Inclusive Jet Cross Section in $\overline{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[23] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]
S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] P. Auchincloss,[26] F. Azfar,[22]
P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26]
A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] E. Barzi,[8] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[23]
S. Behrends,[3] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22]
A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1]
C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[7] D. Bortoletto,[25] J. Boudreau,[24] L. Breccia,[2] C. Bromberg,[18]
N. Bruner,[19] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7] K. L. Byrum,[1]
J. Cammerata,[13] C. Campagnari,[7] M. Campbell,[17] A. Caner,[7] W. Carithers,[15] D. Carlsmith,[34] A. Castro,[21] D. Cauz,[23]
Y. Cen,[26] F. Cervelli,[23] H. Y. Chao,[29] J. Chapman,[17] M.-T. Cheng,[29] G. Chiarelli,[23] T. Chikamatsu,[32] C. N. Chiou,[29]
L. Christofek,[11] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[28] J. Cooper,[7] M. Cordelli,[8]
C. Couyoumtzelis,[23] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] J. D. Cunningham,[3] T. Daniels,[16] F. DeJongh,[7]
S. Delchamps,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[27] B. Denby,[23] M. Deninno,[2] P. F. Derwent,[17]
T. Devlin,[28] M. Dickson,[26] J. R. Dittmann,[6] S. Donati,[23] J. Done,[30] T. Dorigo,[21] A. Dunn,[17] N. Eddy,[17]
K. Einsweiler,[15] J. E. Elias,[7] R. Ely,[15] E. Engels, Jr.,[24] D. Errede,[11] S. Errede,[11] Q. Fan,[26] I. Fiori,[2] B. Flaugher,[7]
G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[31] J. Freeman,[7] J. Friedman,[16] H. Frish,[5] T. A. Fuess,[1] Y. Fukui,[14]
S. Funaki,[32] G. Gagliardi,[23] S. Galeotti,[23] M. Gallinaro,[21] M. Garcia-Sciveres,[15] A. F. Garfinkel,[25] C. Gay,[9] S. Geer,[7]
D. W. Gerdes,[17] P. Giannetti,[23] N. Giokaris,[27] P. Giromini,[8] L. Gladney,[22] D. Glenzinski,[13] M. Gold,[19] J. Gonzalez,[22]
A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[27] H. Grassmann,[23] L. Groer,[28] C. Grosso-Pilcher,[5] G. Guillian,[17]
R. S. Guo,[29] C. Haber,[15] E. Hafen,[16] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[34] R. M. Hans,[35] K. Hara,[32]
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K. Karr,[33] H. Kasha,[35] Y. Kato,[20] T. A. Keaffaber,[25] L. Keeble,[8] K. Kelley,[16] R. D. Kennedy,[28] R. Kephart,[7]
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The inclusive jet differential cross section has been measured for jet transverse energies, E_T, from 15 to 440 GeV, in the pseudorapidity region $0.1 \leq |\eta| \leq 0.7$. The results are based on 19.5 pb^{-1} of data collected by the CDF Collaboration at the Fermilab Tevatron collider. The data are compared with QCD predictions for various sets of parton distribution functions. The cross section for jets with $E_T >$ 200 GeV is significantly higher than current predictions based on $O(\alpha_s^3)$ perturbative QCD calculations. Various possible explanations for the high-E_T excess are discussed. [S0031-9007(96)00658-8]

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We present a measurement of the inclusive differential cross section for jet production in $p\overline{p}$ collisions at 1.8 TeV with precision significantly better than previous experiments and current theoretical predictions. Our measurement is compared to next-to-leading order (NLO) perturbative QCD predictions [1] for jet transverse energies E_T from 15 to 440 GeV in the central pseudorapidity region $0.1 \leq |\eta| \leq 0.7$, corresponding at highest E_T to a distance scale of $O(10^{-17})$ cm. The predictions depend on details of the parton distribution functions (PDFs) and on the strong coupling constant α_S. Our measurement provides precise information about both [2,3]. Apart from these theoretical uncertainties, deviations of the predicted cross section from experiment could arise from physics beyond the standard model. In particular, the presence of quark substructure would enhance the cross section at high E_T. Previous measurements of inclusive jet production were performed with smaller data sets by CDF [4,5] and at lower energy by UA2 [6] and CDF [7].

The measurement described here is based on a data sample of 19.5 pb^{-1} collected in 1992–93 with the CDF detector [8] at the Fermilab Tevatron collider. The data were collected using several triggers with jet E_T thresholds of 100, 70, 50, and 20 GeV. The 70, 50, and 20 GeV triggers were prescaled by 6, 20, and 500, respectively. Cosmic rays and accelerator loss backgrounds were removed with cuts on event energy timing and on missing E_T significance ($\not{E}_T/\sqrt{\sum E_T}$) as described in Ref. [5]. The remaining backgrounds are conservatively estimated to be <0.5% in any E_T bin.

Jets were reconstructed using a cone algorithm [9] with radius $R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2} = 0.7$. Here $\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the beam line and ϕ is the azimuthal angle around the beam. The QCD calculation used a similar algorithm [1]. 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 is modeled by the NLO QCD calculations.

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 [7]. A Monte Carlo simulation, based on the ISAJET [10] program and Feynman-Field [11] jet fragmentation tuned to the CDF data, is used to determine detector response functions. A trial true (unsmeared) 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. We parametrize the unsmeared inclusive jet spectrum with the functional form

$$\frac{d\sigma(E_T^{\text{true}})}{dE_T^{\text{true}}} = P_0(1 - x_T)^{P_6} \times 10^{F(E_T^{\text{true}})}, \qquad (1)$$

where $F(x) = \sum_{i=1}^{5} P_i[\ln(x)]^i$ with E_T^{true} in GeV, $P_0, \ldots, P_6$ are fitted parameters, and x_T is defined as $2E_T^{\text{true}}/\sqrt{s}$. The resulting fit of the smeared true spectrum to our data yields $N_{\text{d.f.}} \equiv \chi^2/N_{\text{d.f.}} = 29.9/34$. The best-fit set of parameters for Eq. (1), i.e., the "standard curve," are listed in Table I. Corrections to the measured E_T and rate for each bin of the raw spectrum are derived from the mapping of the standard curve to the smeared curve. The corrected cross sections and statistical uncertainties are in Fig. 1 and in Table II.

To evaluate systematic uncertainties, the procedure in Ref. [7] is used. New parameter sets for Eq. (1) are derived for ±1 standard deviation shifts in the unsmearing function for each source of systematic uncertainty. The parameters for the seven largest systematic uncertainties are in Table II. They account for the following uncertainties: (a) charged hadron response at high P_T, (b) the calorimeter response to low-P_T hadrons, (c) ±1% on the jet energy for the stability of the calibration of the calorimeter, (d) jet fragmentation functions used in the simulation, (e) ±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 ±3.8%, was derived from the uncertainty in the luminosity measurement [12] (±3.5%) and the efficiency of the acceptance cuts (±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 [13] to model jet fragmentation, were performed and the resulting variations were found to be small. Figures 2(a)–2(h) show the percentage change from the standard curve as a function of E_T for each uncertainty.

In Fig. 1 the corrected cross section is compared with the NLO QCD prediction [1] using MRSD0′ PDFs [14], 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 6 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 [4], which also shows an excess over NLO QCD for the $E_T > 280$ GeV region. A similar excess is observed when we compare CDF data with HERWIG Monte Carlo predictions.

The distributions of the physical variables in the 1192 events above 200 GeV were examined carefully. Data distributions sensitive to the mismeasurement of jet E_T, such as unbalanced jet E_T in dijet events, show good agreement with detector simulation. To look for time and luminosity dependent variations (instantaneous luminosity increased with time), the data were divided into seven time-ordered parts and analyzed independently. No significant time dependence was observed. Finally, these events were individually scanned and no anomalies were discovered.

No single experimental source of systematic uncertainty can account for the high-E_T excess. For example, in order to reconcile the measured CDF spectrum with NLO QCD (MRSD0′, $\mu = E_T/2$) predictions, we would have to change the jet E_T scale by an amount ranging from 0.2% at 175 GeV to 5% at 415 GeV, while keeping the change less than 0.1% between 50 and 160 GeV. No known feature of the detector, its calibration, or the data analysis permits such a change. The effects of all possible

TABLE I. Parameters of the curves corresponding to ±1 standard deviation changes in the systematic uncertainties.

	P_0 (nb/GeV)	P_1	P_2	P_3	P_4	P_5	P_6
Standard	3.090×10^8	−4.128	1.084	−0.845	0.136	0.00279	6.733
High P_T pion (+)	3.000×10^8	−4.110	1.083	−0.847	0.135	0.00213	6.500
High P_T pion (−)	3.118×10^8	−4.132	1.084	−0.844	0.137	0.00299	6.758
Low P_T pion (+)	3.135×10^8	−4.163	1.082	−0.843	0.138	0.00342	7.209
Low P_T pion (−)	3.060×10^8	−4.096	1.085	−0.847	0.135	0.00216	6.272
1.0% E scale (+)	3.066×10^8	−4.140	1.084	−0.844	0.137	0.00294	7.082
1.0% E scale (−)	3.174×10^8	−4.122	1.083	−0.846	0.136	0.00270	6.434
Fragmentation (+)	3.152×10^8	−4.161	1.082	−0.843	0.138	0.00335	7.214
Fragmentation (−)	3.044×10^8	−4.095	1.085	−0.847	0.135	0.00220	6.229
Underly. energy (+)	1.730×10^8	−4.004	1.099	−0.846	0.134	0.00122	6.074
Underly. energy (−)	6.630×10^8	−4.314	1.067	−0.840	0.141	0.00503	8.045
Electron/γ (+)	3.106×10^8	−4.138	1.083	−0.844	0.137	0.00287	6.873
Electron/γ (−)	3.102×10^8	−4.123	1.084	−0.845	0.136	0.00271	6.629
Resolution (+)	2.422×10^8	−4.082	1.090	−0.845	0.136	0.00222	6.645
Resolution (−)	4.262×10^8	−4.201	1.076	−0.843	0.138	0.00366	7.123

combinations of the systematic uncertainties are included in the comparison described below.

To analyze the significance of this excess we use four normalization-independent, shape-dependent statistical tests: signed and unsigned Kolmogorov-Smirnov [15], Smirnov-Cramèr-VonMises [15], and Anderson-Darling [16,17]. 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 is 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 PDFs, as is the significance of the excess at high E_T. The best agreement at high E_T is with CTEQ2M [18] which gives 8%, but the low E_T agreement is reduced to 23%.

We have considered various sources of uncertainty in the theory. The NLO QCD predictions have a weak dependence on the renormalization/factorization scale μ. The change in μ scale from $2E_T$ to $E_T/4$ changes the normalization but maintains the shape for $E_T > 70$ GeV [19]. For the NLO QCD calculations the renormalization and factorization scales have been assumed to be equal. Varying these scales independently also has little effect on the shape of the theoretical curve [20]. However, soft gluon summation may lead to an increase in the cross section at high E_T [21,22]. In addition, the effect of higher order QCD corrections is not known.

The fractional difference between the MRSD0$'$ NLO QCD predictions and predictions using different choices of published PDFs, with $\mu = E_T/2$, is shown in Fig. 1. The excess of data over theory at high E_T remains for CTEQ2M, CTEQ2ML [18], GRV94 [23], MRSA$'$ [24], and MRSG [25] parton distributions. The variations in QCD predictions represent a survey of currently available distributions. They do not represent uncertainties associated with data used in deriving the PDFs. Inclusion of our data in a global fit with those from other experiments

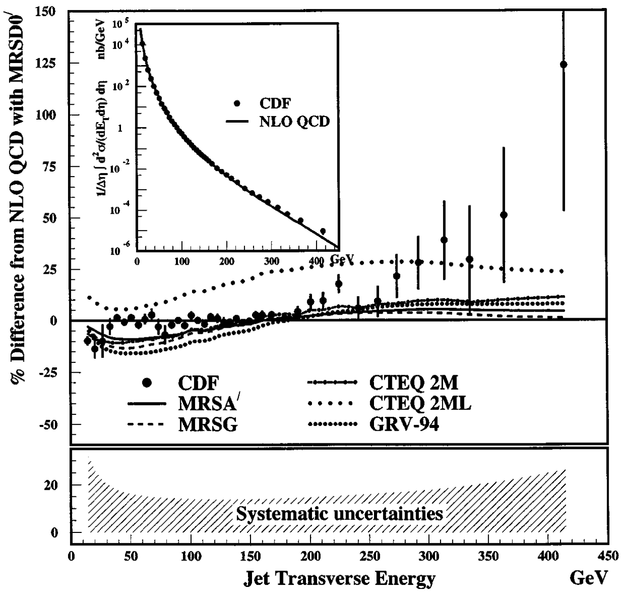

FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0$'$ PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent 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 Fig. 2. NLO QCD predictions using different PDFs are also compared with the one using MRSD0$'$.

TABLE II. The mean corrected jet E_T, cross section, and statistical uncertainty.

$\langle E_T \rangle$ (GeV)	Cross section (nb/GeV)	$\langle E_T \rangle$ (GeV)	Cross section (nb/GeV)
14.5	$(1.14 \pm 0.03) \times 10^{4}$	133.8	$(8.50 \pm 0.12) \times 10^{-2}$
20.3	$(2.31 \pm 0.12) \times 10^{3}$	139.2	$(6.62 \pm 0.10) \times 10^{-2}$
26.9	$(6.30 \pm 0.56) \times 10^{2}$	144.5	$(5.00 \pm 0.08) \times 10^{-2}$
33.3	$(2.36 \pm 0.09) \times 10^{2}$	149.9	$(3.92 \pm 0.07) \times 10^{-2}$
39.5	$(1.02 \pm 0.01) \times 10^{2}$	155.3	$(3.13 \pm 0.06) \times 10^{-2}$
45.5	$(4.89 \pm 0.06) \times 10^{1}$	160.7	$(2.46 \pm 0.05) \times 10^{-2}$
51.3	$(2.61 \pm 0.04) \times 10^{1}$	168.4	$(1.75 \pm 0.03) \times 10^{-2}$
57.0	$(1.42 \pm 0.03) \times 10^{1}$	179.2	$(1.10 \pm 0.02) \times 10^{-2}$
62.7	$(8.62 \pm 0.21) \times 10^{0}$	189.0	$(7.34 \pm 0.20) \times 10^{-3}$
68.3	$(5.43 \pm 0.16) \times 10^{0}$	200.7	$(5.11 \pm 0.17) \times 10^{-3}$
73.9	$(3.24 \pm 0.13) \times 10^{0}$	211.5	$(3.41 \pm 0.13) \times 10^{-3}$
79.4	$(2.05 \pm 0.10) \times 10^{0}$	224.6	$(2.25 \pm 0.09) \times 10^{-3}$
85.0	$(1.44 \pm 0.02) \times 10^{0}$	240.9	$(1.14 \pm 0.06) \times 10^{-3}$
90.5	$(1.02 \pm 0.02) \times 10^{0}$	257.2	$(6.67 \pm 0.47) \times 10^{-4}$
95.9	$(6.94 \pm 0.13) \times 10^{-1}$	273.5	$(4.31 \pm 0.38) \times 10^{-4}$
101.4	$(5.18 \pm 0.11) \times 10^{-1}$	292.0	$(2.50 \pm 0.25) \times 10^{-4}$
106.8	$(3.64 \pm 0.05) \times 10^{-1}$	313.7	$(1.35 \pm 0.19) \times 10^{-4}$
112.2	$(2.64 \pm 0.04) \times 10^{-1}$	335.3	$(6.37 \pm 1.30) \times 10^{-5}$
117.6	$(2.00 \pm 0.04) \times 10^{-1}$	364.0	$(3.03 \pm 0.66) \times 10^{-5}$
123.0	$(1.48 \pm 0.03) \times 10^{-1}$	414.9	$(9.05 \pm 2.86) \times 10^{-6}$
128.4	$(1.10 \pm 0.03) \times 10^{-1}$		

may yield a consistent set of PDFs that accommodate the high-E_T excess within the scope of QCD [3,26].

The presence of quark substructure could appear as an enhancement of the cross section at high E_T. This effect is conventionally parametrized in terms of a contact term of unit strength between left-handed quarks, characterized by the constant Λ_C with units of energy [27]. While NLO standard model QCD predictions have been available for many years, no calculation for compositeness at next-to leading order $[O(\alpha_s^3)]$ is available. Therefore, we have compared our data to a LO QCD calculation including compositeness (using MRSD0′) and have taken the approach of Ref. [4]. We normalize the predicted cross section to the data over the E_T range 95–145 GeV, where the effect of the contact term with $\Lambda_C > 1.0$ TeV is small and perform a χ^2 test on the data above 160 GeV. We find a broad minimum in the χ^2 for $1.5 < \Lambda_C < 1.8$ TeV. The best agreement with our data is for $\Lambda_C = 1.6$ TeV where the χ^2 is 9.8 for 14 degrees of freedom. This hypothetical contact interaction is also expected to lead to dijet production with a more central angular distribution, and this analysis is underway. However, until a realistic method for representing the theoretical uncertainties from higher order QCD corrections and from the PDFs is found, any claim about the presence or absence of new physics is indefensible.

In summary, we have measured the inclusive jet cross section in the E_T range 15–440 GeV and find it to be in good agreement with NLO QCD predictions for $E_T < 200$ GeV using MRSD0′ PDFs. Above 200 GeV, the jet cross section is significantly higher than the NLO predictions. The data over the full E_T range are very precise. They provide powerful constraints on QCD and demand a reevaluation of theoretical predictions and uncertainties within and beyond the standard model.

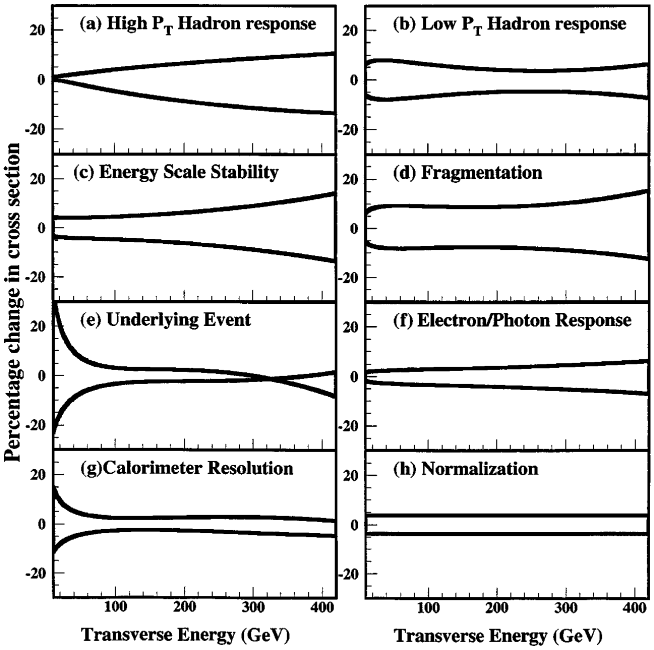

FIG. 2. The percentage change in the inclusive jet cross section when various sources of systematic uncertainty are changed by ±1 standard deviation from their nominal values.

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