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# Measurement of the Inclusive Jet Cross Section Using the $k_T$ Algorithm in $p\bar{p}$ Collisions at $\sqrt{s} =$ 1.96 TeV

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## Measurement of the Inclusive Jet Cross Section Using the $k_T$ Algorithm in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report on a measurement of the inclusive jet production cross section as a function of the jet transverse momentum in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV using data collected with the upgraded Collider Detector at Fermilab in run II, corresponding to an integrated luminosity of  $385 \text{ pb}^{-1}$ . The measurement is carried out for jets with rapidity  $0.1 < |y^{\text{jet}}| < 0.7$  and transverse momentum in the range  $54 < p_T^{\text{jet}} < 700 \text{ GeV}/c$ . Next-to-leading order perturbative QCD predictions are in good agreement with the measured cross section after the necessary nonperturbative parton-to-hadron corrections are included.

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The measurement of inclusive jet production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV constitutes a test of perturbative QCD (pQCD) [1] predictions over more than 8 orders of magnitude in cross section. The increased center-of-mass energy and integrated luminosity in run II at the Tevatron make it possible to measure the cross section for jets with transverse momentum [2]  $p_T^{\text{jet}}$  up to about

$700 \text{ GeV}/c$ , extending the  $p_T^{\text{jet}}$  range by more than  $150 \text{ GeV}/c$  compared with previous results [3]. This Letter presents a new measurement of the inclusive jet production cross section as a function of  $p_T^{\text{jet}}$  for jets with  $p_T^{\text{jet}} > 54 \text{ GeV}/c$  and rapidity [2] in the region  $0.1 < |y^{\text{jet}}| < 0.7$ , where jets are reconstructed with the  $k_T$  algorithm [4,5]. Similar measurements have been carried out

using cone-based jet algorithms in run II [6]. However, the  $k_T$  algorithm has been widely used for precise QCD measurements at both  $e^+e^-$  and  $e^\pm p$  colliders and allows a well defined comparison to the theoretical predictions, without introducing into the calculations additional parameters to emulate the experimental procedure governing the merging or splitting of overlapping cones [5]. The measurements are corrected for detector effects back to the particle (hadron) level [7] and compared to pQCD next-to-leading order (NLO) predictions [8]. Previous measurements using the  $k_T$  algorithm at the Tevatron [9] observed a marginal agreement with NLO pQCD at low  $p_T^{\text{jet}}$ . We find that this discrepancy is removed after nonperturbative corrections are included.

The CDF detector is described in detail elsewhere [10]. The detector has a charged particle tracking system immersed in a 1.4 T magnetic field, aligned coaxially with the beam line. A silicon microstrip detector provides tracking over the radial range 1.35–28 cm and covers the pseudorapidity [2] range  $|\eta| \leq 2$ . A cylindrical 3.1 m long open-cell drift chamber covers the radial range from 44 to 132 cm and provides full tracking coverage for  $|\eta| \leq 1$ . Segmented sampling calorimeters, arranged in a projective tower geometry, surround the tracking system and measure the energy flow of interacting particles in  $|\eta| \leq 3.6$ . The central barrel calorimeter [11,12] covers the region  $|\eta| < 1$ . It consists of electromagnetic and hadronic calorimeters segmented into 480 towers of size 0.1 in  $\eta$  and  $15^\circ$  in  $\phi$ . The measured energy resolution for electrons is  $\frac{\sigma(E)}{E} = (13.5\%/\sqrt{E_T [\text{GeV}]} \oplus 2\%$ . The single-pion energy resolution, as determined from test-beam data, is  $(50\%/\sqrt{E_T [\text{GeV}]} \oplus 3\%$ . A hadronic calorimeter complements the coverage of the central barrel calorimeter in the region  $0.6 < |\eta| < 1.0$  and provides additional forward coverage out to  $|\eta| < 1.3$ . The forward region  $1.1 < |\eta| < 3.6$  is covered by scintillator-plate electromagnetic and hadronic calorimeters. Cherenkov counters in the region  $3.7 < |\eta| < 4.7$  measure the number of inelastic  $p\bar{p}$  collisions to compute the luminosity [13].

Monte Carlo event samples are used to determine the response of the detector and the correction factors to the hadron level. The generated samples are passed through a full CDF detector simulation (based on GEANT3 [14] where the GFLASH [15] package is used to simulate the energy deposition in the calorimeters) and then reconstructed and analyzed using the same analysis chain as for the data. Samples of simulated inclusive jet events have been generated using the PYTHIA 6.203 [16] and HERWIG 6.4 [17] Monte Carlo generators. CTEQ5L [18] parton distribution functions (PDFs) are used for the proton and antiproton. The PYTHIA samples have been created using a special tuned set of parameters, denoted as PYTHIA-TUNE A, that includes enhanced contributions from initial-state gluon radiation and secondary parton interactions between proton/antiproton beam remnants. TUNE A was developed with

dedicated studies of the underlying event using the CDF run I data [19] and describes the measured jet shapes in run II [20].

The  $k_T$  algorithm is used to reconstruct jets from the energy depositions in the calorimeter towers with transverse momentum above 0.1 GeV/ $c$ . First, all towers are considered as protojets. The quantities  $k_{T,i} = p_{T,i}^2$  and  $k_{T(i,j)} = \min(p_{T,i}^2, p_{T,j}^2) \cdot \Delta R_{i,j}^2/D^2$  are computed for each protojet and pair of protojets, respectively, where  $p_{T,i}$  denotes the transverse momentum of the  $i$ th protojet,  $\Delta R_{i,j}$  is the distance ( $y - \phi$  space) between each pair of protojets, and  $D$  is a parameter that approximately controls the size of the jet. All  $k_{T,i}$  and  $k_{T(i,j)}$  values are then collected into a single sorted list. In this combined sorted list, if the smallest quantity is of the type  $k_{T,i}$ , the corresponding protojet is promoted to be a jet and removed from the list. Otherwise, if the smallest quantity is of the type  $k_{T(i,j)}$ , the protojets are combined into a single protojet by summing up their four-vector components. The procedure is iterated over protojets until the list is empty. The jet transverse momentum, rapidity, and azimuthal angle are denoted as  $p_{T,\text{CAL}}^{\text{jet}}$ ,  $y_{\text{CAL}}^{\text{jet}}$ , and  $\phi_{\text{CAL}}^{\text{jet}}$ , respectively. The same jet algorithm is applied to all the final-state particles in the Monte Carlo samples to search for jets at the hadron level. The resulting hadron-level jet variables are denoted as  $p_{T,\text{HAD}}^{\text{jet}}$ ,  $y_{\text{HAD}}^{\text{jet}}$ , and  $\phi_{\text{HAD}}^{\text{jet}}$ .

The measurements presented in this Letter correspond to a total integrated luminosity of  $385 \pm 22 \text{ pb}^{-1}$ . Events are selected on-line using three-level trigger paths [21] with different prescales. In the first-level trigger, a single trigger tower with  $E_T$  above 5 or 10 GeV is required. In the second-level trigger, clusters are formed around the selected trigger towers, and a cluster with  $E_T$  above 15–90 GeV, depending on the trigger path, is required. In the third-level trigger, jets are reconstructed using a cone-based algorithm, and a jet with  $E_T$  above 20–100 GeV is required. Jets are then searched for using the  $k_T$  algorithm, as explained above, with  $D = 0.7$ . For each trigger data sample, the threshold on the minimum  $p_{T,\text{CAL}}^{\text{jet}}$  is chosen in such a way that the trigger selection is fully efficient. The events are required to have at least one jet with rapidity in the region  $0.1 < |y_{\text{CAL}}^{\text{jet}}| < 0.7$  and corrected transverse momentum (see below) above 54 GeV/ $c$ . The events are selected to have at least one reconstructed primary vertex with the  $z$  position within 60 cm around the nominal interaction point. In order to remove beam-related backgrounds and cosmic rays, the events are required to fulfill  $\cancel{E}_T/\sqrt{\Sigma E_T} < F(p_{T,\text{CAL}}^{\text{leading jet}})$ , where  $\cancel{E}_T$  denotes the missing transverse energy [22] and  $\Sigma E_T = \sum_i E_T^i$  is the total transverse energy of the event, as measured using calorimeter towers with  $E_T^i$  above 100 MeV. The threshold function  $F(p_{T,\text{CAL}}^{\text{leading jet}})$  is defined as  $F(p_T^{\text{jet}}) = \min(2 + 0.0125 \times p_T^{\text{jet}}, 7)$ , where  $p_T^{\text{leading jet}}$  is the uncorrected transverse mo-

mentum of the leading jet (highest  $p_T^{\text{jet}}$ ) and the units are GeV. This criterion is designed to preserve more than 95% of the QCD events, as determined from Monte Carlo studies. A visual scan for  $p_{T,\text{CAL}}^{\text{jet}} > 400 \text{ GeV}/c$  showed no remaining backgrounds.

The measured jet transverse momentum includes additional contributions from multiple proton-antiproton interactions per bunch crossing at high instantaneous luminosity. The data were collected at instantaneous luminosities varying between  $0.2 \times 10^{31}$  and  $9.6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ . At the highest instantaneous luminosities, an average of two interactions per bunch crossing are produced. This affects mainly the measured cross section at low  $p_T^{\text{jet}}$ , where the contributions are sizable. In CDF, multiple interactions are identified via the presence of additional primary vertices reconstructed from charged particles. The measured jet transverse momenta are corrected for this effect by removing a certain amount of transverse momentum  $\epsilon$  for each additional primary vertex. A value  $\epsilon = 1.62_{-0.46}^{+0.70} \text{ GeV}/c$  is determined from the data by requiring that, after the correction is applied, the ratio of cross sections at low and high instantaneous luminosities does not show any  $p_T^{\text{jet}}$  dependence.

The reconstruction of the jet variables in the calorimeter is studied using Monte Carlo samples. These studies indicate that the angular variables of a jet are reconstructed with no significant systematic shift and with a resolution better than 0.05 units in  $y$  and  $\phi$  at low  $p_{T,\text{CAL}}^{\text{jet}}$ , improving as  $p_{T,\text{CAL}}^{\text{jet}}$  increases. The measured jet transverse momentum systematically underestimates that of the hadron-level jet, which is attributed mainly to the noncompensating nature of the calorimeter [23]. For jets with  $p_{T,\text{CAL}}^{\text{jet}}$  about 50 GeV/ $c$ , the jet transverse momentum is reconstructed with an average shift of  $-19\%$  and a resolution of 14%. The jet reconstruction improves as  $p_{T,\text{CAL}}^{\text{jet}}$  increases. For jets with  $p_{T,\text{CAL}}^{\text{jet}}$  about 500 GeV/ $c$ , the average shift is  $-5\%$  and the resolution is about 7%. The bisector method [24] is employed to evaluate how well the Monte Carlo calculation reproduces the measured jet energy resolutions. Data and Monte Carlo calculation agree within a relative uncertainty of  $\pm 8\%$  over the whole  $p_{T,\text{CAL}}^{\text{jet}}$  range.

The measured  $p_{T,\text{CAL}}^{\text{jet}}$  distribution is unfolded back to the hadron level using Monte Carlo event samples. PYTHIA-TUNE A provides a reasonable description of the different jet and underlying event quantities and is used to determine the correction factors in the unfolding procedure. In order to avoid any bias on the correction factors due to the particular PDF set used, which translates into slightly different simulated  $p_{T,\text{CAL}}^{\text{jet}}$  distributions, PYTHIA-TUNE A is reweighted until it accurately follows the measured  $p_{T,\text{CAL}}^{\text{jet}}$  spectrum. The unfolding is carried out in two steps. First, an average correction is computed. The correlation

$\langle p_{T,\text{HAD}}^{\text{jet}} - p_{T,\text{CAL}}^{\text{jet}} \rangle$  vs  $\langle p_{T,\text{CAL}}^{\text{jet}} \rangle$  is used to extract correction factors, which are then applied to the measured jets to obtain the corrected transverse momenta  $p_{T,\text{COR}}^{\text{jet}}$ . A raw cross section is defined as  $d^2\sigma/dp_{T,\text{COR}}^{\text{jet}} dy_{\text{CAL}}^{\text{jet}} = \frac{1}{\mathcal{L}} \times (N_{\text{COR}}^{\text{jet}}/\Delta p_{T,\text{COR}}^{\text{jet}} \Delta y_{\text{CAL}}^{\text{jet}})$ , where  $N_{\text{COR}}^{\text{jet}}$  denotes the number of jets in a given  $p_{T,\text{COR}}^{\text{jet}}$  bin,  $\Delta p_{T,\text{COR}}^{\text{jet}}$  is the size of the bin,  $\Delta y_{\text{CAL}}^{\text{jet}}$  denotes the region in  $y_{\text{CAL}}^{\text{jet}}$  considered, and  $\mathcal{L}$  is the luminosity. Second, the measurements are corrected for acceptance and smearing effects using a bin-by-bin unfolding procedure, which also accounts for the efficiency of the selection criteria. The unfolding factors  $U(p_{T,\text{COR}}^{\text{jet}}) = (d^2\sigma/dp_{T,\text{HAD}}^{\text{jet}} dy_{\text{HAD}}^{\text{jet}})/(d^2\sigma/dp_{T,\text{COR}}^{\text{jet}} dy_{\text{CAL}}^{\text{jet}})$  are extracted from Monte Carlo samples and applied to the measured  $p_{T,\text{COR}}^{\text{jet}}$  distribution to obtain the final result. The factor  $U(p_{T,\text{COR}}^{\text{jet}})$  increases with  $p_{T,\text{COR}}^{\text{jet}}$  and varies between 1.04 at low  $p_{T,\text{COR}}^{\text{jet}}$  and 1.3 at very high  $p_{T,\text{COR}}^{\text{jet}}$ .

A detailed study of the different systematic uncertainties was carried out [25]. The measured jet energies were varied by  $\pm 2\%$  at low  $p_T^{\text{jet}}$  and  $\pm 3\%$  at high  $p_T^{\text{jet}}$  to account for the uncertainty on the absolute energy scale in the calorimeter [26]. This introduces an uncertainty in the measured cross section which varies between  $\pm 10\%$  at low  $p_T^{\text{jet}}$  and  $_{-40\%}^{+55\%}$  at high  $p_T^{\text{jet}}$ . A  $\pm 8\%$  uncertainty on the jet energy resolution introduces an uncertainty between  $\pm 2\%$  at low  $p_T^{\text{jet}}$  and  $\pm 8\%$  at high  $p_T^{\text{jet}}$ . The unfolding procedure was repeated using HERWIG instead of PYTHIA-TUNE A to account for the uncertainty on the modeling of the parton cascades and the jet fragmentation into hadrons. This translates into an uncertainty about  $\pm 5\%$  at low  $p_T^{\text{jet}}$ . The unfolding procedure was also carried out using unweighted PYTHIA-TUNE A, to estimate the residual dependence on the  $p_T^{\text{jet}}$  spectrum. This introduces an uncertainty of  $\pm 4\%$  above 400 GeV/ $c$ , which becomes negligible at lower  $p_T^{\text{jet}}$ . The quoted uncertainty on  $\epsilon$  was taken into account. The effect on the measured cross section is less than  $\pm 3\%$  and negligible for jets with  $p_T^{\text{jet}}$  above 200 GeV/ $c$ . An additional 5.8% uncertainty on the total luminosity is not included.

Figure 1 shows the measured cross section as a function of  $p_T^{\text{jet}}$  compared to NLO pQCD predictions. The data are reported in Table I. The cross section decreases by more than 8 orders of magnitude as  $p_T^{\text{jet}}$  increases from 54 up to about 700 GeV/ $c$ . The NLO pQCD predictions are computed using the JETRAD program [8] with CTEQ6.1M PDFs [27] and the renormalization and factorization scales ( $\mu_R$  and  $\mu_F$ ) set to  $\mu_0 = \max(p_T^{\text{jet}})/2$ .

Different sources of uncertainty in the theoretical predictions were considered. The main contribution comes from the uncertainty on the PDFs and was computed using the Hessian method [28]. It varies from  $_{-10\%}^{+20\%}$  at low  $p_T^{\text{jet}}$  and

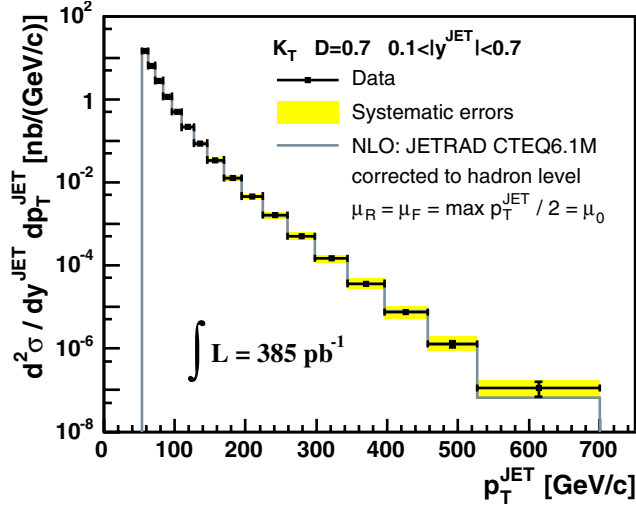


FIG. 1 (color online). Measured inclusive jet cross section (black dots) as a function of  $p_T^{\text{jet}}$  compared to NLO pQCD predictions (histogram). The shaded band shows the total systematic uncertainty on the measurement.

+7% for  $p_T^{\text{jet}}$  about 100 GeV/c to  $^{+70\%}_{-5\%}$  at high  $p_T^{\text{jet}}$ , dominated by the limited knowledge of the gluon PDF. An increase of  $\mu_R$  and  $\mu_F$  from  $\mu_0$  to  $2\mu_0$  reduces the theoretical predictions by 2% at low  $p_T^{\text{jet}}$  and 8% at high  $p_T^{\text{jet}}$ . Values significantly smaller than  $\mu_0$  lead to unstable NLO results and were not considered.

The theoretical prediction includes a correction factor  $C_{\text{HAD}}(p_T^{\text{jet}})$  that approximately accounts for nonperturbative contributions from the underlying event and fragmentation into hadrons (see Table I).  $C_{\text{HAD}}$  was estimated, using PYTHIA-TUNE A, as the ratio between the nominal  $p_{T,\text{HAD}}^{\text{jet}}$  distribution and the one obtained by turning off both the interactions between proton and antiproton remnants and the fragmentation in the Monte Carlo samples. The correction shows a strong  $p_T^{\text{jet}}$  dependence and decreases as  $p_T^{\text{jet}}$  increases from about 1.2 at  $p_T^{\text{jet}}$  of 54 GeV/c and 1.1 for  $p_T^{\text{jet}}$  about 100 GeV/c to 1.02 at high  $p_T^{\text{jet}}$ . The uncertainty on  $C_{\text{HAD}}$  is about 13% at low  $p_T^{\text{jet}}$  and decreases up to 1.6% at high  $p_T^{\text{jet}}$ , as determined using HERWIG instead of PYTHIA-TUNE A.

Figure 2 shows the ratio data/theory as a function of  $p_T^{\text{jet}}$ . Good agreement is observed in the whole range in  $p_T^{\text{jet}}$ . A  $\chi^2$  test, where the different sources of systematic uncertainty on the data are considered independent but fully correlated across  $p_T^{\text{jet}}$  bins and the uncertainty on  $C_{\text{HAD}}$  is also included, gives a  $\chi^2$  probability of 56%. In addition, Fig. 2 shows the ratio of pQCD predictions using MRST2004 [29] and CTEQ6.1M PDF sets, well inside the theoretical and experimental uncertainties.

In summary, we have presented results on inclusive jet production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV using the  $k_T$  algorithm, for jets with transverse momentum  $p_T^{\text{jet}} > 54$  GeV/c and rapidity in the region  $0.1 < |y^{\text{jet}}| < 0.7$ ,

TABLE I. Measured inclusive jet differential cross section as a function of  $p_T^{\text{jet}}$ . An additional 5.8% uncertainty on the luminosity is not included. The parton-to-hadron correction factors  $C_{\text{HAD}}(p_T^{\text{jet}})$  are applied to the pQCD predictions.

$p_T^{\text{jet}}$ [GeV/c]	$(d^2\sigma/dp_T^{\text{jet}}dy^{\text{jet}}) \pm (\text{stat}) \pm (\text{sys})$ [nb/(GeV/c)]	$C_{\text{HAD}} \pm (\text{stat}) \pm (\text{sys})$ parton $\rightarrow$ hadron
54–62	$(14.6 \pm 0.2^{+1.6}_{-1.6}) \times 10^0$	$1.202 \pm 0.013 \pm 0.158$
62–72	$(6.53 \pm 0.04^{+0.75}_{-0.84}) \times 10^0$	$1.154 \pm 0.003 \pm 0.113$
72–83	$(2.81 \pm 0.02^{+0.30}_{-0.30}) \times 10^0$	$1.134 \pm 0.005 \pm 0.094$
83–96	$(1.18 \pm 0.01^{+0.13}_{-0.12}) \times 10^0$	$1.113 \pm 0.006 \pm 0.077$
96–110	$(5.04 \pm 0.04^{+0.56}_{-0.54}) \times 10^{-1}$	$1.098 \pm 0.004 \pm 0.066$
110–127	$(2.15 \pm 0.02^{+0.25}_{-0.22}) \times 10^{-1}$	$1.079 \pm 0.005 \pm 0.047$
127–146	$(8.81 \pm 0.05^{+1.04}_{-0.98}) \times 10^{-2}$	$1.064 \pm 0.003 \pm 0.037$
146–169	$(3.45 \pm 0.02^{+0.46}_{-0.41}) \times 10^{-2}$	$1.057 \pm 0.004 \pm 0.030$
169–195	$(1.28 \pm 0.01^{+0.17}_{-0.17}) \times 10^{-2}$	$1.047 \pm 0.003 \pm 0.023$
195–224	$(4.67 \pm 0.02^{+0.74}_{-0.68}) \times 10^{-3}$	$1.043 \pm 0.003 \pm 0.018$
224–259	$(1.63 \pm 0.01^{+0.30}_{-0.27}) \times 10^{-3}$	$1.039 \pm 0.004 \pm 0.015$
259–298	$(5.08 \pm 0.06^{+1.02}_{-0.93}) \times 10^{-4}$	$1.034 \pm 0.003 \pm 0.010$
298–344	$(1.50 \pm 0.03^{+0.36}_{-0.31}) \times 10^{-4}$	$1.030 \pm 0.005 \pm 0.008$
344–396	$(3.70 \pm 0.14^{+1.07}_{-0.89}) \times 10^{-5}$	$1.016 \pm 0.009 \pm 0.006$
396–457	$(7.50 \pm 0.55^{+2.52}_{-2.01}) \times 10^{-6}$	$1.017 \pm 0.018 \pm 0.009$
457–527	$(1.31 \pm 0.22^{+0.57}_{-0.42}) \times 10^{-6}$	$1.009 \pm 0.003 \pm 0.019$
527–700	$(1.14 \pm 0.43^{+0.63}_{-0.47}) \times 10^{-7}$	$1.018 \pm 0.002 \pm 0.016$



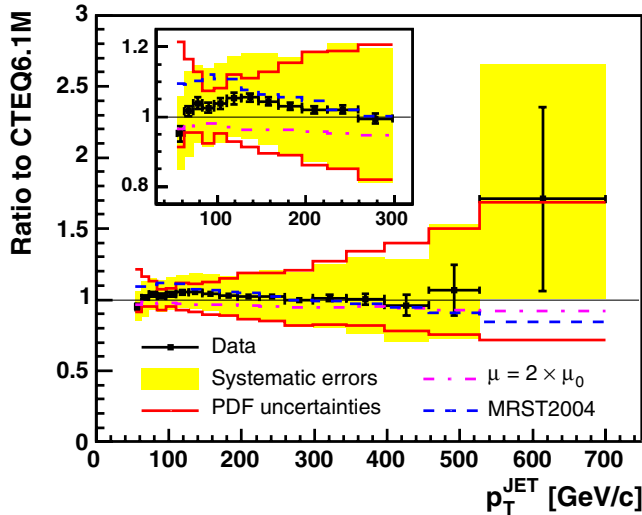


FIG. 2 (color online). Ratio data/theory as a function of  $p_T^{\text{jet}}$ . The enclosed figure expands the region  $p_T^{\text{jet}} < 298$  GeV/c. The error bars (shaded band) show the total statistical (systematic) uncertainty on the data. A 5.8% uncertainty on the luminosity is not included. The solid lines indicate the PDF uncertainty on the theoretical prediction. The dashed line presents the ratio of MRST2004 and CTEQ6.1M predictions. The dotted-dashed line shows the ratio of predictions with  $2\mu_0$  and  $\mu_0$ .

based on  $385 \text{ pb}^{-1}$  of CDF run II data. The measured cross section is in agreement with NLO pQCD predictions after the necessary nonperturbative parton-to-hadron corrections are taken into account.

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