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Measurement of the Inclusive Jet Cross Section in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV *

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ABSTRACT

Inclusive jet production at $\sqrt{s} = 1.8$ TeV has been measured in the CDF detector at the Fermilab Tevatron $\bar{p}p$ Collider. Jets with transverse energies (E_t) up to 250 GeV have been observed. The E_t dependence of the inclusive jet cross section is consistent with leading order Quantum Chromodynamic (QCD) calculations, and comparison with lower energy data shows deviations from scaling consistent with QCD. A lower limit of 700 GeV (95% CL) is placed on the quark compositeness scale parameter, Λ_c , associated with an effective contact interaction.

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In this Letter we present the first measurement of the inclusive jet cross section, σ ($\bar{p}p \rightarrow$ jet + X), for a center-of-mass energy $\sqrt{s} = 1.8$ TeV, at the Fermilab Tevatron $\bar{p}p$ Collider. The jet transverse energy spectrum is compared to leading order predictions of QCD and to lower energy data from the CERN colliders. The higher collision energy available at the Tevatron allows a deeper probe of possible quark substructure.

The Collider Detector at Fermilab (CDF) is described in detail elsewhere[1]. The data presented are based on information from the central calorimeter[2], which is composed of projective towers segmented in azimuth ($\Delta\phi = 15^o$) and pseudorapidity ($\Delta\eta = 0.1$), covering the interval $|\eta| < 1.1$ and $0 < \phi < 2\pi$. The polar angle θ is related to η by $\eta = ln(cot(\theta/2))$. Eighteen radiation lengths of Pb-scintillator electromagnetic (EM) calorimeter is followed by at least four absorption lengths of Fe-scintillator hadron calorimeter. The EM and hadron tower responses were determined in a test beam[2]. Calibrations were maintained at a 1% level using radioactive sources, light pulsers, and electronic charge injection systems. The resolution for single 50 GeV electrons (pions) is 1 GeV (5.5 GeV) RMS. The tower energy is defined to be the sum of the energies in the EM and hadronic compartments. Charged particle momenta were reconstructed with data from a central tracking chamber [1,3] located in a 1.5 T magnetic field. The event vertex position was determined from a set of time projection chambers surrounding the beam pipe [1,4].

Events had to pass a hardware trigger requiring a coincidence of at least one particle in each of the upstream and downstream scintillation counters ($3.2 \leq |\eta| \leq 5.9$) in conjunction with a minimum total transverse energy summed over the calorimeter towers. The coincidence rate in the counters was used to determine the luminosity based on an estimated effective cross section of 44 mb [1,5]. Thresholds for the summed transverse energy triggers were set at 20, 30, 40 and 45 GeV depending on luminosity. For each threshold the integrated luminosity is 0.4 nb^{-1}, 12.6 nb^{-1}, 6.0 nb^{-1} and 6.9 nb^{-1} respectively. The luminosity is uncertain by $\approx 15\%$, due primarily to the extrapolation of the inelastic cross section from lower energies [5].

Jets are identified as local clusters of energy in the calorimeter using the following algorithm. First, preclusters are formed by summing the transverse energies in contiguous towers, requiring at least 1 GeV of transverse energy per tower. For each precluster having more than 2 GeV total transverse energy, a centroid is computed using transverse energy weighting. Next, a circle of radius $R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.6$ is formed around the centroid of each precluster. Here $\Delta\eta$ ($\Delta\phi$) refers to the difference in pseudorapidity (azimuth) between a tower location and the centroid. Towers above 0.2 GeV transverse energy inside this circle form the cluster; the centroid is then recalculated, and a new circle is formed. This process is repeated until the list of towers inside the circle remains unchanged in successive iterations. Finally, if two clusters overlap, they are merged if either cluster shares more than 50% of its energy with the other; if not, they remain separate and towers common to both are assigned to the nearest cluster. The cluster energy, E, is defined to be the scalar sum of the energies in its towers. From E and the polar angle (θ) formed between the beam axis and a line from the event vertex to the cluster centroid, the jet transverse energy is $E_t \equiv E\, sin\theta$.

Backgrounds from stray particles due to accelerator losses, and cosmic ray *bremsstrahlung* inside the calorimeter are 10% of the triggers. Most can be removed using timing information from the central hadron calorimeters because they usually do not coincide with beam-beam collisions. By requiring that the hadron energy occur inside a 35 nsec window bracketing the beam-beam crossing, 99% of the backgrounds were removed. Remaining backgrounds were significant only at high E_t, and constitute 10% of the events with clusters above 70 GeV. These backgrounds were either coincident with the beam-beam interactions or appear only in the EM calorimeter (not instrumented for timing), and were removed with cuts placed on charged particle momenta, the EM content of clusters, and the event missing transverse energy [6].

To ensure full acceptance, a number of requirements were made. The event vertex along the beamline had to be within 60 cm of the center of the detector. The cluster energy also had to be well contained in the central calorimeter. Accordingly, clusters were restricted to a sample with η centroids in the range $0.1 < |\eta| < 0.7$. Finally, each cluster E_t had to satisfy the appropriate transverse energy threshold of the trigger. A total of 16,300 clusters satisfied these criteria.

Observed cluster energies were corrected for nonlinear calorimeter response and for energy deposited in uninstrumented regions. These corrections were obtained from a Monte Carlo study [7] with full detector simulation, which reproduces the central calorimeter response to test beam electrons and pions, and to isolated low energy charged particles observed in $\bar{p}p$ interactions. For particle energies below 10 GeV, the response is nonlinear (up to 40%). This will, on average, reduce the observed energy of 50 GeV jets by 15% since a substantial fraction of jet energy is carried by low energy particles. The Monte Carlo was tuned to reproduce the observed spectrum of charged particles in jets. In addition, 2 GeV was added to each cluster to account for energy lost outside of the clustering circle, and 1 GeV was subtracted to account for the isotropic component of the $\bar{p}p$ interaction (underlying event). The above two corrections were determined from the amount of energy observed at large angular separations from the nearest cluster. The ratio of uncorrected to corrected jet E_t's ranges from 0.86 ± 0.05 for 250 GeV clusters to 0.65 ± 0.13 for 20 GeV clusters [8]. The error on the jet energy correction is systematic and includes uncertainties in both the low energy response and the jet fragmentation function.

From the number of jets and the integrated luminosity, we obtain the differential cross section averaged over the fiducial η interval: $\langle d\sigma/dE_t \rangle_\eta$. This is a convolution of the true cross section with the resolution function for E_t. The energy resolution for jets was determined from the momentum balance of dijet events [9] and has an approximately Gaussian shape with a σ of 9 GeV for 50 GeV jets. The corrected differential cross section was obtained from a deconvolution of the measured cross section and the resolution. The ratio of the uncorrected to the corrected cross section varies from 1.7 for the lowest E_t bin (30 GeV) to 1.1 for the highest (250 GeV). Uncertainties in this procedure give a 25% systematic error at 30 GeV E_t and 5% at 250 GeV.

Table 1 gives the differential cross section. The systematic error for each bin includes contributions from the luminosity uncertainty, the resolution corrections and the energy scale corrections. The systematic error ranges from 70% to 34%, depending on jet E_t. The cross section is plotted as a function of jet E_t in Fig. 1 and is compared to leading order QCD calculations for inclusive jet production. The range of calculations takes into account different choices for the proton structure function [10] and the momentum transfer scale at which the strong coupling constant, α_s, is evaluated. The scale was varied from $q^2 = 4E_t^2$ to $q^2 = E_t^2/4$. The normalization of the QCD predictions is absolute.

To investigate the dependence of the cross section on the collision energy, we compared our measurement with data reported by the UA1 and UA2 experiments [11] at $\sqrt{s} = 0.63$ TeV ($\bar{p}p$) and by the AFS collaboration [12] at $\sqrt{s} = 0.063$ TeV (pp). In Fig. 2 we plot the scaled cross section, $E\frac{d^3\sigma}{dp^3}$ multiplied by E_t^4, versus $x_t \equiv 2E_t/\sqrt{s}$. According to the scaling hypothesis, data at all CMS energies should lie on the same curve, whereas QCD predicts scale breaking effects, resulting in a different curve for each $\sqrt{s}$. Systematic uncertainties reported by the experiments dominate this comparison. To evaluate the significance of the scaling hypothesis, we determined the χ^2 for scaling between our data and the data reported by the other experiments in regions of x_t overlap, with the assumption that the reported uncertainties (both statistical and systematic) are Gaussian distributions. For both UA1 and UA2 data we obtain $\chi^2 = 11$ for 11 d.o.f., and for AFS data, a value of χ^2=17 (2 d.o.f.) is found. The jet cross sections are inconsistent with scaling in the region of overlap with AFS data, but consistent with both scaling and QCD in the region of overlap with UA1-UA2 data.

To search for possible quark substructure we compared our data to the predictions of leading order QCD modified by the addition of a contact interaction with a compositeness scale Λ_c [13]. Addition of this term increases the cross section at high E_t. Data with E_t below 130 GeV were used to normalize the predictions. The data are consistent with an unmodified QCD ($\Lambda_c = \infty$) giving a χ^2 of 9 (7 d.o.f) for $E_t > 130$ GeV, and we obtain a lower limit on Λ_c of 700 GeV at a 95% confidence level. This takes into account Poisson fluctuations in the highest E_t bins, the

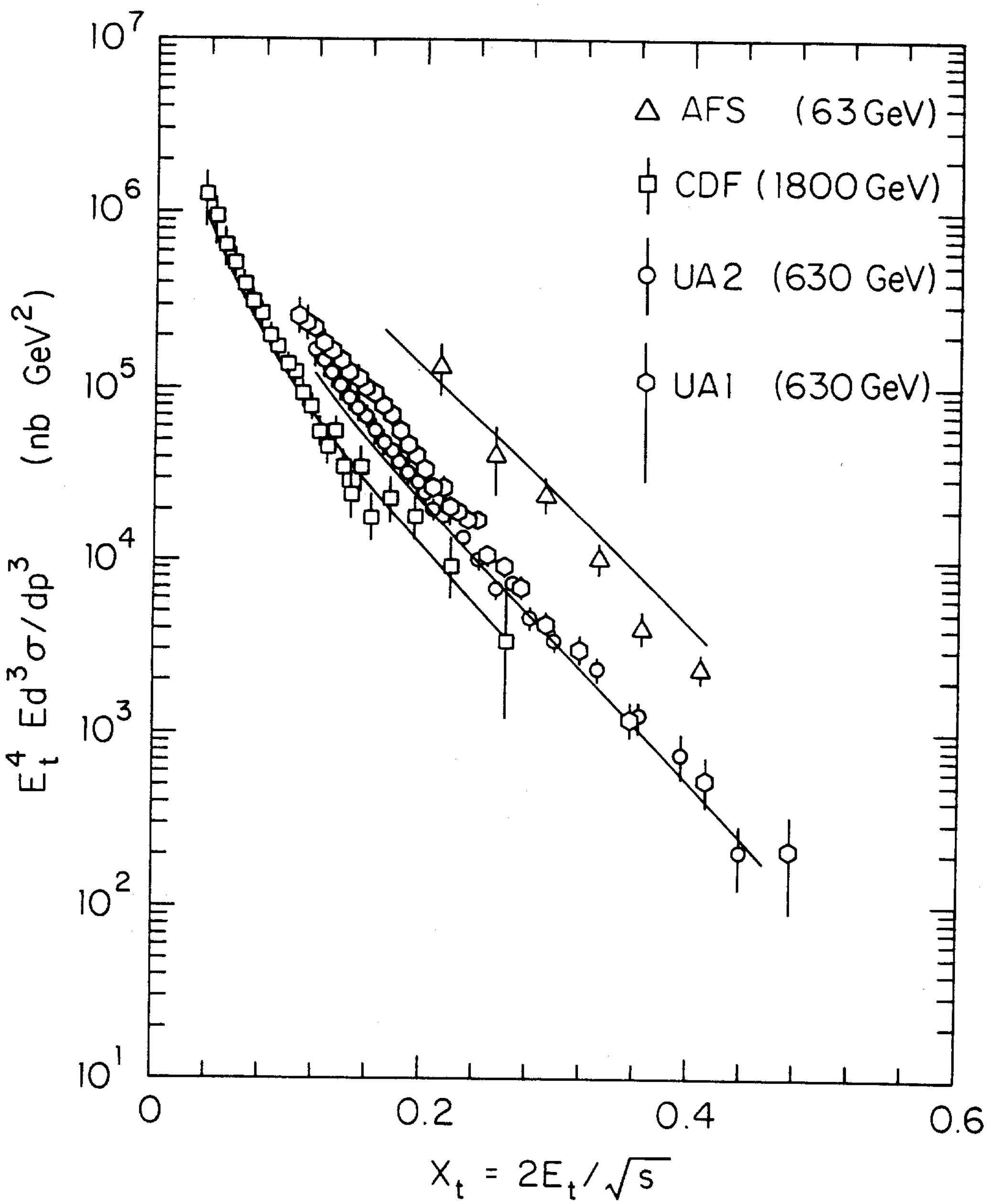

Figure 2: Scaled jet cross section as a function of $x_t \equiv 2E_t/\sqrt{s}$ for CDF, UA1, UA2, and AFS. Also shown are the QCD predictions for the various CMS energies, using Duke and Owens structure functions, set II [10] with $q^2 = E_t^2/2$. The error bars in the legend indicate the normalization uncertainties.

E_t (GeV)	$\langle \frac{d\sigma}{dE_t} \rangle_\eta$ (nb/GeV)	Stat. Error (nb/GeV)	Sys. Error (nb/GeV)
32.7	229.3	7.2	160.0
39.1	99.5	4.9	65.0
45.4	44.2	0.6	26.0
51.5	23.6	0.4	13.0
57.8	12.8	0.3	6.7
63.8	7.6	0.2	3.9
69.7	5.0	0.2	2.5
75.5	3.0	0.1	1.5
81.4	2.01	0.10	0.92
86.9	1.33	0.08	0.60
92.0	1.00	0.07	0.41
97.6	0.63	0.06	0.28
103.2	0.45	0.05	0.20
108.8	0.28	0.04	0.14
114.3	0.20	0.03	0.11
119.9	0.207	0.032	0.073
125.4	0.112	0.024	0.055
130.7	0.070	$^{+0.025}_{-0.019}$	0.042
136.6	0.086	$^{+0.027}_{-0.022}$	0.031
144.2	0.038	$^{+0.013}_{-0.010}$	0.022
156.3	0.038	$^{+0.013}_{-0.010}$	0.013
172.5	0.0221	$^{+0.0069}_{-0.0055}$	0.0066
198.3	0.0075	$^{+0.0036}_{-0.0026}$	0.0026
235.5	0.0016	$^{+0.0021}_{-0.0011}$	0.0008

Table 1: The inclusive jet cross section. The systematic error quoted includes all known systematic uncertainties, including the effect of uncertainties in the energy scale.

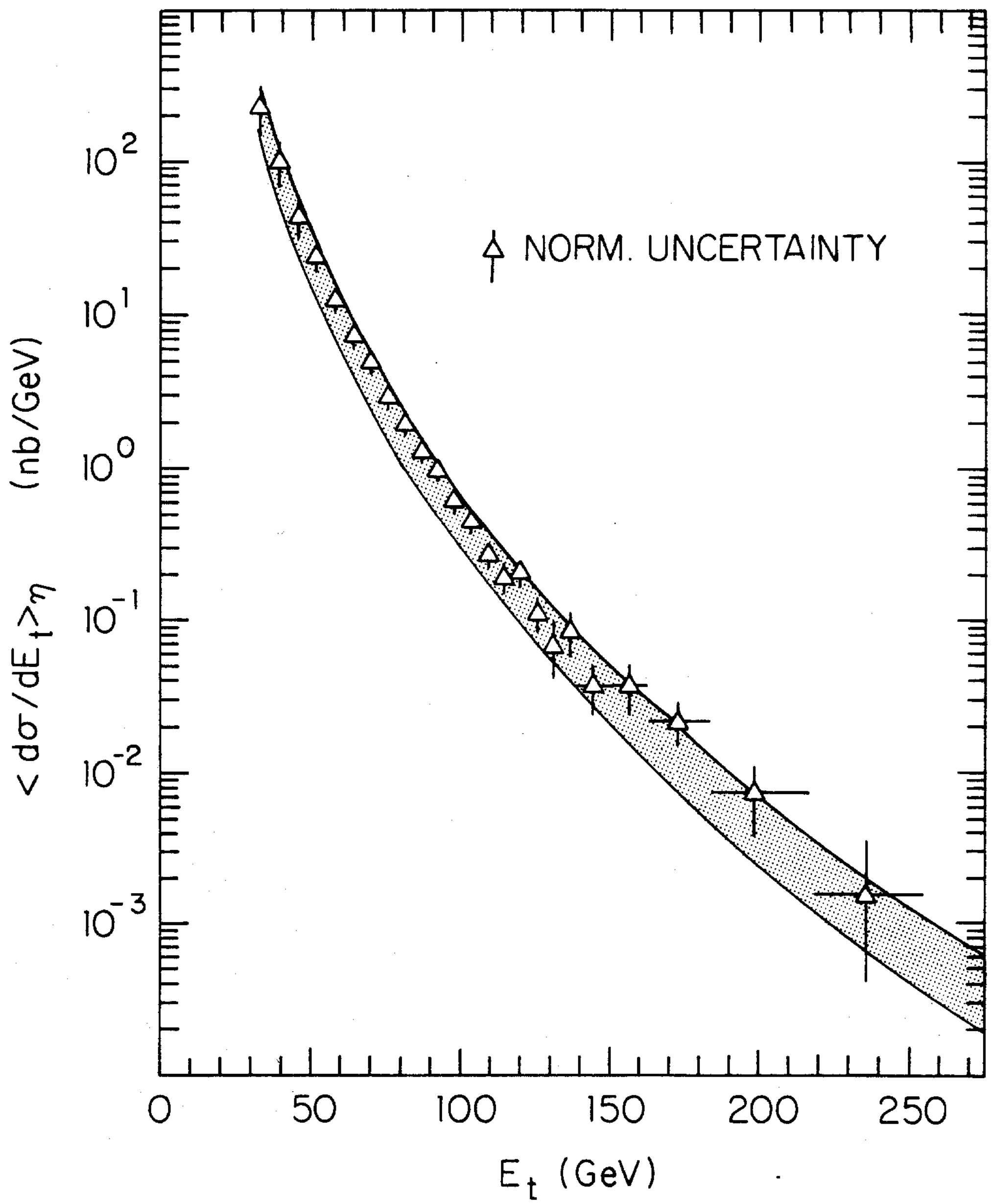

Figure 1: The inclusive jet cross section at $\sqrt{s} = 1.8\ TeV$ compared to a range of QCD predictions (shaded), described in the text. The error bars include the statistical error and the E_t dependent part of the systematic error. A normalization uncertainty (E_t independent part) of 34%, common to all points, is also indicated.

absence of jets with $E_t > 255$ GeV, and uncertainties in both structure functions and process scale.

In summary, we have measured the inclusive jet cross section in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. Leading order QCD calculations satisfactorily describe the differential cross section in the central rapidity region. In comparison to data taken at $\sqrt{s} = 0.063$ TeV in a common region of x_t, we find the data inconsistent with scaling but consistent with leading order QCD. A lower limit on the energy scale associated with quark compositeness, Λ_c, is set at 700 GeV (95% CL).

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6. Events were accepted if they satisfied two of the following three requirements, that: a) the ratio of EM to total cluster energy be greater than 10% and less than 95%; b) the ratio of the scalar sum of charged momenta to the cluster energy be greater than 10%; c) the event missing transverse energy be within 6 standard deviations from zero.

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