The Inclusive Jet Cross Section in $p\bar{p}$ Collisions at $\sqrt{s}=1.8$ TeV using the kT Algorithm


To cite this version:

V. Zutshi, E.G. Zverev, and A. Zylbersteyn (DO Collaboration)

1 Universidad de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4 Institute of High Energy Physics, Beijing, People’s Republic of China
5 Universidad de los Andes, Bogotá, Colombia
6 Charles University, Center for Particle Physics, Prague, Czech Republic
7 Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic
8 Universidad San Francisco de Quito, Quito, Ecuador
9 Institut des Sciences Nucléaires, IN2P3-CNRS, Université de Grenoble 1, Grenoble, France
10 CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
11 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS, Orsay, France
12 LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
13 DAPNIA/Service de Physique des Particules, CEA, Saclay, France
14 Universität Mainz, Institut für Physik, Mainz, Germany
15 Panjab University, Chandigarh, India
16 Delhi University, Delhi, India
17 Tata Institute of Fundamental Research, Mumbai, India
18 Seoul National University, Seoul, Korea
19 CINVESTAV, Mexico City, Mexico
20 FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
21 University of Nijmegen/NIKHEF, Nijmegen, The Netherlands
22 Institute of Nuclear Physics, Kraków, Poland
23 Joint Institute for Nuclear Research, Dubna, Russia
24 Institute for Theoretical and Experimental Physics, Moscow, Russia
25 Moscow State University, Moscow, Russia
26 Institute for High Energy Physics, Protvino, Russia
27 Lancaster University, Lancaster, United Kingdom
28 Imperial College, London, United Kingdom
29 University of Arizona, Tucson, Arizona 85721
30 Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
31 University of California, Davis, California 95616
32 California State University, Fresno, California 93740
33 University of California, Irvine, California 92697
34 University of California, Riverside, California 92521
35 Florida State University, Tallahassee, Florida 32306
36 Fermi National Accelerator Laboratory, Batavia, Illinois 60510
37 University of Illinois at Chicago, Chicago, Illinois 60607
38 Northern Illinois University, DeKalb, Illinois 60115
39 Northwestern University, Evanston, Illinois 60208
40 Indiana University, Bloomington, Indiana 47405
41 University of Notre Dame, Notre Dame, Indiana 46556
42 Iowa State University, Ames, Iowa 50011
43 University of Kansas, Lawrence, Kansas 66045
44 Kansas State University, Manhattan, Kansas 66506
45 Louisiana Tech University, Ruston, Louisiana 71272
46 University of Maryland, College Park, Maryland 20742
47 Boston University, Boston, Massachusetts 02215
48 Northeastern University, Boston, Massachusetts 02115
49 University of Michigan, Ann Arbor, Michigan 48109
50 Michigan State University, East Lansing, Michigan 48824
51 University of Nebraska, Lincoln, Nebraska 68588
52 Columbia University, New York, New York 10027
53 University of Rochester, Rochester, New York 14627
54 State University of New York, Stony Brook, New York 11794
55 Brookhaven National Laboratory, Upton, New York 11973
56 Langston University, Langston, Oklahoma 73050
57 University of Oklahoma, Norman, Oklahoma 73019
The central inclusive jet cross section has been measured using a successive-combination algorithm for reconstruction of jets. The measurement uses 87.3 pb⁻¹ of data collected with the DO detector at the Fermilab Tevatron pp Collider during 1994-1995. The cross section, reported as a function of transverse momentum ($p_T > 60$ GeV) in the central region of pseudorapidity ($|\eta| < 0.5$), exhibits reasonable agreement with next-to-leading order QCD predictions, except at low $p_T$ where the agreement is marginal.
Jet production in hadronic collisions is understood within the framework of Quantum Chromodynamics (QCD) as a hard scattering of constituent partons (quarks and gluons), that, having undergone the interaction, manifest themselves as showers of collimated particles called jets. Jet finding algorithms associate clusters of these particles into jets so that the kinematic properties of the hard-scattered partons can be inferred and thereby compared to predictions from perturbative QCD (pQCD).

Historically, only cone algorithms have been used to reconstruct jets at hadron colliders [1]. Although well-suited to the understanding of the experimental systems present in the complex environment of hadron colliders, the cone algorithms used in previous measurements by the Fermilab Tevatron experiments [2] present several difficulties: an arbitrary procedure must be implemented to split and merge overlapping calorimeter cones, a set of ad-hoc parameters, $R_{\text{sep}}$ [4], is required to accommodate the differences between jet definitions at the parton and detector levels, and improved theoretical predictions calculated at the next-to-next-to-leading-order (NNLO) in pQCD are not infrared safe, but exhibit sensitivity to soft radiation [5].

A second class of jet algorithms, which does not suffer from these shortcomings, has been developed by several groups [5-8]. These recombination algorithms successively merge pairs of nearby objects (partons, particles, or calorimeter towers) in order of increasing relative transverse momentum. A single parameter, $D$, which approximately characterizes the size of the resulting jets, determines when merging stops. No splitting or merging is involved because each object is uniquely assigned to a jet. There is no need to introduce any ad-hoc parameters, because the same algorithm is applied at the theoretical and experimental level. Furthermore, by design, clustering algorithms are infrared and collinear safe to all orders of calculation. In this Letter, we present the first measurement of the inclusive jet cross section using the $k_{\perp}$ algorithm [3] to reconstruct jets at the $\sqrt{s} = 1.8$ TeV Tevatron proton-antiproton collider.

The differential jet cross section was measured in bins of $p_T$ and pseudorapidity, $\eta \equiv -\ln[\tan(\theta/2)]$, where $\theta$ is the polar angle relative to the $z$ axis pointing in the proton beam direction. The $k_{\perp}$ algorithm implemented at DO [8] is based on the clustering algorithm suggested in Ref. [2]. The algorithm starts with a list of objects. For each object with transverse momentum $p_{T,i}$, we define $d_{ii} = p_{T,i}^2$, and for each pair of objects, $d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) (\Delta R_{ij})^2/D^2$, where $D$ is the free parameter of the algorithm and $(\Delta R_{ij})^2 = (\Delta \phi_{ij})^2 + (\Delta \eta_{ij})^2$ is the square of their angular separation. If the minimum of all $d_{ii}$ and $d_{ij}$ is $d_{ij}$, then the objects $i$ and $j$ are combined, becoming the merged four-vector $(E_i + E_j, \vec{p}_i + \vec{p}_j)$. If the minimum is a $d_{ii}$, the object $i$ is defined as a jet and removed from subsequent iterations. This procedure is repeated until all objects are combined into jets. Thus $k_{\perp}$ jets do not have to include all objects in a cone of radius $D$, and they may include objects outside of this cone.

The primary tool for jet detection at DO is the liquid-argon/uranium calorimeter [10], which has nearly full solid-angle coverage for $|\eta| < 4.1$. The first stage (hardware) trigger selected inelastic collisions as defined by signal coincidence in the hodoscopes located near the beam axis on both sides of the interaction region. The next stage required energy deposition in any $\Delta \eta \times \Delta \phi = 0.8 \times 1.6$ region of the calorimeter corresponding to a transverse energy ($E_T$) above a preset threshold. Selected events were digitized and sent to an array of processors. At this stage jet candidates were reconstructed with a cone algorithm (with radius $R = (|\Delta \eta|^2 + (\Delta \phi)^2)^{1/2} = 0.7$), and the event was recorded if any jet $E_T$ exceeded a specified threshold. Jet $E_T$ thresholds of 30, 50, 85, and 115 GeV accumulated integrated luminosities of 0.34, 4.46, 51.5, and 87.3 pb$^{-1}$, respectively [11].

Jets were reconstructed offline using the $k_{\perp}$ algorithm, with $D = 1.0$. This value of $D$ was chosen because, at next-to-leading-order (NLO), it produces a theoretical cross section that is essentially identical to the cone prediction for $R = 0.7$ [8], which DO used in its previous publications on jet production [1]. The vertices of the events were reconstructed using the central tracking system [10]. A significant portion of the data was taken at high instantaneous luminosity, where more than one interaction per beam crossing was probable. When an event had more than one reconstructed vertex, the quantity $S_T = \sum |p_T^v|^{1/2}$ was defined for the two vertices that had the largest numbers of associated tracks, and the vertex with the smallest $S_T$ was used for calculating all kinematic variables [11]. To preserve the pseudo-projective nature of the DO calorimeter, the vertex $z$-position was required to be within 50 cm of the center of the detector. This requirement rejected $(10.6 \pm 0.1)%$ of the events, independent of jet transverse momentum.

Isolated noisy calorimeter cells were suppressed with online and offline algorithms [11]. Background introduced by electrons, photons, detector noise, and accelerator losses that mimicked jets were eliminated with jet quality cuts. The efficiency of the jet selection is approximately 99.5% and nearly independent of jet $p_T$. The imbalance in transverse momentum, “missing transverse energy,” was calculated from the vector sum of the $E_{x,y}$ values in all cells of the calorimeter. Background from cosmic rays or incorrectly vertexed events was eliminated by requiring the missing transverse energy in each event to be less than 70% of the $p_T$ of the leading jet. This criterion caused essentially no loss in efficiency.

The DO jet momentum calibration [2], applied on a jet-by-jet basis, corrects on average the reconstructed calorimeter jet $p_T$ to that of the final-state particles in the
The measured cross section is distorted in $p_T$ by the momentum resolution of the DO calorimeter. The fractional momentum resolution was determined from the imbalance in $p_T$ in two-jet events. Although the resolution in jet $p_T$ is essentially Gaussian, the steepness of the $p_T$ spectrum shifts the observed cross section to larger values. At 100 (400) GeV, the fractional resolution is $0.061\pm0.006$ ($0.039\pm0.003$). The distortion in the cross section due to the resolution was corrected by assuming an ansatz function, $A p_T^B (1 - 2 p_T/\sqrt{s})^C$, smearing it with the measured resolution, and fitting the parameters $A$, $B$, and $C$ so as to best describe the observed cross section. The bin-to-bin ratio of the original ansatz to the smeared one was used to remove the distortion due to resolution. The unsmeared correction reduces the observed cross section by $(5.7\pm1)\%$ ($(6.1\pm1)\%$) at 100 (400) GeV.

The final, fully corrected cross section for $|\eta| < 0.5$ is shown in Fig. 1 along with the statistical uncertainties. Listed in Table I are the $p_T$ range, the best $p_T$ bin centroid, the cross section, and uncertainties in each bin. The systematic uncertainties include contributions from jet and event selection, unsmeared, luminosity, and the uncertainty in the momentum scale, which dominates at all transverse momenta. The fractional uncertainties for the different components are plotted in Fig. 1 as a function of the jet transverse momentum.

The results are compared to the pQCD NLO prediction from JETRAD, with the renormalization and factorization scales set to $p_T^{max}/2$, where $p_T^{max}$ refers to the $p_T$ of the leading jet in an event. The comparisons are made using parametrizations of the parton distribution functions (PDFs) of the CTEQ and MRST families. Figure 2 shows the ratios of (data-theory)/theory. The predictions lie below the data by about 50% at the lowest $p_T$ and by $(10-20)\%$ for $p_T > 200$ GeV. To quantify the comparison in Fig. 2, the fractional systematic uncertainties are multiplied by the predicted cross section, and a $\chi^2$ comparison, using the full correlation matrix, is carried out. The results are shown in Table II. Though the agreement is reasonable ($\chi^2$/dof ranges from 1.56 to 1.12, the probabilities from 4 to 31\%), the differences in normalization and shape, especially at low $p_T$, are quite

### Table I. Inclusive jet cross section of jets reconstructed using the $k_L$ algorithm in the central pseudorapidity region ($|\eta| < 0.5$).

<table>
<thead>
<tr>
<th>$p_T$ Bin (GeV)</th>
<th>Plotted $p_T$ (GeV)</th>
<th>Cross Sec. ± Stat. (nb/GeV)</th>
<th>Systematic Uncer. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 − 70</td>
<td>64.6</td>
<td>$(8.94\pm0.06) \times 10^3$</td>
<td>−13, +14</td>
</tr>
<tr>
<td>70 − 80</td>
<td>74.6</td>
<td>$(3.78\pm0.04) \times 10^3$</td>
<td>−13, +14</td>
</tr>
<tr>
<td>80 − 90</td>
<td>84.7</td>
<td>$(1.77\pm0.02) \times 10^3$</td>
<td>−13, +14</td>
</tr>
<tr>
<td>90 − 100</td>
<td>94.7</td>
<td>$(8.86\pm0.25) \times 10^2$</td>
<td>−13, +14</td>
</tr>
<tr>
<td>100 − 110</td>
<td>104.7</td>
<td>$(4.68\pm0.04) \times 10^1$</td>
<td>−14, +14</td>
</tr>
<tr>
<td>110 − 120</td>
<td>114.7</td>
<td>$(2.68\pm0.03) \times 10^1$</td>
<td>−14, +14</td>
</tr>
<tr>
<td>120 − 130</td>
<td>124.8</td>
<td>$(1.53\pm0.02) \times 10^1$</td>
<td>−14, +14</td>
</tr>
<tr>
<td>130 − 140</td>
<td>134.8</td>
<td>$(9.19\pm0.16) \times 10^1$</td>
<td>−14, +14</td>
</tr>
<tr>
<td>140 − 150</td>
<td>144.8</td>
<td>$(5.77\pm0.12) \times 10^2$</td>
<td>−14, +14</td>
</tr>
<tr>
<td>150 − 160</td>
<td>154.8</td>
<td>$(3.57\pm0.03) \times 10^2$</td>
<td>−15, +14</td>
</tr>
<tr>
<td>160 − 170</td>
<td>164.8</td>
<td>$(2.39\pm0.02) \times 10^2$</td>
<td>−15, +14</td>
</tr>
<tr>
<td>170 − 180</td>
<td>174.8</td>
<td>$(1.56\pm0.02) \times 10^2$</td>
<td>−15, +14</td>
</tr>
<tr>
<td>180 − 190</td>
<td>184.8</td>
<td>$(1.05\pm0.02) \times 10^2$</td>
<td>−15, +14</td>
</tr>
<tr>
<td>190 − 200</td>
<td>194.8</td>
<td>$(7.14\pm0.13) \times 10^2$</td>
<td>−16, +15</td>
</tr>
<tr>
<td>200 − 210</td>
<td>204.8</td>
<td>$(4.99\pm0.08) \times 10^3$</td>
<td>−16, +15</td>
</tr>
<tr>
<td>210 − 220</td>
<td>214.8</td>
<td>$(3.45\pm0.07) \times 10^3$</td>
<td>−16, +15</td>
</tr>
<tr>
<td>220 − 230</td>
<td>224.8</td>
<td>$(2.43\pm0.06) \times 10^3$</td>
<td>−16, +15</td>
</tr>
<tr>
<td>230 − 250</td>
<td>239.4</td>
<td>$(1.50\pm0.03) \times 10^3$</td>
<td>−17, +16</td>
</tr>
<tr>
<td>250 − 270</td>
<td>259.4</td>
<td>$(7.52\pm0.23) \times 10^4$</td>
<td>−17, +16</td>
</tr>
<tr>
<td>270 − 290</td>
<td>279.5</td>
<td>$(4.47\pm0.17) \times 10^4$</td>
<td>−18, +17</td>
</tr>
<tr>
<td>290 − 320</td>
<td>303.8</td>
<td>$(1.93\pm0.09) \times 10^4$</td>
<td>−18, +18</td>
</tr>
<tr>
<td>320 − 350</td>
<td>333.9</td>
<td>$(7.61\pm0.59) \times 10^5$</td>
<td>−19, +19</td>
</tr>
<tr>
<td>350 − 410</td>
<td>375.8</td>
<td>$(2.36\pm0.23) \times 10^5$</td>
<td>−20, +21</td>
</tr>
<tr>
<td>410 − 560</td>
<td>461.8</td>
<td>$(1.18\pm0.33) \times 10^6$</td>
<td>−23, +27</td>
</tr>
</tbody>
</table>
FIG. 2. Fractional experimental uncertainties on the cross section. The discontinuities in the luminosity uncertainty are related to the use of different triggers [11].

\[
\frac{\chi^2}{\text{dof}} = \frac{\chi^2}{\text{dof}} \\
\text{PDF} & \chi^2 & \chi^2/\text{dof} & \text{Probability} (%) \\
\MRST & 26.8 & 1.12 & 31 \\
\MRSTg & 33.1 & 1.38 & 10 \\
\CTEQ3M & 37.5 & 1.56 & 4 \\
\CTEQ4M & 31.2 & 1.30 & 15 \\
\CTEQ4HJ & 27.2 & 1.33 & 29 \\
\MRST+Hadroniz. & 24.0 & 1.00 & 46 \\
\CTEQ4HJ+Hadroniz. & 24.3 & 1.01 & 44 \\
\]}

TABLE II. \(\chi^2\) comparison (24 degrees of freedom) between JETRAD, with renormalization and factorization scales set to \(p_T^{\text{max}}/2\), and data for various PDFs. The last entries include a hadronization correction obtained from HERWIG (see text).

large. The points at low \(p_T\) have the highest impact on the \(\chi^2\). If the first four data points are not used in the \(\chi^2\) comparison, the probability increases from 29\% to 77\% when using the CTEQ4HJ PDF.

While the NLO predictions for the inclusive cross section for \(k_T\) (\(D = 1.0\)) and cone jets (\(R = 0.7\), \(R_{\text{sep}} = 1.3\) in the same \(|\eta| < 0.5\) interval are within 1\% of each other for the \(p_T\) range of this analysis [1], the measured cross section using \(k_T\) is 37\% (16\%) higher than the previously reported cross section using the cone algorithm [3] at 60 (200) GeV. This difference in the cross sections is consistent with the measured difference in \(p_T\) for cone jets matched in \(\eta - \phi\) space to \(k_T\) jets. \(k_T\) jets were found to encompass 7\% (3\%) more transverse energy at 60 (200) GeV than cone jets [3][1].

The effect of final-state hadronization on reconstructed energy, which might account for the discrepancy between the observed cross section using \(k_T\) and the NLO predictions at low \(p_T\), and also for the difference between the \(k_T\) and cone results, was studied using HERWIG (version 5.9) [6] simulations. Figure 3 shows the ratio of \(p_T\) spectra for particle-level to parton-level jets, for both the \(k_T\) and cone algorithms. Particle cone jets, reconstructed from final state particles (after hadronization), have less \(p_T\) than the parton jets (before hadronization), because of energy loss outside the cone. In contrast, \(k_T\) particle jets are more energetic than their progenitors at the parton level, due to the merging of nearby partons into a single particle jet. Including the hadronization effect derived from HERWIG in the NLO JETRAD prediction improves the \(\chi^2\) probability from 29\% to 44\% (31\% to 46\%) when using the CTEQ4HJ (MRST) PDF. We have also investigated the sensitivity of the measurement to the modeling of the background from spectator partons through the use of minimum bias events, and found that it has a small effect on the cross section: at low \(p_T\), where the sensitivity is the largest, an increase of as much as 50\% in the underlying event correction decreases the cross section by less than 6\%.

In conclusion, we have presented the first measurement in proton-antiproton collisions at \(\sqrt{s} = 1.8\) TeV of the inclusive jet cross section using the \(k_T\) algorithm. Quantitative tests show reasonable agreement between data and NLO pQCD predictions, except at low \(p_T\) where the agreement is marginal. Although NLO pQCD theory predicts similar cross sections for jets reconstructed with cone (\(R = 0.7\)) and \(k_T\) (\(D = 1.0\)) algorithms, we find the measurement for \(k_T\) to lie above the result published for the cone algorithm [2]. This difference is partially explained by incorporating a hadronization contribution of the kind predicted by HERWIG, which also improves the agreement between data and NLO pQCD predictions.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA),
FIG. 4. Ratio of particle-level over parton-level HERWIG $p_T$ spectra for jets, as a function of the parton jet transverse momentum.

Commissariat à L’Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), and the A.P. Sloan Foundation.

* Visitor from University of Zurich, Zurich, Switzerland.
† Visitor from Institute of Nuclear Physics, Krakow, Poland.