# Feynman-$x$ and Transverse Momentum Dependence of $D$ Meson Production in 250 GeV $\pi$, $K$, and $p$ Interactions with Nuclei

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We measure the differential cross sections with respect to Feynman $x$ ($x_F$) and transverse momentum ($p_T$) for $\pi$, $K$, and $p$-induced charm meson production using fully reconstructed $D^+$, $D^0$, and $D_s$ decays. The shapes of these cross sections are compared to the theoretical predictions for charm quark production of next-to-leading order perturbative QCD using modern parametrizations of the pion and nucleon parton distributions. We observe the differences expected in production induced by projectiles with different gluon distributions, harder distributions being indicated for mesons than for protons. [S0031-9007(96)01095-2]

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Perturbative QCD predictions of differential cross sections for charm quark production in hadronic collisions depend, through the dominant gluon-gluon fusion process, on the momentum distributions of the gluons in the projectile and target particles [1]. Furthermore, the shapes of these cross sections are relatively insensitive to theoretical uncertainties [2]. Although nonperturbative processes, particularly hadronization, additionally impact the $x_F$ and $p_T$ distributions of charm hadrons, these effects are reasonably assumed to be independent of initial-state gluon distributions. As a consequence, the shapes of these differential cross sections should be sensitive to differences in beam-particle gluon distributions.

In this Letter we report measurements, for $\pi$, $K$, and $p$ beams, of $D$ meson differential cross sections versus $x_F$ and $p_T$, the latter distributions for $x_F > 0$. Fermilab E769 is the first experiment in which charm production induced by $\pi$, $K$, and $p$ beams is studied at a common beam energy and using a single target and spectrometer. Moreover, few published measurements of charm differential cross-section distributions benefit from full mass reconstruction and identification and momentum determination of secondary particles. In this category, our data set represents a factor-of-2 improvement in the number of $\pi$-induced charm decays; for $K$ and $p$ beams, tenfold and threefold increases in statistics, respectively, are realized [3–5]. Note that the distributions presented are absolutely normalized; results on the total forward cross sections of charm particles are presented in the preceding Letter [6].

$D$ meson signals are obtained by combining the decays $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$, $D_s^+ \to \phi\,\pi^+$ ($\phi \to K^+K^-$), and $D_s^+ \to \overline{K}^*(892)^0 K^+$ ($\overline{K}^{*0} \to K^-\pi^+$). Throughout this paper charge conjugate decays are also implied. Our previously published data for $\pi^-$ beam [7] have been augmented with $\pi^+$ beam data for purposes of comparison with $K$ and $p$ beam results.

The E769 data set was collected using collisions of negatively and positively charged 250 GeV mixed secondary beams on a multifoil target of Be, Cu, Al, and W. Event-by-event tagging, described in [6], allowed identification of the five beam particle types ($\pi^\pm$, $K^\pm$, and $p$) used in this analysis. Detailed descriptions of the TPL Spectrometer, our on-line triggers, and our off-line event reconstruction and secondary vertex filter are found in [7], and references quoted therein. Analysis cuts were applied to select events with one or more of the aforementioned $D$ decays. These cuts were based on vertex information and the transverse momenta of the decay tracks with respect to the direction of the parent $D$; this analysis is similar to that presented for $D^+$ and $D^0$ decays in a previous paper [7]. In addition, for $D_s \to K^*K$ decays, the absolute

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value of the cosine of the angle between the $D_s$ and decay pion directions (measured in the $K^*$ center-of-mass frame) was required to be $>0.2$. For $D_s$ decays to $\phi\ \pi$ ($K^*K$), the invariant mass of the $KK$ (relevant $K\pi$) pair was required to be within 10 (50) MeV of the $\phi$ ($K^*$) mass. For all decays, Čerenkov information was used to exclude identified pions as candidate kaons.

Particles produced in all target materials are combined in this analysis. Consistent with previous findings [8,9], $D$ meson differential cross sections are assumed independent of nuclear effects. The final $D$ meson data samples used for this analysis are as follows: $1665 \pm 54$ events for $\pi$ beam (70% $\pi^-$, 30% $\pi^+$), $388 \pm 26$ events for $K$ beam (30% $K^-$, 70% $K^+$), and $320 \pm 26$ events for $p$ beam. For all three beams, $D$ samples consist of approximately 50% $D^+$, (40–45)% $D^0$, and (5–10)% $D_s$.

$D^+$, $D^0$, and $D_s$ components of $D$ signals were combined into common mass plots by shifting the masses of the latter two to the $D^+$ mass. Differential distributions were determined by making such mass plots for each bin of $x_F$ and $p_T^2$. Binned maximum-likelihood fits, using Gaussian signals (center fixed to $D^+$ mass, widths fixed according to the Monte Carlo simulation) and linear backgrounds, were used to obtain signal estimates. The Gaussian widths are independent of $p_T$ but range from 8 MeV at low $x_F$ up to 20 MeV at high $x_F$. Bin widths at high $p_T$ were increased in order to expand the range over which signals retained statistical significance.

Acceptances were calculated using a complete Monte Carlo simulation of the experiment as described in [7]. The simulation models the effects of the resolution, geometry, and efficiency of the spectrometer components, efficiencies associated with the transverse-energy triggers, and all analysis cuts. Integrated acceptances vary somewhat for the different beams due to the different trigger mixes and average drift chamber efficiencies characterizing the corresponding data samples; their dependences on $x_F$ and $p_T$, however, are quite stable. Differential acceptances are also found to be insensitive to the relative mixture of $D^+$, $D^0$, and $D_s$ assumed in the signals. Over the range $-0.1 < x_F < 0.8$, the acceptances start at less than 1% for negative $x_F$, peak at up to 6% at $x_F$ of 0.25, and then drop to about a third of their maximum value at high $x_F$. Versus $p_T$, the acceptances rise from (2–4)% to (7–8)% in the range 0 to 4 GeV. Systematic errors in the acceptance shapes due to uncertainties in the trigger simulation, detector efficiencies, and analysis cuts are all found to be small compared to statistical errors in the data; results are therefore given with only the latter quoted.

Data samples for the $D^+$, $D^0$, and $D_s$ are combined in order to obtain a high-statistics measurement of the dependence of charm quark production on the gluon distributions of the initial-state hadrons. In order to justify this procedure, differential cross-section results for each meson were obtained and compared. Consistency of distribution shapes was quantified by summing the $\chi^2$ of the difference in each bin, calculated while allowing the overall relative normalization to float. In all cases, the three charm mesons yielded consistent cross-section shapes versus $x_F$ and $p_T$. The same procedure was used to check the legitimacy of combining negative $\pi$ and $K$ beam samples with corresponding positive beam samples; our data sample provides the first opportunity to make such comparisons. Again, the distribution shapes were found to be consistent.

Our measurements of $D$ meson $d\sigma/dx_F$ and $d\sigma/dp_T^2(x_F > 0)$ for $\pi$, $K$, and $p$ beams are shown in Figs. 1 and 2, respectively; values for these cross sections may be obtained through the electronic Physics Auxiliary Publication Service [10]. Also shown are next-to-leading order (NLO) QCD predictions for charm quark production generated using the program of Mangano *et al.* [2] assuming HMRSB (SMRS2) parton distribution functions for target nucleons and beam protons (pions) [11]. Theoretical parameters [charm quark mass ($m_c$), renormalization scale ($\mu_R$), factorization scale ($\mu_F$), and $\Lambda_{\rm QCD}$] were set to the default values used in [1]. Normalizations of the $\pi$ ($p$) beam theory curves are floated for best fit to the $\pi$ ($p$) beam data. It should be emphasized that the theory has not been modified to model nonperturbative effects such as intrinsic parton $p_T$ and hadronization.

Remarkably, $D$ meson $d\sigma/dx_F$ distributions induced by $\pi$ and $p$ beams are well fit [$\chi^2$ upper-tail probabilities (UTPs) $> 50\%$] by the corresponding predictions for charm quarks. These latter shapes are found to be insensitive to variation of parameters typically used to gauge theoretical uncertainty ($m_c$, $\mu_R$, $\mu_F$) [1,12]. Furthermore, the $\pi$ and $p$ beam predictions for $d\sigma/dx_F$ are quite distinct, the former being significantly harder and peaking at 0.03 rather than being symmetric about $x_F$ of zero. Accordingly, the $\pi$ and $p$ beam data distribution shapes are found to be inconsistent, with a $\chi^2$ lower-tail probability (LTP) greater than 99%. The $K$ beam data, in addition to being consistent with the $\pi$ beam data (UTP $> 95\%$), is well fit by the $\pi$ beam theory, indicating similarity in pion and kaon gluon distributions.

The predicted separation between $\pi$ and $p$ beam-induced charm production is not as pronounced for $d\sigma/dp_T^2$ as it is for $d\sigma/dx_F$; the $\pi$ beam distribution is expected to be somewhat harder. These shapes, further, show a dependence on moderate variations in $m_c$ ($\pm 0.3$ GeV) which is similar for both beams and on the order of the difference between them. Over the range for which there is $K$ and $p$ beam data ($p_T^2 < 8$ GeV$^2$), the data distributions for the three beams are found to have consistent shapes (UTPs $> 20\%$); the $K$ and $p$ beam shapes are fit well by either theory curve. The $\pi$ beam data distribution, however, while fit well (UTP $> 15\%$) by the theoretical distribution generated using $\pi$ parton distributions for the beam, is inconsistent with the $p$ beam theory (LTP $> 99\%$).

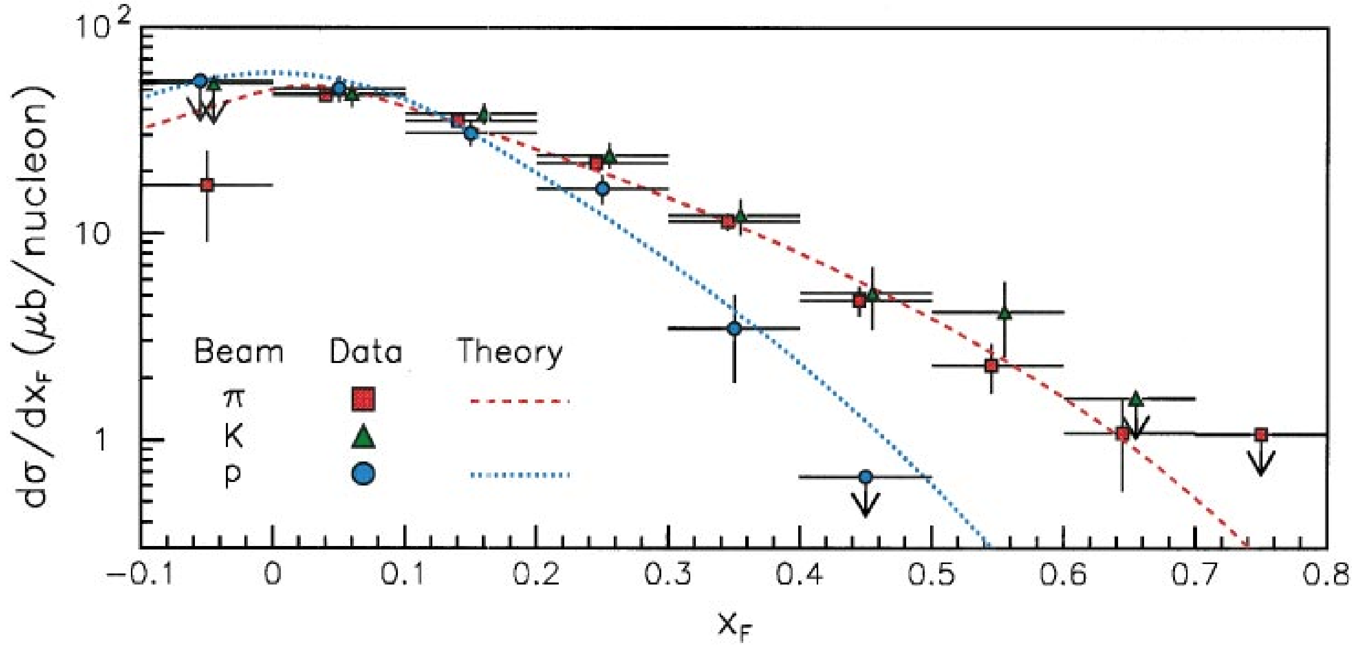


FIG. 1(color). Measured $D$ meson ($D^+$, $D^-$, $D^0$, $\overline{D}^0$, $D_s^+$, and $D_s^-$) $d\sigma/dx_F$ for production induced by $\pi$, $K$, and $p$ beams and NLO QCD predictions [2] for charm quarks ($\pi$ and $p$ beams). In addition to the statistical errors shown, there are overall normalization errors of about 6%, 6%, and 9% for $\pi$, $K$, and $p$ results, respectively. The abscissas of some data points are slightly offset to make them easily visible. Arrows indicate 90% confidence level upper limits.

Various parametrizations of $d\sigma/dx_F$ and $d\sigma/dp_T^2$ have appeared in the literature and have been used to compare measurements from different experiments. The form $(1 - x_F)^n$ gives good fits to our measured distributions for positive $x_F$, but the $n$ values returned show a systematic dependence on the lower boundary of the fit range chosen. For $d\sigma/dp_T^2$, the forms $\exp(-bp_T^2)$ and $\exp(-b'p_T)$ are used to fit the distributions at low and high $p_T$, respectively. The former, while fitting the relatively low-statistics $K$ and $p$ beam results well, does not adequately describe the $p_T$ dependence of the $\pi$ beam distribution, even over the limited range $p_T < 2$ GeV;

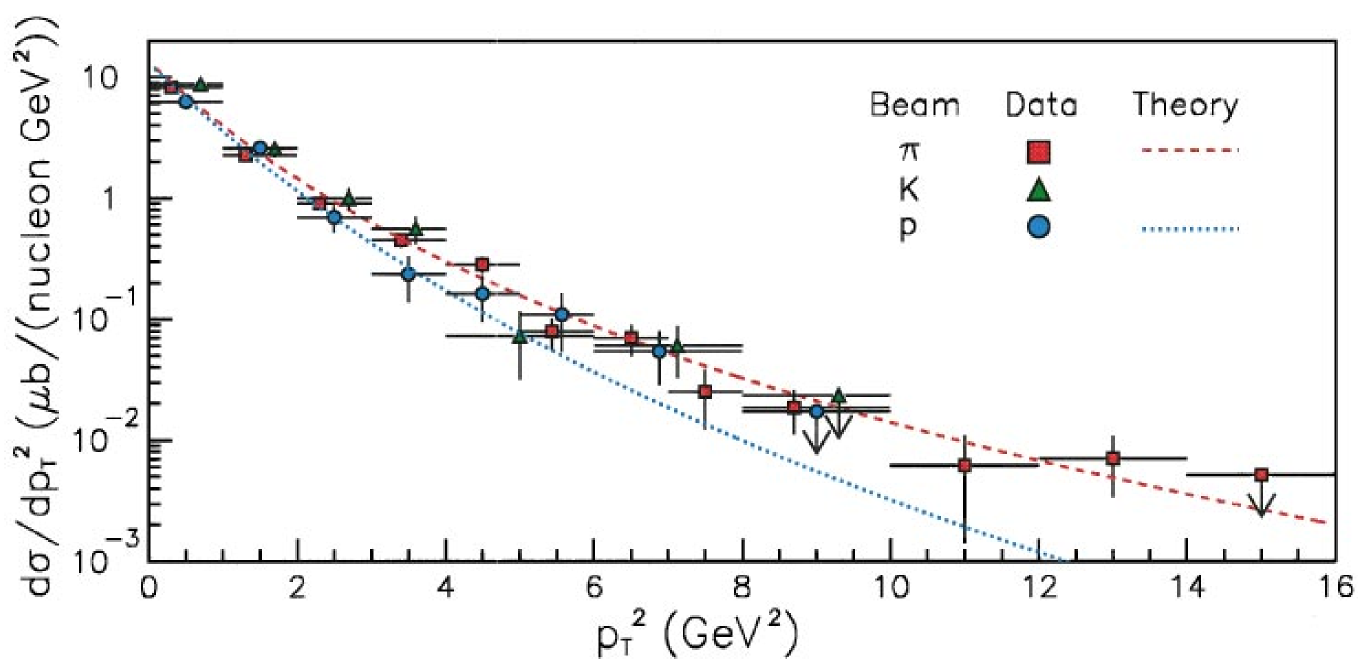


FIG. 2(color). Measured $D$ meson ($D^+$, $D^-$, $D^0$, $\overline{D}^0$, $D_s^+$, and $D_s^-$) $d\sigma/dp_T^2(x_F > 0)$ for production induced by $\pi$, $K$, and $p$ beams and NLO QCD predictions [2] for charm quarks ($\pi$ and $p$ beams). See explanation in Fig. 1 caption.

TABLE I. $D$ meson[a] production parameters (described in text) from fits to E769 data compared with previous measurements [3–5]. E769 values of $n$, $b$, and $b'$ shown correspond to fit ranges of $x_F > 0$, $p_T < 2$ GeV, and $p_T > 1$ GeV, respectively. See text for discussions of fit quality and dependence of production parameters on fit range.

| Beam | Expt. | $P_{\text{beam}}$ (GeV) | Target(s) | $n$ | $b$ (GeV$^{-2}$) | $b'$ (GeV$^{-1}$) |
|---|---|---|---|---|---|---|
| $\pi^{\pm}$ | E769 | 250 | Be, Al, Cu, W | $4.03 \pm 0.18$ | $1.08 \pm 0.05$ | $2.74 \pm 0.09$ |
| $\pi^{-}$ | NA32 | 230 | Cu | $3.7 \pm 0.2 \pm 0.4$ | $0.83 \pm 0.03 \pm 0.02$ | |
| $\pi^{-}$ | NA27 | 360 | H | $3.8 \pm 0.6 \pm 0.4$ | $0.83^{+0.18}_{-0.16}$ | |
| $K^{\pm}$ | E769 | 250 | Be, Al, Cu, W | $3.8 \pm 0.4$ | $1.05 \pm 0.09$ | $3.0 \pm 0.3$ |
| $K^{-}$ | NA32 | 230 | Cu | $3.6^{+1.08}_{-0.99} \pm 0.36$ | $1.36^{+0.32}_{-0.26} \pm 0.04$ | |
| $p$ | E769 | 250 | Be, Al, Cu, W | $6.1 \pm 0.7$ | $1.08 \pm 0.09$ | $3.0 \pm 0.3$ |
| $p$ | NA32 | 200 | Si | $5.5^{+2.1}_{-1.8}$ | $1.4^{+0.6}_{-0.4}$ | |
| $p$ | NA27 | 400 | H | $4.9 \pm 0.5 \pm 0.4$ | $0.99 \pm 0.09$ | |

[a]For E769, this includes $D^+$, $D^-$, $D^0$, $\overline{D}^0$, $D_s^+$, and $D_s^-$; for other experiments, only $D^+$, $D^-$, $D^0$, and $\overline{D}^0$ are included.

the $b$ parameter also shows sensitivity to the fit range used. The form $\exp(-b' p_T)$, on the other hand, fits all distributions well over the range $p_T > 1$ GeV. Despite the limitations of these parametrizations, in Table I we present production parameters resulting from least-squares fits to our measured differential cross sections, compared with previous measurements from experiments with beam energies close to our own. Frixione *et al.* [13] have introduced the $d\sigma/dp_T^2$ parametrization $(\alpha m_c^2 + p_T^2)^{-\beta}$. This form is found to fit our measured distributions well over the entire $p_T$ range. For $\pi$ beam, the resulting parameter values (with $m_c = 1.5$ GeV) are $\alpha = 1.4 \pm 0.3$ and $\beta = 5.0 \pm 0.6$.

In summary, we have measured differential cross sections for $D$ meson production with sufficient sensitivity to observe their dependence on the gluon distributions of the projectile particles, thereby providing new evidence of the relative hardness of the gluons in pions and kaons compared to those in protons. The agreement between experiment and theory reinforces the applicability of a perturbative framework for high-energy production of charm.

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[9] In Table I of [7], production parameters are broken down by target material; no $A$ dependence is indicated.

[10] See AIP Document No. E-PAPS: E-PRLTA-77-2392-20KB for two tables of $D$ meson differential cross-section values ($d\sigma/dx_F$ and $d\sigma/dp_T^2$). E-PAPS document files may be retrieved free of charge from our FTP server (http://www.aip.org/epaps/epaps.html). For further information, e-mail: paps@aip.org; or fax: 516–576–2223.

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