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Measurement of Prompt Charm Meson Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

We report on measurements of differential cross sections $d\sigma/dp_T$ for prompt charm meson production in $pp$ collisions at $\sqrt{s} = 1.96$ TeV using $5.8 \pm 0.3$ pb$^{-1}$ of data from the CDF II detector at the Fermilab Tevatron. The data are collected with a new trigger that is sensitive to the long lifetime of hadrons containing heavy flavor. The charm meson cross sections are measured in the central rapidity region $|y| \leq 1$ in four fully reconstructed decay modes: $D^0 \rightarrow K^- \pi^+$, $D^{+} \rightarrow D^0 \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^+_s \rightarrow \phi \pi^+$, and their charge conjugates. The measured cross sections are compared to theoretical calculations.

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Measurements of the production cross sections of hadrons containing $b$ quarks or charm quarks (heavy flavor hadrons) in $pp$ collisions provide an opportunity to test predictions based on quantum chromodynamics (QCD). Previous measurements of $B$ meson production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV [1,2] were about 3 times larger than next-to-leading-order (NLO) QCD predictions [3], although recent calculations with a more accurate description of $b$ quark fragmentation have reduced this discrepancy to a factor 1.7 [4,5]. Charm meson production cross sections have not been measured in $p\bar{p}$ collisions and may help with understanding this disagreement. The upgraded Collider Detector at Fermilab (CDF II) has a new capability to trigger on tracks displaced from the beam line originating from the decay of long-lived hadrons containing heavy flavor quarks. We report here measurements of prompt charm meson cross sections using data recorded with this trigger in February and March 2002, corresponding to $5.8 \pm 0.3$ pb$^{-1}$ of integrated luminosity.

An overview of the CDF II detector can be found elsewhere [6]; only the components relevant to this analysis are described here. The CDF coordinate system has the $z$ axis pointing along the proton momentum; $\phi$ is the azimuth, $\theta$ is the polar angle, and $r$ is the distance from the proton beam axis. The CDF II central tracking region covers the pseudorapidity region $|\eta| \leq 1$, where $\eta = -\ln[\tan(\theta/2)]$. A superconducting solenoid provides a nearly uniform axial field of 1.4 T. The silicon vertex detector (SVX II) [7] consists of double-sided microstrip sensors arranged in five concentric cylindrical shells with radii between 2.5 and 10.6 cm. Surrounding the SVX II is the central outer tracker (COT) [8], an open cell drift chamber covering radii from 40 to 137 cm. The COT has...
96 layers, organized in 8 superlayers, alternating between axial and ±2° stereo readout.

CDF II has a three-level trigger system. We describe here the trigger used in this analysis. At the first trigger level, charged tracks are reconstructed in the COT axial projection by a hardware processor (XFT) [9].

The trigger for hadronic charm decays requires two oppositely charged tracks with \( p_T \geq 2 \text{ GeV}/c \) and the scalar sum of the \( p_T \)'s larger than 5.5 GeV/c, where \( p_T \) is the magnitude of the component of the momentum transverse to the beam axis. At the second trigger level, the silicon vertex tracker (SVT) [10] associates axial strip clusters from the four inner SVX II layers with XFT track information. The SVT measures the distance of the closest approach of a track relative to the beam axis (impact parameter or \( d_0 \)) with a resolution of 50 \( \mu \text{m} \), which includes a contribution of 30 \( \mu \text{m} \) from the beam spot transverse size. Events containing hadronic decays of heavy flavor hadrons are selected by requiring two tracks with 120 \( \mu \text{m} \leq d_0 \leq 1 \text{ mm} \) each. At the third trigger level, a farm of computers performs complete event reconstruction online: the opening angle \( \delta \varphi \) between the two trigger tracks is required to be between 2° and 90°, and the intersection point in the \( r-\varphi \) plane projected along the net momentum vector of the two tracks must be more than 200 \( \mu \text{m} \) from the beam line.

We reconstruct charm mesons in the following decay modes: \( \Lambda^0 \rightarrow K^- \pi^+ \), \( D^0 \rightarrow D^0 \pi^0 \) with \( D^0 \rightarrow K^- \pi^+ \), \( D^+ \rightarrow K^- \pi^+ \pi^+ \), \( D_s^+ \rightarrow \phi \pi^+ \) with \( \phi \rightarrow K^+ K^- \), and their charge conjugates. For every track pair that satisfies the trigger requirements (trigger pair), we form one \( D^0 \rightarrow K^- \pi^+ \) candidate and a second candidate with the mass assignments swapped. No particle identification is used in this analysis. \( D^0 \) candidates within 3 standard deviations of the \( D^0 \) mass are combined with a third track with \( p_T \geq 0.5 \text{ GeV}/c \) to form \( D^{*+} \rightarrow D^0 \pi^+ \) candidates. The three-body decays of the \( D^+ \) and \( D_s^+ \) are reconstructed by combining a trigger pair with a third track having axial hits in at least three out of five SVX II layers and performing a vertex fit based on axial track information only. For \( D_s^+ \) reconstruction, we specifically require the \( K^- \pi^+ \) pair to satisfy the trigger requirements, since the typical opening angle between two kaons from \( \phi \) decay is close to the \( \delta \varphi \approx 2° \) trigger requirement. Each \( \phi \) candidate is required to have a mass within ±20 MeV of the world average \( \phi \) mass [11]. The \( D \) meson candidates are binned in \( p_T \) as indicated in Table I. The signals summed over all \( p_T \) bins are shown in Fig. 1.

The \( D^0 \) yield is obtained from a binned maximum likelihood fit to the \( K^- \pi^+ \) invariant mass distribution, with a linear function for the combinatoric background, a narrow Gaussian for the \( D^0 \) signal, and a wide Gaussian with the same normalization describing \( D^0 \rightarrow K^- \pi^+ \) with the wrong mass assignment. We determine the shape of the mass distribution resulting from the wrong mass assignment using \( D^0 \) from \( D^{*+} \) decay where the charge of the low-momentum pion determines the mass assignment of the \( D^0 \) decay products. The \( D^{*+} \) yield is extracted from the distribution of \( \Delta m = m(K^- \pi^+ \pi^-) - m(K^- \pi^+) \), the mass difference between the \( K^- \pi^- \pi^+ \) and the \( K^- \pi^+ \) combination. The signal is modeled with two Gaussians with equal means, and the background is characterized as \( a \sqrt{\Delta m - m_\pi} \exp(b(\Delta m - m_\pi)) \), where \( a \) and \( b \) are free parameters in the fit. The \( D^+ \) signal is described with two Gaussians, one corresponding to the \( D^+ \) and one to the \( D_s^+ \). We find 36 804 ± 409, \( D^0 \rightarrow K^- \pi^+ \); 5515 ± 85, \( D^{*+} \rightarrow D^0 \pi^+ \); 28 361 ± 294, \( D^+ \rightarrow K^- \pi^+ \pi^+ \); and 851 ± 43, \( D_s^+ \rightarrow \phi \pi^+ \), where the uncertainties quoted are statistical only. We vary the signal and background models and attribute systematic uncertainties on the signal yield in the range of 1%–6%, depending on the decay mode and the \( p_T \) range of the candidates.

We separate charm directly produced in \( p\bar{p} \) interactions (prompt charm) from charm from \( B \) decay (secondary charm) using the impact parameter of the net momentum vector of the charm candidate to the beam line [12]. Prompt charm mesons point to the beam line. The shape of the impact parameter distribution of secondary charm is obtained from a generator-level Monte Carlo (MC) simulation of the \( B \) meson production [2] and decay [13], smeared with a resolution function (Gaussian + exponential tails) obtained from a sample of \( K_S^0 \rightarrow \pi^+ \pi^- \) decays that satisfy the trigger requirements. The impact parameter distribution of the reconstructed charm samples, shown for the \( D^0 \) in Fig. 2, is fit to a prompt and a secondary component. The prompt fraction is measured for each \( p_T \) bin. Averaged over all \( p_T \) bins, (86.6 ± 0.4)% of the \( D^0 \) mesons, (88.1 ± 1.1)% of \( D^{*+} \), (89.1 ± 0.4)% of \( D^+ \), and (77.3 ± 3.8)% of \( D_s^+ \) are promptly produced (statistical uncertainties only). The systematic uncertainties on the prompt fractions are estimated by removing the non-Gaussian tail in the resolution function and evaluating the variation. The relative uncertainty is found to be in the 3%–4% range, depending on the decay mode.

Using a hit-level simulation of the COT, overlaid with data events from the hadronic heavy flavor trigger to reproduce a realistic occupancy, we measure a reconstruction efficiency in the COT of 99% for tracks with \( p_T \geq 2 \text{ GeV}/c \), falling to 95% at \( p_T = 0.5 \text{ GeV}/c \). The efficiency for finding three SVX II axial hits on a reconstructed track is measured from data to be about 85%. The efficiencies of the trigger hardware XFT and SVT to reconstruct tracks are measured from data samples without XFT or SVT requirements [12]. The XFT tracking efficiency is greater than 95%. In the data-taking period considered, the SVX II and the SVT were not yet fully operational, and the efficiency varied as certain SVX II modules were included or excluded from the trigger.
The curves show the results of the fits described in the text.

FIG. 1. Charm signals summed over all \( p_T \) bins: (a) invariant mass distribution of \( D^0 \to K^- \pi^+ \) candidates; (b) mass difference distribution of \( D^{*+} \to D^0 \pi^- \) candidates; (c) invariant mass distribution of \( D^+ \to K^- \pi^+ \pi^- \) candidates; (d) invariant mass distribution of \( D^* \to \phi \pi^+ \) and \( D^{*+} \to \phi \pi^+ \) candidates. The curves show the results of the fits described in the text.
of the cross section inside each \( p_T \) bin. Systematic uncertainties on the trigger and reconstruction efficiency arise predominantly from the uncertainty on single-track efficiencies and two-track efficiency correlations. They also have contributions from ionization energy loss, hadronic interactions in the inner tracker material, and the size of the interaction region. The combined systematic uncertainty on the trigger and reconstruction efficiency is in the range of 8\%-14\%, depending on the decay mode and the \( p_T \) range of the \( D \) mesons.

The total cross sections are obtained by summing over all \( p_T \) bins. However, the last \( p_T \) bin is replaced by an inclusive bin with \( p_T > 12 \) GeV/c. We find \( \sigma(D^0, p_T \geq 5.5 \) GeV/c, \( |y| \leq 1) = 13.3 \pm 0.2 \pm 1.5 \) \( \mu b \), \( \sigma(D^{++}, p_T \geq 6.0 \) GeV/c, \( |y| \leq 1) = 5.2 \pm 0.1 \pm 0.8 \) \( \mu b \), \( \sigma(D^+, p_T \geq 6.0 \) GeV/c, \( |y| \leq 1) = 4.3 \pm 0.1 \pm 0.7 \) \( \mu b \), and \( \sigma(D_s^+, p_T \geq 8.0 \) GeV/c, \( |y| \leq 1) = 0.75 \pm 0.05 \pm 0.22 \) \( \mu b \), where the first uncertainty is statistical and the second systematic. To calculate the differential cross sections, we divide \( \sigma_j \) by the width of the \( p_T \) bin. Since we report \( d\sigma/dp_T \) at the center of each \( p_T \) bin, we apply a correction to account for the nonlinear shape of the cross section, using the \( p_T \) reweighted MC to obtain the shape of the cross section inside each \( p_T \) bin. The results are listed in Table I.

The measured differential cross sections are compared to two recent calculations [16,17], as shown in Fig. 3. The uncertainties on the calculated cross sections are evaluated by varying independently the renormalization and factorization scales between 0.5 and 2 times the default scale. Reference [16] uses a default scale of \( \sqrt{m_c^2 + p_T^2} \), where \( m_c = 1.5 \) GeV/c\(^2 \) is the \( c \) quark mass, while Ref. [17] uses a default scale of \( 2\sqrt{m_c^2 + p_T^2} \).

Contributions from other sources, such as the charm quark mass, the value of the strong coupling constant, and the fragmentation functions, were reported to be smaller and are not taken into account.

In conclusion, the measured differential cross sections are higher than the theoretical predictions by about 100\% at low \( p_T \) and 50\% at high \( p_T \). However, they are compatible within uncertainties. The same models also underestimate \( B \) meson production at \( \sqrt{s} = 1.8 \) TeV by similar factors [2,4,5].

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\[ \text{FIG. 3. The measured differential cross section measurements for } |y| \leq 1, \text{ shown by the points. The inner bars represent the statistical uncertainties; the outer bars are the quadratic sums of the statistical and systematic uncertainties. The solid curves are the theoretical predictions from Cacciari and Nason [16], with the uncertainties indicated by the shaded bands. The dashed curve shown with the } D^{++} \text{ cross section is the theoretical prediction from Kniehl [17]; the dotted lines indicate the uncertainty. No prediction is available yet for } D_s^+ \text{ production.} \]

\[ \text{from 0.12\% to 1.9\% depending on the decay mode and the } p_T \text{ bin. Systematic uncertainties on the trigger and reconstruction efficiency arise predominantly from the uncertainty on single-track efficiencies and two-track efficiency correlations. They also have contributions from ionization energy loss, hadronic interactions in the inner tracker material, and the size of the interaction region. The combined systematic uncertainty on the trigger and reconstruction efficiency is in the range of 8\%-14\%, depending on the decay mode and the } p_T \text{ range of the } D \text{ mesons.} \]