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D0 and CDF

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Inclusive jet production and subjets at the Tevatron

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Abstract
The DØ and CDF proton-antiproton collider experiments at the Tevatron accumulated large samples of high energy jet production data during Run I (1992-1996). Presented here are measurements of the central inclusive jet cross section at center-of-mass energies of 1800 and 630 GeV (by the DØ and CDF experiments) and a forward ($|\eta| < 1.5$) inclusive cross section measurement by the DØ experiment at 1800 GeV. Cross sections are compared to next-to-leading order QCD predictions with recent parton distribution functions. Also included is a measure of subjet multiplicity in jets produced at 1800 GeV using a successive combination type of jet algorithm.

1. Introduction

The Tevatron Collider program completed its first run of data taking in early 1996. The large statistical sample collected by the two collider detectors (DØ and CDF) enables a number of jet related measurements and studies to be performed which can be compared to predictions from Standard Model QCD. Measurements included in this presentation are:

- From both DØ and CDF:
  - recently published measurements of the central inclusive jet cross section at a proton-antiproton center-of-mass (cm) energy of 1800 GeV and
  - preliminary measurements of the ratio of this cross section to that at a lower cm energy (630 GeV).
- Also from DØ:
  - a preliminary measurement of the forward ($|\eta| < 1.5$) inclusive jet cross section at 1800 GeV and
  - a preliminary measure of subjet multiplicity which utilizes a successive combination type jet algorithm.

Cross sections are compared to next-to-leading order (NLO) QCD predictions using a number of recent parton distribution functions. The subjet multiplicity result is compared to a naive Leading Order (LO) QCD prediction and to HERWIG predictions.

2. Inclusive Jet Cross Sections

Data recorded by the DØ and CDF detectors in Run I have yielded the first high statistics measurement of the inclusive jet cross section over a wide range in jet transverse energy (E_T), where the cross section drops by eleven orders of magnitude. An increased cross section at high jet E_T could indicate quark compositeness and new physics beyond the Standard Model. In the absence of that, comparison of these cross sections to QCD predictions indicates how well we understand the proton structure: the adequacy of NLO predictions and sensitivity of the predictions to current pdf's (parton distribution functions).

Details of the jet finding algorithm, jet reconstruction, event selection, and measurements of the central inclusive cross section along with many other measurements by both DØ and CDF can be found in the 1999 "Annual Review of Nuclear and Particle Science" [1]. Both experiments used an integrated luminosity of nearly 100 pb^{-1} of data at the higher cm energy (1800 GeV) jet cross section measurements, and about 5 pb^{-1} at the lower cm energy (630 GeV).

2.1. Jet Reconstruction and Data Selection

All jet measurements described here use primarily calorimetry to identify jets and measure their energy and orientation. Both experiments reconstruct jets using an iterative algorithm with a fixed cone size of radius $R = 0.7$ in $\eta - \phi$ space. The pseudorapidity η is defined as $\eta = \ln[\tan\frac{\theta}{2}]$ where θ is the angle of the jet relative to the incoming proton beam. The angle ϕ is the azimuthal angle about the beam axis. Vertex, jet and event quality criteria are imposed to eliminate backgrounds caused by electrons, photons, noise and cosmic rays. Additional corrections are applied to measured energies to obtain jet energies corrected for calorimeter response, noise, showering outside of the cone radius, and energy deposits from spectator interactions. Unsmearing corrections are also applied to remove the effect of a finite E_T resolution.

2.2. Central Cross Sections at 1800 GeV

Both experiments compare their measurements to NLO QCD calculations from JETRAD and EKS [2]. Each of these programs produces equivalent results given the same input specifications.

Jets are the manifestation of partons produced in the primary parton-parton collision. Partons in the NLO calculation may have any angular separation, while the fixed cone size used to experimentally reconstruct jets may envelop more than one NLO parton. Therefore, partons in the NLO calculations are required to be separated by an angular difference of $\Delta R_{sep} = 1.3 \times R$ in order to be counted as distinct jets.

The Run I CDF measurement of the central inclusive jet cross section at a cm energy of 1800 GeV indicates a rise in the cross section at high jet transverse energy but is otherwise in agreement with the NLO prediction. The DØ measurement is consistent with the NLO QCD prediction over the full range of jet transverse energy, particularly at $E_T \geq 350$ GeV.

In order to understand the apparent discrepancy at high jet E_T, both the experimental and theoretical assumptions were scrutinized. Large uncertainties in the theoretical prediction were revealed, and, in particular, the realization that there remains considerable flexibility in the gluon distribution at high x. The CTEQ collaboration [3] then performed an additional global pdf fit giving a large emphasis to the CDF high E_T data: This new pdf set is denoted CTEQ4HJ [4].

The top plot in Figure 1 shows the [Data-Theory]/Theory for the Run I DØ (solid triangles) and CDF (open diamonds) data sets in the pseudorapidity region $(0.1 < |\eta| < 0.7)$ relative to the JETRAD prediction with CTEQ4HJ pdf's and a renormalization scale $\mu_R = 0.5E_T^{max}$. While this new pdf set is somewhat contrived, it is consistent with both collider experiment data sets.

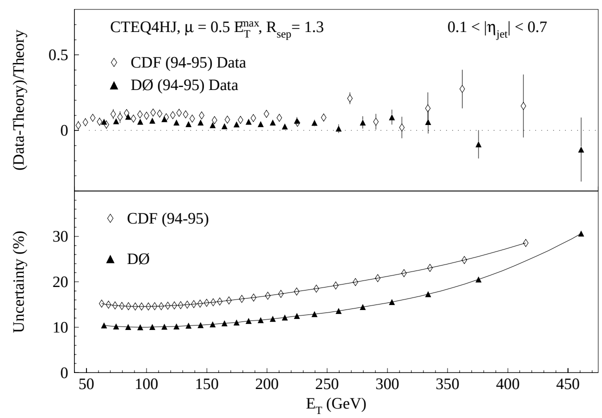

Figure 1. $(Data - Theory)/Theory$ comparison of Run Ib DØ and CDF inclusive jet cross section in the pseudorapidity region $0.1 < |\eta| < 0.7$ as a function of jet E_T relative to a QCD prediction from the JETRAD monte carlo using CTEQ4HJ pdf's and $\mu_R = 0.5E_T^{max}$ at a cm energy of 1800 GeV.

The lower half of Figure 1 shows the percentage uncertainty in the DØ and CDF measurements based on the quadrature sum of the uncertainty components. A χ^2 comparison of the DØ and CDF measurements shows that the measurements agree with a high degree of probability (96%) when account is taken for full systematic uncertainties in the covariance matrix and the 2.7% normalization difference † is removed.

It is interesting to note that the DØ measurement has considerably smaller systematic uncertainties and is consistent with NLO predictions using any of the modern pdf sets. Experimental uncertainties in this measurement are now lower than the theoretical uncertainties. We look forward to the measurement of the inclusive jet cross section in Run II from both experiments as well as to refined predictions from perturbative QCD.

2.3. Forward Cross Sections at 1800 GeV

DØ has extended its inclusive jet cross section measurement into the forward region of pseudorapidity. The top and bottom plots of Figure 2 show the [Data-Theory]/Theory comparison of the measured cross section relative to the prediction in the pseudorapidity ranges from $0.5 \leq |\eta| < 1.0$ and $1.0 \leq |\eta| < 1.5$, respectively. The predicted cross section is calculated using JETRAD with CTEQ3M

† A normalization difference arises due to the difference in the total cross section used by each experiment: CDF uses its own measurement, DØ uses the world average.

pdf's and a renormalization scale $\mu_R = E_T^{max}/2$. The bands reflect the total systematic uncertainty in the measurement, while the error bars indicate the statistical error. DØ finds the data and theory in good agreement and is now working to finalize this analysis and extend the measurement to $|\eta| < 3.0$.

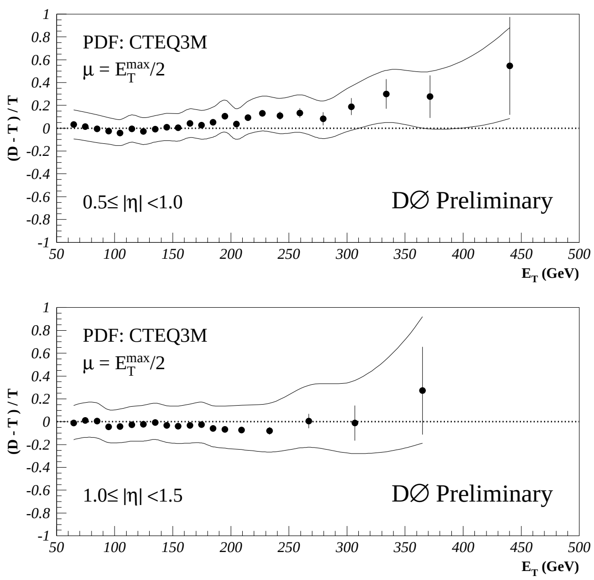

Figure 2. The pseudorapidity dependence of the inclusive jet cross section (top: $0.5 \leq |\eta| < 1.0$, bottom: $1.0 \leq |\eta| < 1.5$) relative to the NLO QCD prediction from JETRAD using CTEQ3M pdf's.

2.4. Central Cross Section Ratio

Both experiments also recorded data at a cm energy of 630 GeV during Run I. A more stringent test of NLO QCD is then the ratio of cross sections because of the substantial reduction in both experimental and theoretical uncertainties. More specifically, we measure the ratio of $R = \sigma_s^{630}/\sigma_s^{1800}$ as a function of X_T, where σ_s is the scale invariant cross section: $\sigma_s = (E_T^3/2\pi)(d^2\sigma/dE_T d\eta)$ and X_T is the jet transverse momentum fraction: $X_T = 2E_T/\sqrt{s}$. In the naive parton model, this ratio is flat in X_T. Deviations from this model result from scaling evolution (of both pdf's and α_s) and terms beyond LO.

Shown in Figure 3 is ratio of the scaled invariant cross section ($\sqrt{s} = 630$ GeV to that at 1800 GeV) measured by CDF (solid circles) and DØ (open circles). The discrepancy at low X_T has yet to be resolved. Both experiments qualitatively agree for $X_T > 0.1$ where both differ from the NLO prediction beyond simple variations in the pdf assumptions (three of which are indicated by the lines above the data points). A quantitative

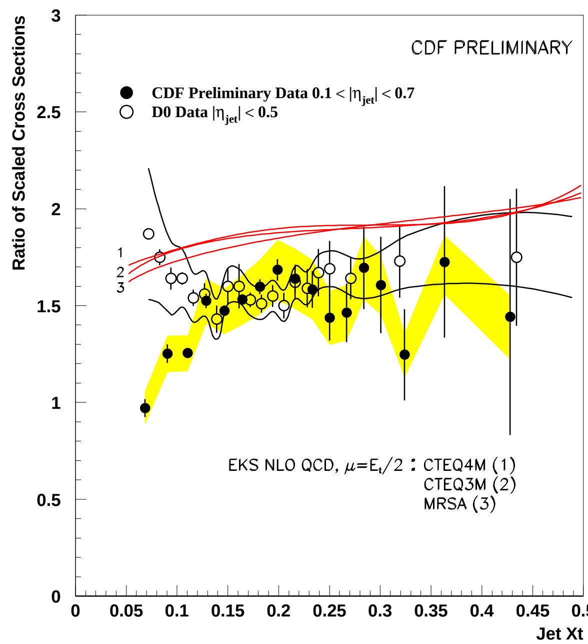

Figure 3. The ratio of the scaled invariant cross section ($\sqrt{s} = 630$ GeV to that at 1800 GeV) measured by CDF (solid circles) and DØ (open circles). Error bars show the statistical uncertainties while the band around each of the data points indicates the systematic uncertainties.

χ^2 analysis shows a nearly 3σ deviation from NLO QCD for the scale choices that give the best agreement for the 1800 GeV cm energy. In further analysis, DØ found that using different renormalization scales for the lower cm energy data produced good quantitative agreement with the theory. To summarize, further corrections to the NLO calculation are required to reduce the scale dependence and improve the predictive power of the calculation.

3. Subjet Multiplicity

While a number of important measurements have been accomplished using the cone algorithm, the DØ collaboration is exploring the use of a Durham or 'k_T-type' algorithm for jet reconstruction. Experimentally, any jet reconstruction algorithm associates a collection of energy clusters in the calorimeter with a 'jet', whose energy and direction are highly correlated with partons emerging from the primary hard parton-parton interaction. The cone algorithm groups energy clusters based on what falls within a fixed cone size. The k_T-type algorithm used by DØ [5] combines energy clusters (i and j) based on their relative angular separation (ΔR_{ij} in $\eta - \phi$ space) and transverse energy ($E_{T,i}$ and $E_{T,j}$) by successive combination: $d_{ij} =$

$min(E_{T,i}, E_{T,j})\Delta R_{ij}^2/D^2$ where D is a stopping parameter ($D = 0.5$ for this analysis). Clusters are combined, recalculating all $E_{T,i}$ and ΔR_{ij} until no d_{ij} is less than d_{ii}. The algorithm starts with a collection of pre-clusters (required to reduce the event size during data processing) separated by $\Delta R_{ij} \geq 0.2$. After running the successive combination algorithm, a list of jets is produced, each with transverse energy $E_T(jet)$ and separated by $\Delta R > D$ from any other jet.

This analysis is more fully described elsewhere [6]. To calculate the subjet multiplicity, the k_T algorithm is rerun on each jet, starting with the preclusters, which are combined successively until all $d_{ij} > y_{cut}E_T^2(jet)$. The subjet multiplicity is the number of found objects within each jet. The subjet multiplicity approaches 1 as the resolution parameter, y_{cut}, gets larger than D, and approaches the number of preclusters at $y_{cut} \ll D$. A $y_{cut} = 10^{-3}$ is used for this analysis.

LO QCD predicts that gluons radiate more than quarks in proportion to the ratio of their color charges R which is equal to 9/4 (or 2.25). Gluon jets, then, should on average have higher subjet multiplicity than quark jets. While any jet in the DØ detector cannot be unambiguously classified as gluon or quark in origin, samples of jets known to be gluon or quark enriched can be identified: Because t-channel production dominates at the Tevatron, jets with $55 < E_T < 100$ GeV produced at a cm energy of 1800 GeV are known to be gluon enhanced relative to jets in the same E_T range produced at 630 GeV. These samples comprise the gluon and quark enriched samples, respectively, in this analysis. By choosing jets in the same E_T range, experimental biases and systematic effects are reduced.

We assume the quark and gluon subjet multiplicities are independent of the cm energy. Uncorrected gluon and quark subjet multiplicities are obtained by combining the measured subjet multiplicities in the quark and gluon enriched samples with the estimated fraction of gluon jets at the two cm energies (calculated using the HERWIG [7] monte carlo). Corrections to these multiplicities are made to unsmear the calorimeter jet particle multiplicity back to the particle level using HERWIG monte carlo samples and a detector simulation.

Figure 4 shows the corrected subjet multiplicity distribution for quark (solid points) and gluon (open squares) jets. The average multiplicity for gluon jets is clearly higher than that of quark jets, as expected in naive QCD since gluons are expected to radiate more. The measured ratio of average gluon to quark subjet multiplicity is $R_{DØ} = 1.91 \pm 0.04$. This is consistent with the ratio obtained from the HERWIG monte carlo of $R_{HERWIG} = 1.86 \pm 0.04$, but is much smaller than the naive LO prediction of $R_{LO} = 9/4$. This difference from LO is expected due to higher order effects from color connections, initial and final state radiation, and hadronization effects, factors which seem to be properly taken into account by the HERWIG/detector simulation.

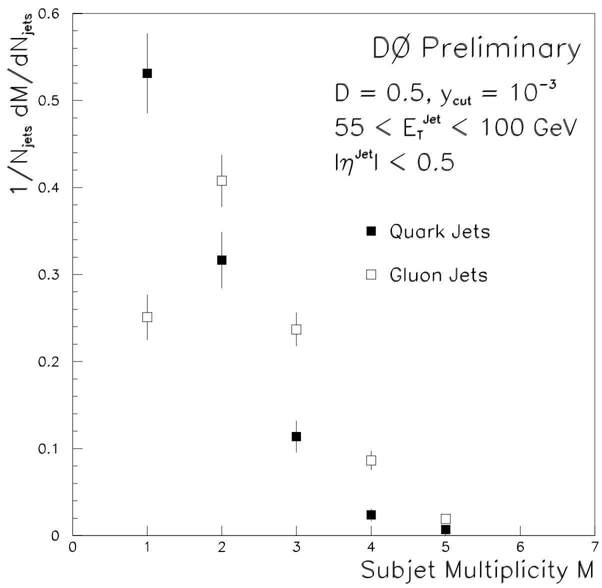

Figure 4. Corrected subjet multiplicity in quark and gluon jets.

Sources of systematic error in the measurement include the estimation of the gluon jet fraction (largest source), the jet E_T cut, detector simulation, and smearing uncertainty.

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