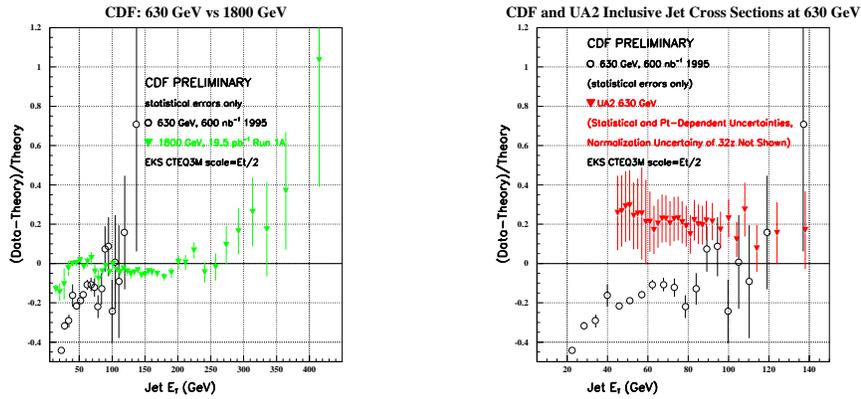


Figure 15: Inclusive jet cross sections at CDF 0.630 TeV and 1.8 TeV vs E_T , and the comparison to UA2

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 15 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 two measurements into agreement.

7 Summary and Conclusions

The inclusive jet measurements^{5,2} are 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 these measurements were released, new results on PDF's, and soft gluon resummation have been generated, as well as a number of possible new physics explanations. The angular distributions do not support new physics explanations with an isotropic component. The low CM energy data suggests that there may be another problem with the QCD predictions, however this is still a preliminary result. If it turns out that 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 α_s . However, if it turns out that QCD can not describe the data then we have the possibility of discovering something new.

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