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E791

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Asymmetries between the production of D^+ and D^- mesons from 500 GeV/c π^--nucleus interactions as a function of x_F and p_t^2

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Abstract

We present asymmetries between the production of D^+ and D^- mesons in Fermilab experiment E791 as a function of x_F and p_t^2. The data used here consist of 74,000 fully-reconstructed charmed mesons produced by a 500 GeV/c π^- beam on C and Pt foils. The measurements are compared to results of models which predict differences between the production of heavy-quark mesons that have a light quark in common with the beam (leading particles) and those that do not (non-leading particles). While the default models do not agree with our data, we can reach agreement with one of them, PYTHIA, by making a limited number of changes to parameters used.

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Among the least understood aspects of quantum chromodynamics (QCD) is fragmentation, the non-perturbative dressing of bare quarks into hadrons. Certain asymmetries in the production of particles and antiparticles are especially sensitive to fragmentation effects, while largely free of experimental bias in the measurement process. In this paper we present high statistics measurements of charmed particle asymmetries from π-nucleus interactions at experiment E791 at Fermilab.

Early studies of charm particle production [1–5] showed evidence of a large enhancement in the forward production of charmed particles that contain a quark or antiquark in common with the beam (leading particles) over those that do not (non-leading particles). Leading-order QCD calculations predict no asymmetry between quark and antiquark production. Several other models were developed to explain this effect [6,7], although none fully accounted for the difference in production between leading and non-leading particles. As sample sizes and signal-to-background ratios increased, experiments [8,9] with signals on the order of a thousand charmed mesons continued to find a forward production asymmetry, one much higher than predicted even by next-to-leading-order (NLO) QCD calculations which became available [10]. Now, we report results based on 74,000 fully reconstructed $D^{\pm}$ decays, enough to examine the asymmetry both as a function of Feynman-x ($x_F \equiv p_z/p_z^{max}$) and transverse momentum squared (p_t^2).

For a π^- beam, NLO QCD calculations predict a small enhancement in the number of $\bar{c}$ quarks over c quarks in the very forward direction. However, as has been previously shown [9], this does not fully account for the observed leading particle enhancement. We compare our results to two current models which predict a much larger enhancement than NLO QCD. We also report changes to parameter values within one of these models (PYTHIA) [11,12] that provide agreement with our data.

One possible explanation of the asymmetry is given by the beam-dragging model in which forward momentum is added to the produced heavy quark if it combines with a remnant light quark from the incoming beam particle, forming a leading particle. This causes leading charmed particles to have a harder x_F spec-

trum than non-leading particles. This feature is characteristic of the Lund string-fragmentation model which is the basis of the fragmentation simulation software JETSET used in PYTHIA.

A second class of models [13–15] postulates charm may be produced as virtual $c\bar{c}$ pairs in the beam particle in addition to being produced perturbatively. An example of the former process is the intrinsic charm model proposed by Vogt and Brodsky [13]. Here, the incoming π^- beam particle fluctuates into a $|\bar{u}dc\bar{c}\rangle$ Fock state. Since the virtual $c\bar{c}$ quarks have nearly the same velocity as the original $\bar{u}$ and d quarks in the pion, they are likely to coalesce with these remnant quarks, forming leading particles. Charmed quarks can also hadronize via fragmentation mechanisms which do not distinguish between leading and non-leading charm production. In reference [13] specifically, the fragmentation mechanism assumes that the momentum of the D meson is equal to the momentum of the c quark.

To quantify the difference in the production of leading and non-leading particles, an asymmetry parameter A is defined for each region of phase space:

$$A(x_F, p_t^2) \equiv \frac{\sigma_L - \sigma_{NL}}{\sigma_L + \sigma_{NL}}. \tag{1}$$

Here, $\sigma_L(\sigma_{NL})$ is the production cross section for the leading (non-leading) particle being studied. Experiments WA82 [8] and E769 [9] found large values of A ($\simeq 0.5$) for high values of x_F ($\simeq 0.6$).

For the $\pi^-(d\bar{u})$ beam in E791, the $D^0(c\bar{u})$ and $D^-(\bar{c}d)$ are leading charmed mesons. However, a large fraction of the D^0's are produced by the $D^{*+} \rightarrow D^0\pi^+$ decay process. The original D^{*+} is actually a *non*-leading particle. Therefore, the observed D^0's come from a mixture of leading and non-leading processes, making their study more complex. In order to minimize systematic errors, we restrict ourselves to studies of the asymmetries in the $D^\pm$ spectra.

The data were recorded from 500 GeV/c π^- interactions in five thin foils (one platinum, four diamond) separated by gaps of 1.34 to 1.39 cm. The E791 spectrometer is an upgraded version of the apparatus used in Fermilab experiments

E516, E691, and E769 [16]. Momentum analysis is provided by two dipole magnets which bend particles in the horizontal plane and 35 planes of drift chambers. Silicon microstrip detectors (6 in the beam, 17 downstream of the target) provide precision track and vertex reconstruction.

E791 recorded 2×10^{10} events with a loose transverse energy trigger. After reconstruction, events with evidence of multiple vertices are kept for further analysis. We search for $D^{\pm}$ mesons in the decay mode $D^{+}(D^{-}) \rightarrow K^{-}\pi^{+}\pi^{+}(K^{+}\pi^{-}\pi^{-})$. The selection criteria listed below are chosen to maximize $N_S/\sqrt{N_S + N_B}$ where N_S and N_B are the number of signal and background events.

To help ensure that the reconstructed secondary vertex is a true decay vertex, we require that it be separated from the primary vertex by at least 9.0 σ_l [17], where σ_l is our resolution on the separation, and separated from the nearest target foil by at least 0.75 σ_l [18]. In addition, we impose two requirements to ensure that the candidate decay tracks do not originate at the primary vertex. First, each of the three decay tracks must have an impact parameter with respect to the primary vertex greater than 5.5 σ_p, where σ_p is the resolution on the impact parameter [19]. Second, we form the ratio of each track's distance from the secondary vertex to that from the primary vertex and require the product of these three ratios to be less than 0.002. Another two requirements ensure that the reconstructed charged D is consistent with originating at the primary vertex. First, the impact parameter of the reconstructed D momentum vector with respect to the primary vertex must be less than 50 μm [20]. Second, the component of the reconstructed D momentum perpendicular to the $D^{\pm}$ line-of-flight (as determined from the primary and secondary vertex positions) must be less than 0.7 GeV/c. Finally, to help ensure that the three measured tracks come from the decay of a high mass particle, the sum of the squares of the tracks' momenta transverse to the direction of the reconstructed candidate momentum must be greater than 0.4 (GeV/c)^2. The resulting $K\pi\pi$ mass spectra are shown in Fig. 1 for D^{+} and D^{-} candidates.

The $K\pi\pi$ spectrum, in each region of phase space, was fit to a Gaussian curve

for the signal plus a linear distribution for the background. The number of D candidates is determined from the total area under the Gaussian curve. The width of the Gaussian was fixed for each region, with the evolution of the width as a function of x_F determined by Monte Carlo simulations. The systematic error in the number of mesons caused by the uncertainty in the width was estimated by increasing and decreasing the width by 10%, recalculating the yield each time. The resulting systematic uncertainties are small compared to the statistical uncertainties.

Detailed studies of our charged particle reconstruction using both data and Monte Carlo simulations show a small difference in reconstruction efficiency between positively and negatively charged particles due mainly to degradation over time of the wire tracking chambers in the vicinity of the incident beam. Because the negative beam particles are bent by the analysis magnets, the center of degradation was shifted slightly from the center of our detector. The effect on the measured values of A was determined using Monte Carlo simulations and is significant only in the high x_F region, increasing the value of A by ~ 0.15 in the highest bin. The systematic uncertainty caused by the efficiency correction was estimated by modeling the degradation of our chambers for four different time periods during our run, including periods near the beginning and the end of our data-taking. The rms spread of the asymmetries from the four different efficiency corrections was used to estimate the systematic uncertainties. These uncertainties are comparable to the uncertainties resulting from statistical errors.

Figure 2 shows the value of the asymmetry parameter calculated for different bins of x_F, compared to results from experiments E769 and WA82. The E791 error bars shown on all plots include both systematic errors (from the uncertainty on the mass resolution and from the uncertainty on the reconstruction efficiency) and statistical errors, added in quadrature. Our measured asymmetries are higher than in those two experiments, especially at low x_F, perhaps due to the different beam momenta (500 GeV/c for E791, 340 GeV/c for WA82 and 250 GeV/c for E769).

In Fig. 3 we compare our values of A to predictions based on two models for D

production previously discussed and to the prediction for charm quarks by NLO QCD. The results from the Lund string fragmentation model used in PYTHIA are shown in two different curves. The dashed line shows the prediction from the default PYTHIA and is significantly higher than our data for $-0.2 < x_F < 0.4$. This is due to the fact that PYTHIA predicts a higher overall production ratio of D^- to D^+ than is seen in data. We also explored a range of parameters to determine if our results could be accommodated within the PYTHIA model. A tuned PYTHIA prediction [21] that is consistent with our data is shown as the solid line in Fig. 3. This tuning included increasing the mass of the c quark (m_c) from 1.35 GeV/c^2 to 1.7 GeV/c^2 and increasing the average primordial k_t^2 of the partons from (0.44 GeV/c)^2 to (1.0 GeV/c)^2. This decreases the likelihood that the remnant d quark can combine with the $\bar{c}$ quark with a small enough invariant mass to collapse to a D^- meson. While this value of mean k_t^2 may seem unphysically high, similar values of k_t^2 are suggested by other observations from photo- and hadro-production charm experiments [22].

In Fig. 3 we also compare our results to a recent prediction involving intrinsic charm by Vogt and Brodsky, specifically calculated for a 500 GeV/c π^- beam [13,23]. Although the shape of the A vs x_F curve is similar to our data, the prediction is too low for all x_F. This model assumes equal numbers of D^- and D^+ mesons were produced, unlike the PYTHIA model, and changing this ratio may produce better agreement with data.

Figure 4 shows our data compared to the predictions for A from these same models versus p_t^2 for $-0.2 \leq x_F \leq 0.8$. Again, the default PYTHIA model predicts values which are too high for most points, while the tuned PYTHIA is in good agreement with our data. The intrinsic charm model of Vogt and Brodsky predicts values close to zero, indicative of the assumption that D^- and D^+ mesons are produced in equal numbers.

In the intrinsic charm model, coalescence occurs dominantly at low p_t^2 ($\sim m_c^2$) [13]. Thus, in the context of coalescence alone, A should be large at high x_F and low p_t^2, increasing as p_t^2 goes to zero. In order to address this issue, we show the

asymmetry as a function of p_t^2 for mesons with high x_F values ($0.4 \leq x_F \leq 0.8$) in Fig. 5. Here, the intrinsic charm model predicts values of A that are too low to match our data. However, we note that fragmentation mechanisms alternative to the one used in reference [13] can soften equally the x_F spectrum of both the leading and non-leading D's. This would emphasize the hardness of the x_F spectrum of leading D's produced by coalescence and thereby increase the predicted asymmetry at high x_F. Independent of this over all scale, the model predicts an increase in the value of A as p_t^2 goes to zero. Our data show no indication of this increase.

In summary, we see a substantial leading-particle effect at high x_F which cannot be accounted for using current perturbative QCD calculations. The beam-dragging model used in PYTHIA can account for the asymmetries between D^- and D^+ production if a limited number of changes are made to the parameters used in the model. Neither the default PYTHIA nor the intrinsic charm model is consistent with our data.

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[17] σ_l is calculated here by adding in quadrature the longitudinal uncertainty in the positions of the primary and secondary vertices. The primary vertex had a typical uncertainty of .035 cm. The secondary vertex had a typical uncertainty of .036 cm for a 70 GeV/c D and the uncertainty increased roughly linearly with a slope of 0.003 cm per 10 GeV/c.

[18] σ_l here depends only on the longitudinal uncertainty in the position of secondary vertices as the target foil edge is taken to be known with infinite precision.

[19] A typical value of σ_p is 0.0011 cm.

[20] The precise requirement we impose is: $d \leq (\Delta_l/\sigma_l)(0.002 \text{ cm})$, where d is the D impact parameter, Δ_l is the separation of the D vertex from the nearest target foil and σ_l is the resolution on the separation. In addition, the maximum allowed value for d is 0.005 cm.

[21] Specific parameters that we changed were `PMAS(4,1)` (the c quark mass in GeV/c^2) increased from `1.35` to `1.7`, `PARP(91)` (the average k_t^2 in (GeV/c)^2) increased from `0.44` to `1.0`, `PARP(93)` (the maximum allowable k_t in GeV/c) increased from `2.0` to `5.0`, and `MSTP(92)` (the remnant quark-diquark energy splitting function) changed from 4 to 3.

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FIGURES

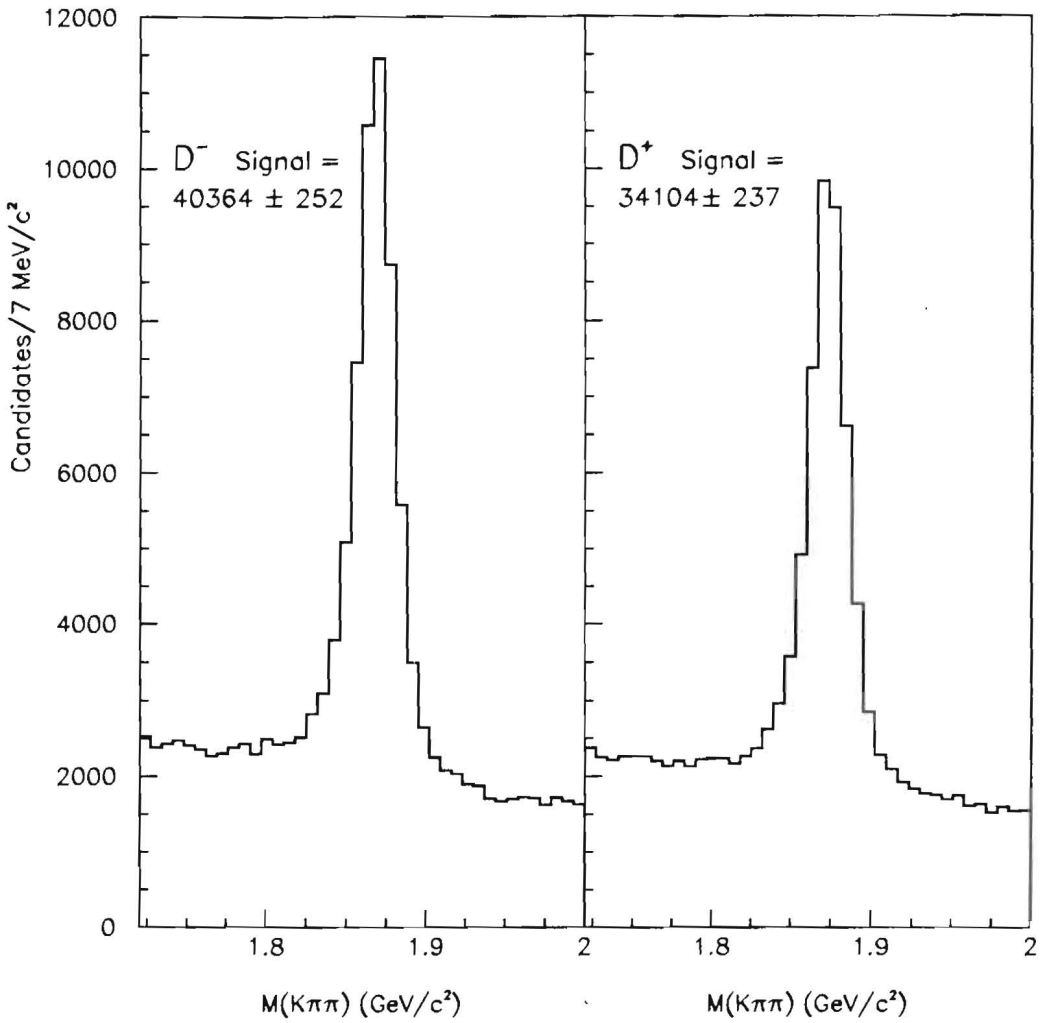

FIG. 1. $K\pi\pi$ mass distributions for D^+ and D^- candidates after all selection criteria are applied.

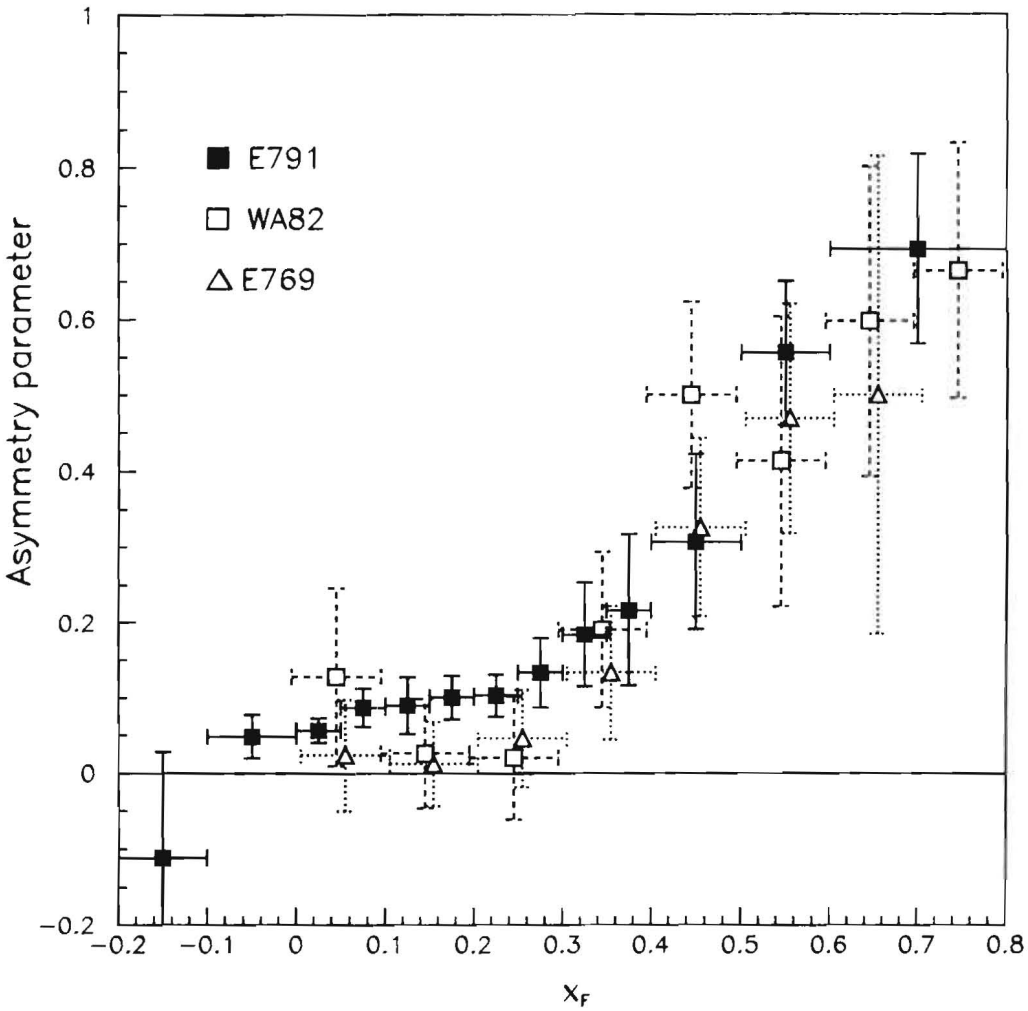

FIG. 2. The charged D production asymmetry A as a function of x_F. The E791 results are compared to previous results from WA82 [8] and E769 [9]. WA82 data are for $D^{\pm}$ from a 340 GeV/c π^- beam, E769 data are for $D^{\pm}$ and $D^{*\pm}$ from a 250 GeV/c $\pi^{\pm}$ beam, and E791 data are for $D^{\pm}$ from a 500 GeV/c π^- beam. E791 and E769 data are for mesons with p_t^2 less than 10 (GeV/c)^2.

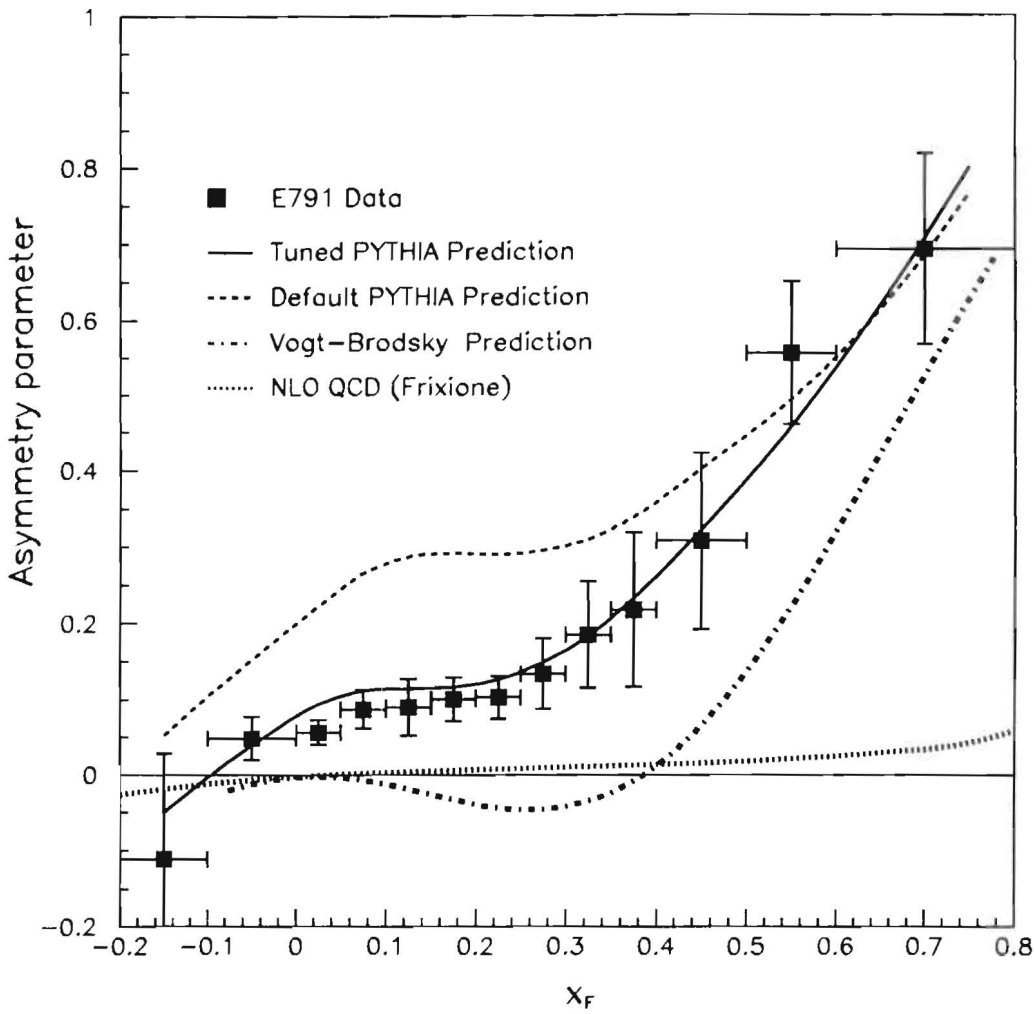

FIG. 3. The $D^{\pm}$ asymmetry A as a function of x_F for E791 data (points with error bars), for three models, and for NLO QCD. The tuned PYTHIA prediction [21] is from the default PYTHIA Monte Carlo software with the c quark mass increased to 1.7 GeV/c^2 and the average primordial k_t^2 of partons increased to (1.0 GeV/c)^2, as discussed in the text. The Vogt-Brodsky prediction is specifically calculated for the E791 beam momentum [23]. Both data and model predictions are for $D^{\pm}$ mesons with p_t^2 less than 10 (GeV/c)^2. The NLO QCD prediction is for charm quarks rather than D mesons [10].

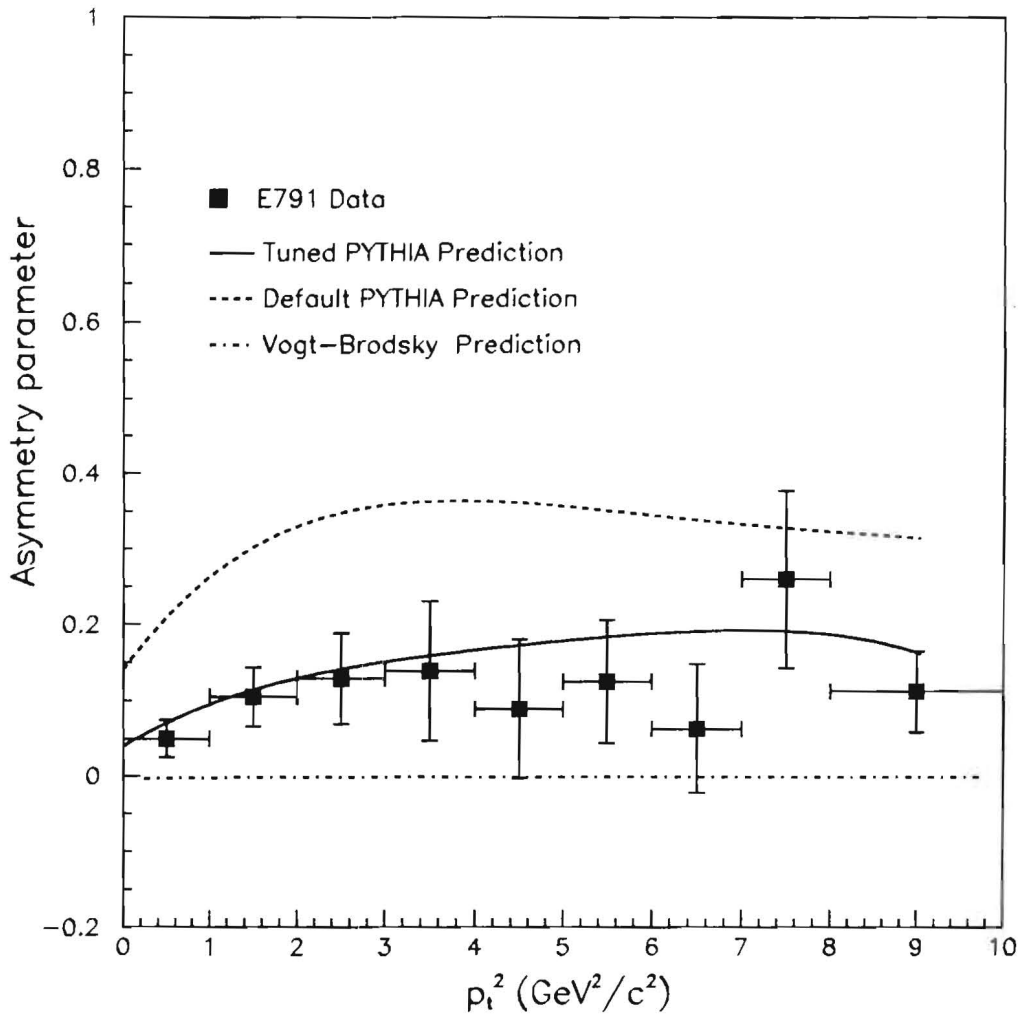

FIG. 4. The $D^{\pm}$ asymmetry A as a function of p_t^2 for our full range of x_F ($-0.2 \leq x_F \leq 0.8$). The data points correspond to the measured values. The curves represent theoretical predictions. The tuned PYTHIA prediction [21] is from the default PYTHIA Monte Carlo software with the c quark mass increased to 1.7 GeV/c^2 and the average primordial k_t^2 of partons increased to (1.0 GeV/c)^2 as discussed in the text. The intrinsic charm prediction is specifically calculated for the E791 beam momentum [23].

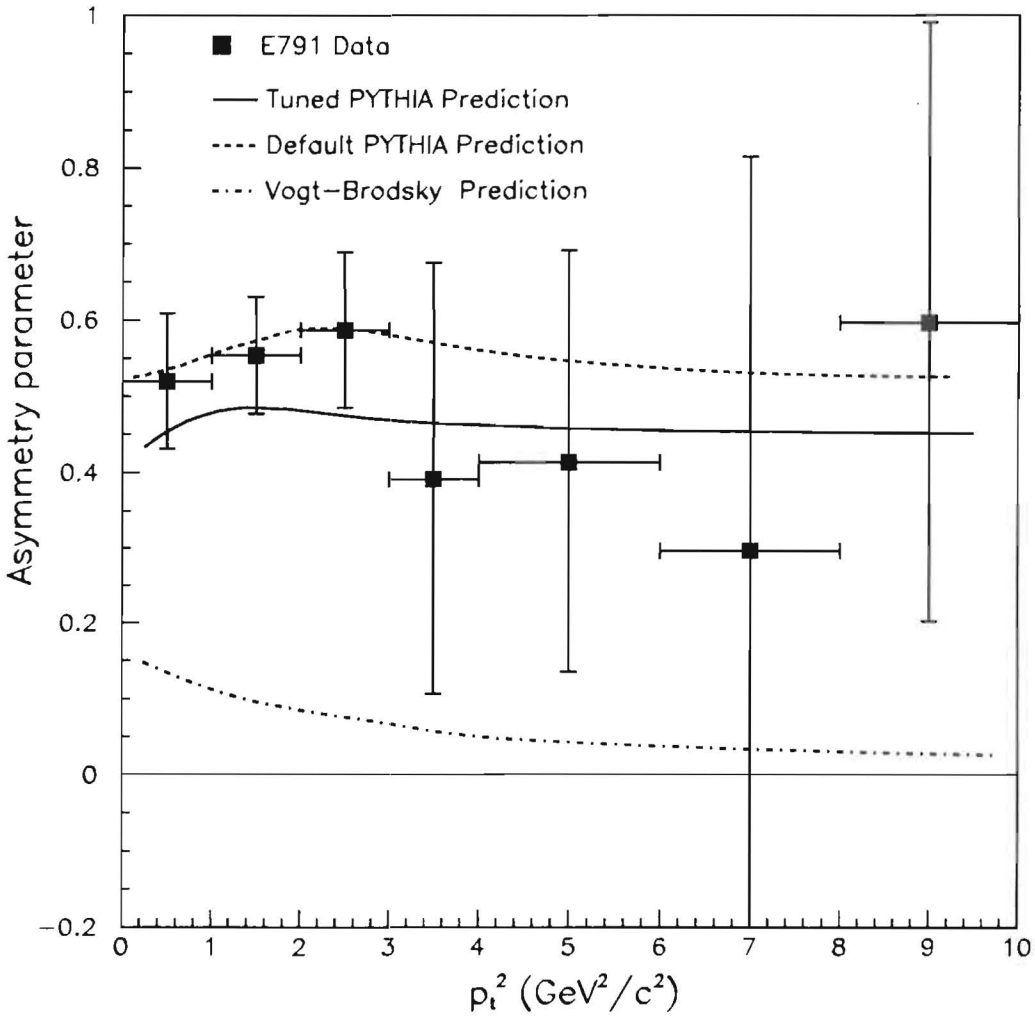

FIG. 5. The $D^{\pm}$ asymmetry A as a function of p_t^2 for high values of x_F ($0.4 \leq x_F \leq 0.8$). The data points correspond to the measured values. The curves represent theoretical predictions. The rise in A at low values of p_t^2 predicted by the Vogt-Brodsky model is a key feature which is not reproduced by our data.