Enhanced Leading Production of $D^{\pm}$ and $D^{*\pm}$ in 250 GeV $\pi^{\pm}$-Nucleon Interactions

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A leading charm meson is one with longitudinal momentum fraction, $x_F > 0$, whose light quark (or antiquark) is of the same type as one of the quarks in the beam particle. We report on the production asymmetry, $A = [\sigma(\text{leading}) - \sigma(\text{nonleading})]/[\sigma(\text{leading}) + \sigma(\text{nonleading})]$ as a function of x_F. The data consist of 1500 fully reconstructed $D^{\pm}$ and $D^{*\pm}$ decays in Fermilab experiment E769. We find a significant asymmetry at large x_F, consistent with the recent result of CERN experiment WA82. Such an asymmetry for the production of charm quarks is not expected in perturbative quantum chromodynamics.

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Heavy quark production in hadronic interactions can be treated with quantum chromodynamic perturbation theory when the quantity $\ln(m_Q/\Lambda)$ is large, where m_Q is the mass of the heavy quark and Λ ($\sim$ 200 MeV) is the QCD scale factor. This condition is met in increasingly better approximation by the charm, beauty, and top quarks. However, when a heavy quark binds with a light antiquark to form a meson, via a process called fragmentation, an exchange of low-q^2 gluons typically takes place, making the process intrinsically nonperturbative. In addition to its fundamental interest, this fragmentation may have important consequences for flavor tagging of neutral beauty mesons, which is necessary for measuring their CP violating decay rate asymmetries. For example, Gronau, Nippe, and Rosner have proposed that flavor tagging may be possible via a kinematic correlation between the beauty meson and an associated pion formed in the fragmentation of the beauty quark [1]. Another type of kinematic correlation useful for flavor tagging may arise if a light quark in an initial state particle is transferred to the produced beauty meson. This could result in a leading particle effect at high x_F in which there is a preponderance of antibeauty over beauty [2]. Such an effect for charm production is the subject of this paper.

For charm meson production, for which more measurements are available than for beauty, the major features of the cross section are consistent with the predictions of perturbative quantum chromodynamics (PQCD) for charm quark production. This applies to the dependence of the differential cross sections on the longitudinal momentum fraction in the center of mass frame, Feynman x (x_F), the transverse momentum (P_T) [3–5], and the dependence of the total charm cross section on the atomic mass of the target [6,7]. Although previous measurements from CERN experiment NA32 [3] and from this experiment (E769) [4,5] show a consistent trend of a small difference in the x_F dependence of leading and nonleading charm meson production, the difference is not statistically significant in either experiment alone. However, the CERN WA82 Collaboration recently reported a significant difference between the leading and nonleading x_F distributions [8], predominantly in a range of x_F that contributes only a small amount to the total production. A leading charm meson is defined, for $x_F > 0$, as one whose light quark (or antiquark) is of the same type as one of the quarks in the beam particle. In WA82, with a π^- beam particle (quark content $\bar{u}d$), D^- ($\bar{c}d$) is leading and D^+ ($c\bar{d}$) is nonleading. In general, the asymmetry is defined as

$$A \equiv \frac{\sigma(\text{leading}) - \sigma(\text{nonleading})}{\sigma(\text{leading}) + \sigma(\text{nonleading})},$$

where σ(leading) is the cross section for the leading charm particle of a given species. WA82 found a large value for A ($\sim$ 0.5) at large values of x_F ($\sim$ 0.6). As

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discussed in more detail below, such a large value of A cannot be explained by a conventional calculation of the perturbative production of the charm quarks. A confirmation of the effect seen by WA82 is important to establish it firmly.

In this paper, we report a measurement of A using data from Fermilab experiment E769 for $D^{\pm}$ and $D^{*\pm}$ mesons produced with π^- and π^+ beams. The D^0 ($\overline{D}^0$) meson is not usually included in studies of leading particles because a large fraction of these mesons originate from decays of D^{*+} or D^{*0}. Because the light quark contents of D^{*+} and D^0 are different, the leading or nonleading assignment of a D^0 is ambiguous between a directly produced D^0 and one from a D^* decay.

In E769, flavor-tagged, charged secondary beams of 250 GeV momentum interacted in targets of Be, Cu, Al, and W. The interaction products were detected in an extensively instrumented, open geometry spectrometer with good acceptance for $x_F > 0$. The spectrometer is described in [4] and [6] and the references quoted therein. The major components are a silicon vertex detector, a two-magnet spectrometer with proportional wire chambers and drift chambers, two multicell threshold Cherenkov counters, and electromagnetic and hadron calorimeters. The beam particle is identified with a transition radiation detector and a differential Cherenkov counter.

The data analysis techniques used here are the same as described in our previous papers [4–6] on $D^{\pm}$, $D^{*\pm}$, and D^0 ($\overline{D}^0$) production with π^- and π^+ beams. The decay modes used here (with charge conjugates implied) are $D^+ \rightarrow K^-\pi^+\pi^+$ (919 ± 37 events) and $D^{*+} \rightarrow \pi^+ D^0$ (600 ± 30), with $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, or $K^-\pi^+\pi^0$. The numbers in parentheses are signal estimates from fits to mass plots allowing for signal and background terms. About 3/4 of the signal comes from π^- beam data and 1/4 from π^+ beam data, due to the different integrated flux, detector efficiency, and trigger prescaling for each beam polarity.

We previously reported the use of a subset of these signals to fit the differential cross sections in x_F for leading and nonleading $D^{\pm}$ and $D^{*\pm}$ separately, and the overall asymmetry integrated over x_F. The asymmetry versus x_F could be extracted from these fits with the use of some approximations which are discussed below. However, there are several advantages in computing the asymmetry directly from the numbers (N) of leading and nonleading particles in each bin of x_F according to the formula

$$A = \frac{N(\text{leading}) - N(\text{nonleading})}{N(\text{leading}) + N(\text{nonleading})}.$$

The acceptance does not appear in this formula since it is the same for positive and negative charmed particles. Using Monte Carlo simulations we verified that the contribution to the asymmetry from the acceptance is consistent with zero to an accuracy much better than the statistical errors in the measurements.

The previous fits did not include all the data that can be used for the asymmetry measurement. They did not include data in the range $0.0 < x_F < 0.1$ because the functional form, $(1 - x_F)^n$, did not provide a good fit in this range. In this paper, the data are reported for this range. Also, the asymmetries reported here do not depend on any assumed parametrization for $d\sigma/dx_F$. Thus, there is no systematic error from an assumed functional form.

Other additional data come from two sources. We use $D^{\pm}$ produced with a π^+ beam whereas only $D^{\pm}$ produced with a π^- beam were used for the previously reported fits. Also, we use a larger data set than before by allowing a wider range of trigger types based on calorimeter transverse energy. Some of the data from these triggers were not used previously, to reduce the systematic error due to trigger acceptance which is not relevant in this analysis.

Our results for asymmetry versus x_F are shown in Fig. 1 with bins of 0.1 in x_F. The asymmetry includes data for both beam polarities and both particle types ($D^{\pm}$ and $D^{*\pm}$). Our data show a trend of increasing asymmetry with x_F, but with large statistical errors for $x_F > 0.4$. The positive sign of A indicates enhanced leading production. To test whether the data are consistent with the hypothesis of A = const, we performed a least squares fit which gave $\chi^2 = 15.5$ for 6 degrees of freedom (d.o.f.). The probability for $\chi^2 \geq 15.5$ with 6 d.o.f. (the

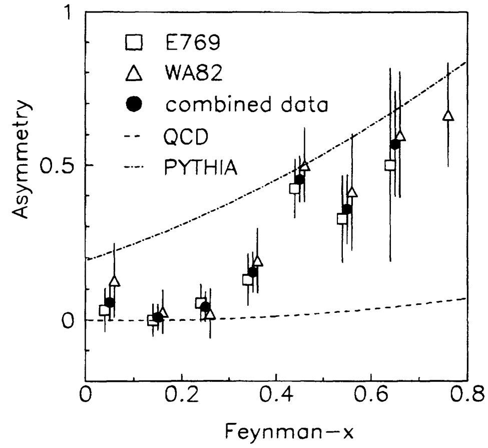

FIG. 1. Asymmetry versus x_F. The E769 data include $D^{\pm}$ and $D^{*\pm}$ produced with π^- and π^+ beams. The WA82 data are for $D^{\pm}$ with a π^- beam. The solid circles show the combined data from the two experiments. The abscissas of the data points for both experiments are shown slightly offset to make them easily visible. For both experiments the bin width is 0.1 in x_F. The dashed curve is based on the NLO perturbative QCD prediction for charmed quark production. The dot-dashed curve is the prediction for $D^{\pm}$ from the PYTHIA Monte Carlo program.

upper tail probability) is 1.7%. Thus, our data are inconsistent with this hypothesis at the 98.3% confidence level (C.L.), as suggested qualitatively by inspection of Fig. 1. We also tested whether our data for A are different for separate beam types (π^- or π^+) and separate particle types ($D^\pm$ or $D^{*\pm}$). We performed this test with a polynomial fit to each data set. In all cases, the corresponding parameters of the different fits are equal within errors. Since all the separate distributions are consistent with coming from the same parent distribution, we show only the combined data, which have the best statistical significance.

The data for $A(D^\pm)$ versus x_F from CERN experiment WA82, also shown in Fig. 1, are based on a signal of 771 ± 30 fully reconstructed $D^\pm$ decays. The experiment employed a 340 GeV π^- beam on Si, Cu, and W targets. By again testing with a polynomial fit, we verified that the A distributions from both experiments are consistent. The WA82 data, alone, when fit with a constant A give $\chi^2 = 29.4$ for 7 d.o.f. which corresponds to a C.L. of $(1\text{–}1.2)\times 10^{-4}$. The combined data from both experiments are also shown in Fig. 1. For the combined data, a fit to the hypothesis of $A =$ const gives $\chi^2 = 46.3$ for 7 d.o.f. and C.L. $= (1\text{–}7.6) \times 10^{-8}$. Thus, the combined data strengthen the evidence for nonconstant A. Clearly, the data from both experiments show the same qualitative trend of A increasing with x_F. Although there is a significant leading effect at large x_F, because the differential cross section falls off rapidly with x_F, the asymmetry integrated over $x_F > 0$ is small compared to the dramatic effect at large x_F.

In leading order QCD, c and $\bar{c}$ quarks are produced with the same cross section from gluon fusion. However, in next to leading order (NLO), diagrams arise which depend on the quark content of the initial state. These diagrams give rise to a small asymmetry favoring a $\bar{c}$ quark over a c quark at large x_F when produced with an incident π^-. Since both D^{*-} and D^- contain a $\bar{c}$ quark, the observed asymmetry A would be positive. The prediction shown in Fig. 1 is based on the calculation by Nason, Dawson, and Ellis [9]. Clearly, the data show much larger values of A than the small value predicted at high x_F for charm quarks using PQCD. There are several possible explanations. If the large A is due to the charm quark production itself, this might arise from nonperturbative (higher order) effects or from an intrinsic charm component to the initial state quark sea [10]. Alternatively, the asymmetry may arise from fragmentation of the charmed quarks by interaction with the spectator quarks. This latter mechanism is implemented in the Lund string fragmentation model incorporated in the PYTHIA Monte Carlo program [11]. As shown in Fig. 1, PYTHIA qualitatively reproduces the trend of increasing A versus x_F, but predicts too large a value for A.

We also report the first measurement of the dependence of A on the transverse momentum, P_T, of the charm meson. We have data in the range $0 < P_T^2 < 10$ GeV^2 which are shown in Fig. 2 with bins of 1 GeV^2 in P_T^2. A fit of these data to a constant value of A gives $A = 0.054 \pm 0.032$ with $\chi^2 = 11.6$ for 9 d.o.f. which corresponds to an upper tail probability of 24%. Thus, the data are reasonably interpreted as consistent with A independent of P_T^2.

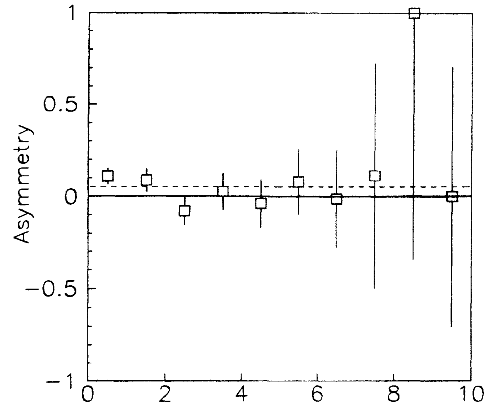

FIG. 2. E769 data for asymmetry versus P_T^2 including $D^\pm$ and $D^{*\pm}$ produced with π^- and π^+ beams. The data are consistent with a constant asymmetry of 0.054, shown as a dashed line in the figure.

Since A is large only for large x_F, it is of interest to establish the joint dependence of A on x_F and P_T^2. For $D^\pm$, we found that the shape of $d\sigma/dP_T^2$ for $x_F > 0.3$ is the same, within error, as that for $x_F > 0$, which falls rapidly with P_T^2 as we previously reported [4]. Thus, for $x_F > 0.3$, the large value of A is dominated by the cross section at low P_T^2; about 90% of the observed $D^\pm$ signal for $x_F > 0.3$ has $P_T^2 < 3$ GeV^2.

In conclusion, we find that the data from E769 strengthen the evidence for enhanced leading charm production with increasing x_F. The asymmetry increases from ~ 0 near $x_F = 0$ to ~ 0.5 at $x_F = 0.65$. This effect is now a firmly established behavior in which the production of particles containing heavy quarks is different from the perturbative prediction for the production of the quarks themselves. This effect may be explained by the fragmentation process or by production mechanisms in addition to the perturbative prediction.

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