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Inclusive Jet Production at 630 and 1800 GeV

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INCLUSIVE JET PRODUCTION AT 630 AND 1800 GEV

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Inclusive jet cross sections measured at the Fermilab Tevatron $p\bar{p}$ Collider are presented and compared to theoretical predictions. The cross sections are reported as a function of jet E_T at beam energies of $\sqrt{s} = 0.63$ TeV and $\sqrt{s} = 1.8$ TeV. A recent preliminary result at $\sqrt{s} = 1.8$ TeV by the CDF collaboration confirms an earlier published result which is in good agreement with Quantum Chromodynamics (QCD) below $E_T = 250$ GeV, but which shows excess jet production above 250 GeV. A final result by the DØ collaboration is in good agreement with QCD at all E_T. An uncertainty analysis, including a final DØ systematic error matrix, indicates the two measurements are consistent. Preliminary $\sqrt{s} = 0.63$ TeV cross sections from the two experiments are consistent with one another but somewhat lower than QCD predictions. Likewise, preliminary measurements of the ratio of cross sections at $\sqrt{s} = 0.63$ TeV and $\sqrt{s} = 1.8$ TeV are experimentally consistent, but approximately 20% below predictions.

1 Introduction

Within the framework of quantum chromodynamics (QCD), inelastic scattering between a proton and an antiproton can be described as an elastic collision between a single proton constituent and a single antiproton constituent. These constituents are often referred to as partons. After the collision, the outgoing partons manifest themselves as localized streams of particles or "jets". Predictions for the inclusive jet cross section are given by the folding of parton scattering cross sections with experimentally determined parton distribution functions (pdf's). These predictions have recently improved with next-to-leading order (NLO) QCD scattering calculations [1] and new, accurately measured pdf's [2]. Thus, measurement of the inclusive jet cross section provides a basic test of perturbative NLO QCD and a measurement of the pdf's.

Using data collected in a 1994–1995 run, the DØ [3] and CDF [4] collaborations have recently measured the inclusive jet cross section at beam energies of $\sqrt{s} = 0.63$ TeV and $\sqrt{s} = 1.8$ TeV. CDF recorded integrated luminosities of 0.56 and 87 pb^{-1} at $\sqrt{s} = 0.63$ TeV and $\sqrt{s} = 1.8$ TeV, respectively. DØ logged 0.54 and 92 pb^{-1} of data at the two energies. The inclusive jet cross section is typically reported as $d^2\sigma/dE_T d\eta$. E_T, the transverse energy of the jet, equals $E sin\theta$ where E is jet energy and θ is the angle between the proton direction and the jet. The pseudorapidity, η, is defined as $-ln(tan(\theta/2))$. Both collaborations employ fixed–cone jet finding algorithms to cluster energy. The cone radius is $\mathcal{R}$=0.7 in $\eta - \phi$ space, where ϕ is the azimuthal angle of the jet. The CDF measurements required jets to be in the rapidity interval $0.1 \leq |\eta| \leq 0.7$ while the D0 measurements include the interval $|\eta| \leq 0.5$ as well as $0.1 \leq |\eta| \leq 0.7$.

The jet analyses placed similar requirements on both the events and jets used in calculation of the cross sections. Both collaborations eliminated poorly measured events by requiring the event vertices to be near the center of the detector. Background events (such as cosmic rays) were eliminated by rejecting events with large missing E_T. The D0 collaboration rejected background jets from instrumental and accelerator sources by placing quality cuts on each jet. Although their procedures are quite different, both experiments apply jet energy and resolution corrections to the data. For a fuller description of the two analyses see References 5 and 6.

The ratio of the dimensionless cross sections $\sigma_d = ({E_T}^3/2\pi)(d^2\sigma/dE_T d\eta)$ at different beam energies versus $x_T = 2E_T/\sqrt{s}$ provides a complementary and sensitive test of QCD. The ratio of the two cross sections $\sigma_d^{630}/\sigma_d^{1800}$ has considerably less uncertainty from theoretical and experimental errors than the inclusive cross sections alone. The precise ratio is given by pdf evolution, the behaviour of gluon emission, and the running of the strong coupling constant. DØ and CDF have calculated the ratio in the rapidity regions $|\eta| \leq 0.5$ and $0.1 \leq |\eta| \leq 0.7$, respectively.

2 Inclusive Jet Cross Section at $\sqrt{s} = 1.8$ TeV

Figure 1 shows the final inclusive jet cross section as measured by the DØ collaboration in the rapidity region $|\eta| \leq 0.5$ [5]. These results have been submitted to Physical Review Letters. The figure also shows a theoretical prediction for the cross section from the NLO event generator JETRAD [1]. There is good agreement over seven orders of magnitude.

Inputs to the NLO calculation are the renormalization scale μ (equal to the factorization scale), the parton distribution function, and the parton clustering algorithm. For the calculation shown here, the renormalization scale is set equal to the leading jet E_T , $\mu = 0.5E_T^{\max}$, and the pdf is CTEQ3M[2]. Partons separated by less than $\mathcal{R}_{\rm sep}$=1.3$\mathcal{R}$ were clustered if they were also within $\mathcal{R}$=0.7

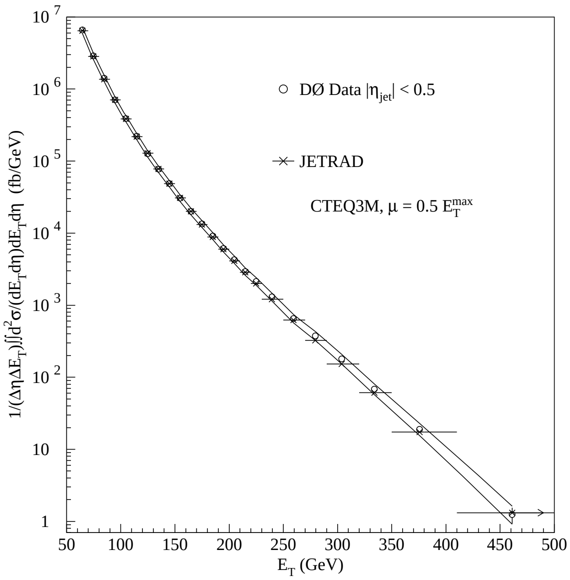

Figure 1: The DØ 1800 GeV, $|\eta| \leq 0.5$ inclusive cross section. Statistical uncertainties are invisible on this scale. The solid curves represent the $\pm 1\sigma$ systematic uncertainty band on the data.

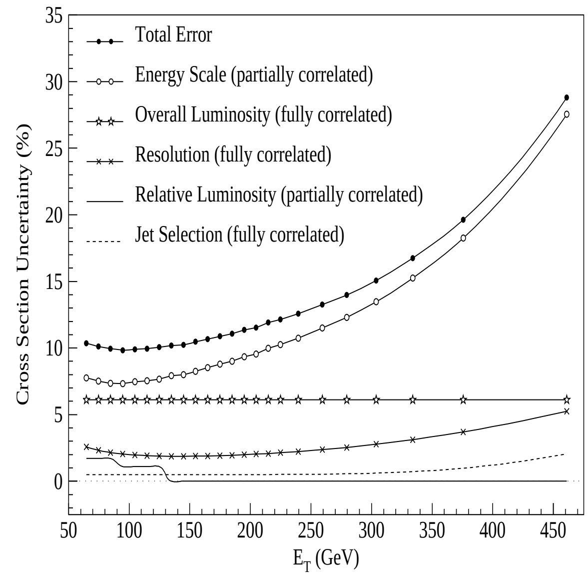

Figure 2: Contributions to the DØ , $|\eta| \leq 0.5$ cross section uncertainty plotted by component.

of their E_T-weighted η-ϕ centroid. This choice of $\mathcal{R}_{\rm sep}$ is discussed in Ref. 7. Variations in the predicted cross section due to the input choices are about 30% [8]. These variations are dominated by the choice of renormalizaton scale and pdf.

Figure 2 shows the uncertainties for the DØ , $|\eta| \leq 0.5$ cross section. Each curve represents the average of nearly symmetric upper and lower uncertainties. The energy scale uncertainty varies from 8% at low E_T to 22% at 400 GeV. This contribution dominates all other sources of uncertainty, except at low E_T, where the 6.1% luminosity uncertainty is of comparable magnitude. The total systematic error is 10% at 100 GeV and 23% at 400 GeV. These uncertainties have improved by a factor of two since the initial presentation of this data in 1996.

Figure 3 shows the ratios $(D - T)/T$ for the DØ data (D) and JETRAD NLO theoretical predictions (T) based on the CTEQ3M, CTEQ4M and MRST pdf's [2] for $|\eta| \leq 0.5$. Given the experimental and theoretical uncertainties, the predictions are in agreement with the data; in particular, the data above 350 GeV show no indication of an excess relative to QCD.

The data and theory can be compared quantitatively with a χ^2 test incorporating the uncertainty covariance matrix. The matrix elements are constructed by analyzing the mutual correlation of the uncertainties in Fig. 2 at each pair of E_T values. The overall systematic uncertainty is highly correlated. The bin-to-bin correlations in the full uncertainty for representative E_T bins are greater than 40% and positive.

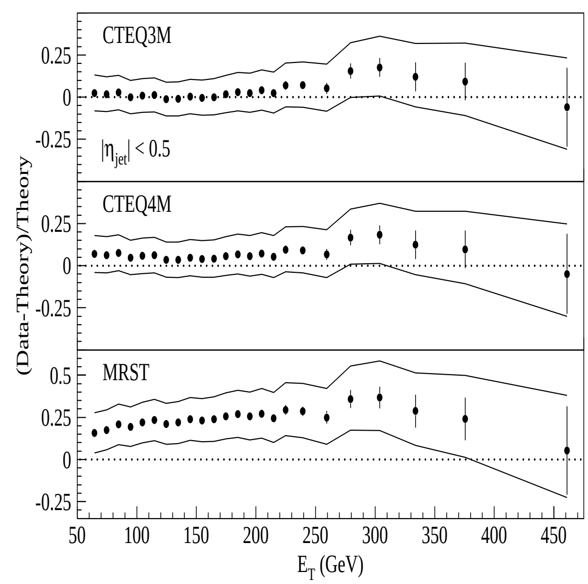

Figure 3: Difference between DØ data and JETRAD QCD predictions normalized to predictions. The bands represent the total experimental uncertainty.

Table 1: χ^2 comparisons between JETRAD and DØ , $|\eta| \leq 0.5$ and $0.1 \leq |\eta| \leq 0.7$ data for $\mu = 0.5E_T^{max}$, $\mathcal{R}_{sep}$=1.3$\mathcal{R}$, and various pdf's. There are 24 degrees of freedom.

pdf	$\|\eta\| \leq 0.5$	$0.1 \leq \|\eta\| \leq 0.7$
CTE3M	23.9	28.4
CTEQ4M	17.6	23.3
CTEQ4HJ	15.7	20.5
MRSA´	20.0	27.8
MRST	17.0	19.5

Table 1 lists χ^2 values for several JETRAD predictions incorporating various pdf's[2]. Each comparison has 24 degrees of freedom. The JETRAD predictions have been fit to a smooth function of E_T . All five predictions describe the $|\eta| \leq 0.5$ cross section very well (the probabilities for χ^2 to exceed the listed values are between 47 and 90%). A similar measurement in the $0.1 \leq |\eta| \leq 0.7$ interval is also well described (probabilities between 24 and 72%). The probabilities calculated by comparing the data to EKS[1] predictions for $\mu = (0.25, 0.5, 1.0)E_T^{max}$ and $\mu = (0.25, 0.5, 1.0)E_T^{jet}$ are all greater than 57% .

Fig. 4 shows the published jet cross section from the CDF collaboration[6]. The $0.1 \leq |\eta| \leq 0.7$ cross section was measured with a 19.7 pb^{-1} data set taken during a 1992–1993 data run. As demonstrated by the inset, the cross section spans an impressive eleven orders of magnitude. The data points are compared, on a linear scale, to a NLO QCD prediction incorporating the MRSD0´ pdf, $\mu = 0.5E_T^{jet}$, and $\mathcal{R}_{sep}$=2.0$\mathcal{R}$. The data and theory are in excellent agreement below 250 GeV. However, above 250 GeV there seems to be excess production relative to QCD. The systematic uncertainty at 100 GeV is 13% and at 400 GeV 25%.

A preliminary inclusive jet cross from CDF using the larger 1994–1995 data set is shown in Fig. 5. The new cross section (solid symbols) is consistent with the published measurement (open symbols) at all E_T . Here the data are compared to a NLO QCD prediction incorporating the MRSD0´ pdf, $\mu = 0.5E_T^{jet}$, and $\mathcal{R}_{sep}$=2.0$\mathcal{R}$. Although the more recent analysis is not yet complete, the systematic errors are expected to be comparable to those of the published result.

The top panel in Fig. 6 shows $(D-T)/T$ for the D0 and 1994–1995 CDF data sets in the $0.1 \leq |\eta| \leq 0.7$ region relative to an EKS calculation using the CTEQ3M pdf, $\mu = 0.5E_T^{jet}$, and $\mathcal{R}_{sep}$=2.0$\mathcal{R}$. For this rapidity region, DØ has carried out a χ^2 comparison between their data and the nominal curve describing the central val-

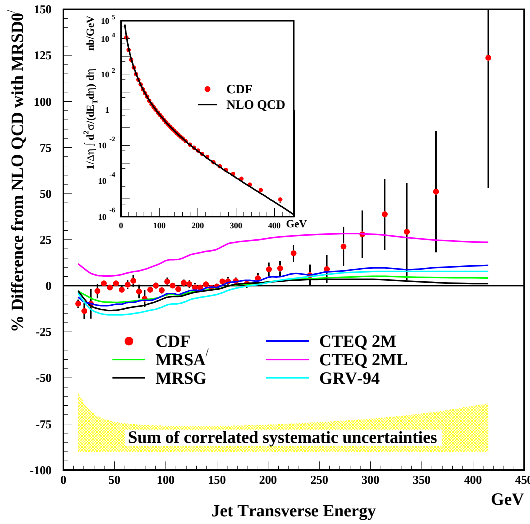

Figure 4: The published CDF 1800 GeV, $0.1 \leq |\eta| \leq 0.7$ inclusive cross section compared to several NLO QCD predictions. Statistical errors are shown on the points. Systematic errors are given by the hatched region.

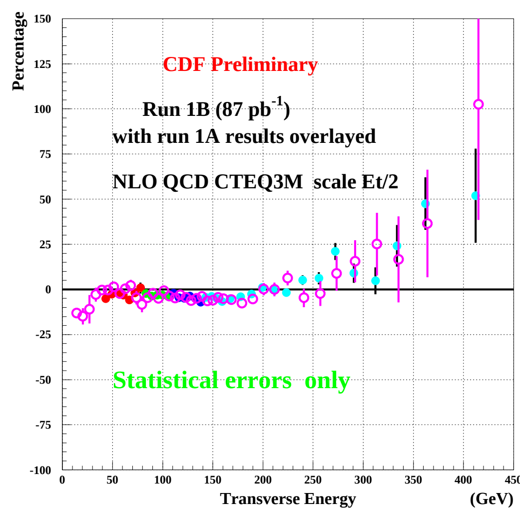

Figure 5: The recent preliminary CDF 1800 GeV, $0.1 \leq |\eta| \leq 0.7$ inclusive cross section compared to a NLO QCD prediction. The open symbols are from the 1992–1993 data set and the closed symbols from the 1994–1995 data set. Only statistical errors are shown.

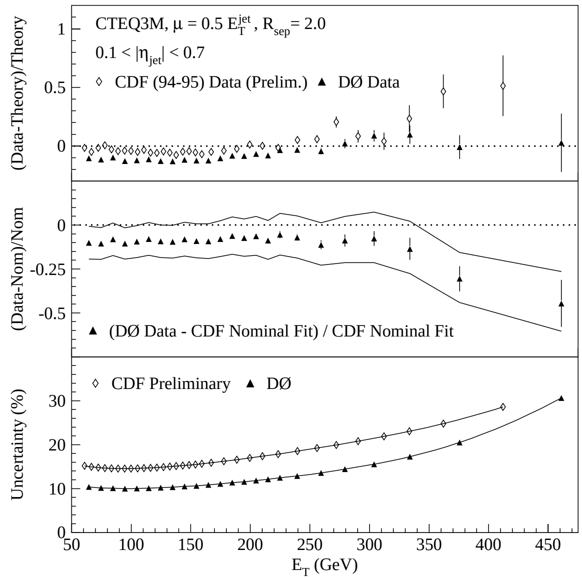

Figure 6: Top: Normalized comparisons of D0 and CDF data to EKS. Middle: Difference between DØ data and smoothed results of CDF nominal fit normalized to the latter. The band represents the uncertainty on DØ data. Bottom: DØ and CDF uncertainty.

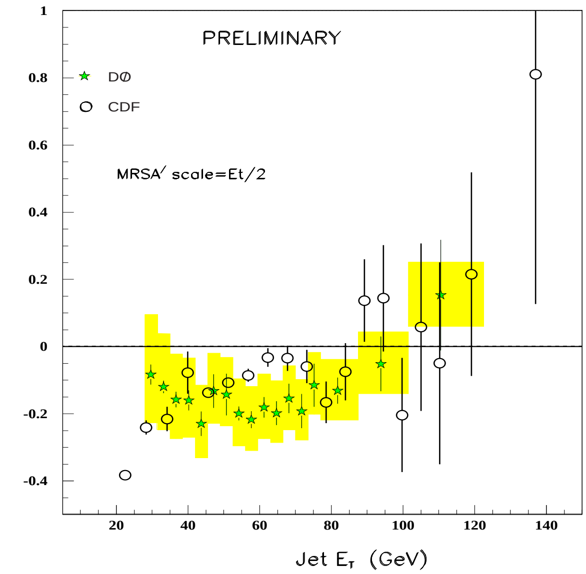

Figure 7: Preliminary DØ and CDF $\sqrt{s} = 0.63$ TeV cross sections compared to NLO QCD predictions. The shaded boxes represent the DØ systematic errors.

ues of the CDF data. Comparison of the D0 data to the nominal curve, as though it were theory, yields a χ^2 of 63.2 for 24 degrees of freedom (probability of 0.002%). Thus the DØ data cannot be described with this parameterization. As illustrated in the middle panel of Fig. 6, the data and the curve differ at low and high E_T ; such differences cannot be accommodated by the highly correlated uncertainties of the DØ data. The bottom panel, which shows the magnitude of the DØ and CDF uncertainties, implies that the two data sets are consistent. In fact, if the systematic uncertainties of the CDF data are included in the covariance matrix, the χ^2 is reduced to 24.7 (probability of 42%).

3 Inclusive Cross Section at 630 GeV and the Ratio of Dimensionless Cross Sections

CDF and DØ have also measured the inclusive jet cross section at $\sqrt{s} = 0.63$ TeV in the regions $0.1 \leq |\eta| \leq 0.7$ and $|\eta| \leq 0.5$, respectively. Fig. 7 shows the data minus theory normalized to theory as a function of jet E_T for the CDF and DØ data and NLO theoretical predictions using the MRSA′ pdf and $\mu = 0.5E_T$. The two preliminary measurements are in agreement above 80 GeV, but some discrepancy exists near and below 60 GeV. The discrepancies are within the 20–30% DØ systematic uncertainties represented by the shaded boxes. With regards to theory, the QCD prediction is larger, but not significantly, than the data for E_T less than 80 GeV.

As mentioned earlier, the ratio of the dimensionless cross sections $\sigma_d^{630}/\sigma_d^{1800}$ offers reduced theoretical and experimental uncertainties. Fig. 8 shows a preliminary ratio for the DØ data as a function of x_T. The uncertainty is about 7%, much less than the 15-30% uncertainty on the cross sections. Many of the energy scale and luminosity uncertainties cancel in the ratio. The figure also shows NLO QCD JETRAD predictions for the ratio using $\mu = 0.5E_T^{\max}$, $\mathcal{R}_{\rm sep}$=1.3$\mathcal{R}$ and three different pdf's. There is an absence of pdf dependence. Generally, the theoretical uncertainty in the ratio is reduced by 50% relative to the inclusive measurements.

The ratios of dimensionless cross sections versus x_T for DØ and CDF are both shown in Fig. 9. The discrepancy between the two measurements is very similar to the $\sqrt{s} = 0.63$ TeV discrepancy. The shaded boxes represent the ±7% DØ systematic errors. The two data sets are consistent for $x_T \geq 0.1$, but some difference may exist for $x_T \leq 0.1$. The significance of the difference must await completion of the CDF systematic uncertainties. The two curves are EKS predictions using CTEQ3M and MRSA′ and $\mu = 0.5E_T^{\max}$. The theory seems to be 20% higher than expected at roughly a three standard deviation significance.

4 Conclusions

The recent preliminary CDF $\sqrt{s} = 1.8$ TeV inclusive jet cross section confirms an earlier publication which noted excellent agreement with NLO QCD below E_T = 250

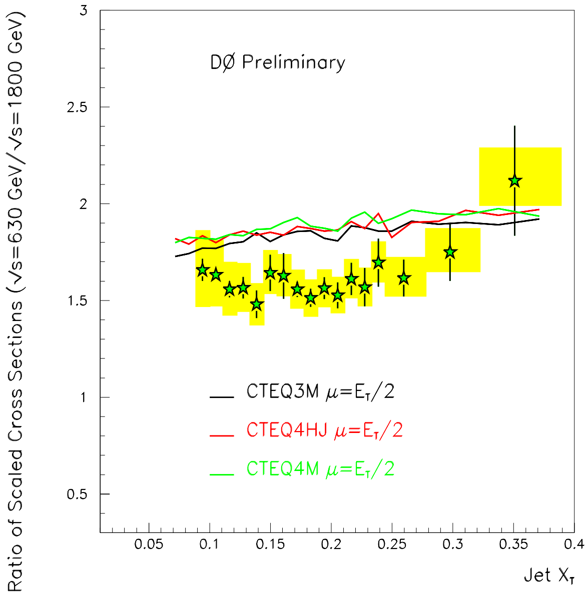

Figure 8: The preliminary ratio of dimensionless cross sections versus x_T as measured by DØ . The curves are NLO QCD predictions for various pdf's.

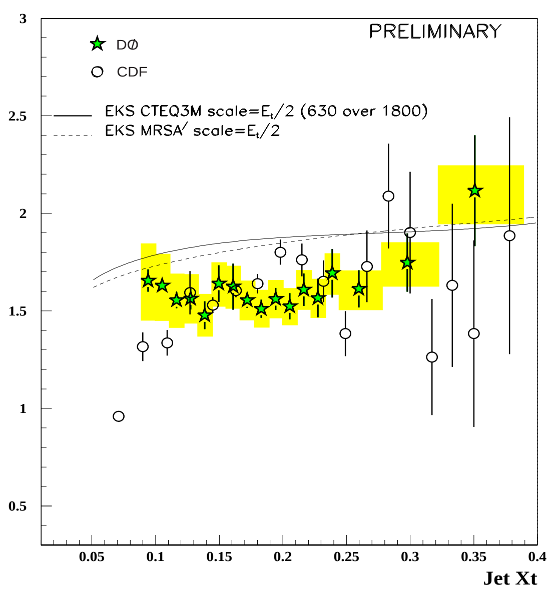

Figure 9: The preliminary ratio of dimensionless cross sections versus x_T as measured by DØ and CDF. Shaded boxes represent the DØ systematic errors. Curves are NLO QCD predictions.

GeV, but excess jet production at larger E_T . The final DØ result has improved accuracy and is in good agreement with NLO QCD at all E_T. The DØ results shows no indication of excess jet production at large E_T. A detailed uncertainty analysis by the DØ collaboration shows the two results to be consistent.

Both experiments have also measured the inclusive jet cross section at $\sqrt{s} = 0.63$ TeV. The two results are consistent but approximately 20%, below NLO QCD predictions. This discrepancy is not significant. The discrepancy persists in the ratio of dimensionless cross sections. The DØ collaboration has presented a ratio 20% lower than expected at a significance of approximately three standard deviations. The CDF ratio is consistent with the DØ result, but final uncertainties must be completed before the significance can be determined.

In the past few years, the inclusive jet cross sections from the Tevatron have been substantially extended and improved. In general, there is good agreement between the cross sections and NLO QCD as a function of E_T and beam energy. However, 20% differences have been observed between the ratio of dimensionless cross sections and theoretical predictions. Completion of the Tevatron results in the next few months should shed some light on this curious discrepancy.

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