E791 Results on Hadroproduction of Charm from 500 GeV π^-–N Interactions

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Abstract. E791 took data with a 500 GeV π^- beam on a nuclear target during the 1991 Fermilab fixed-target run. We present a sample of charm production results from these data. We measure production asymmetries of $D^{\pm}$ and $D_s^{\pm}$ mesons, Λ_c baryons and the Λ, Ξ, and Ω hyperons. These asymmetries provide insight into the fragmentation process. We also present results from the E791 analysis of events with two fully reconstructed D mesons. By looking at correlations between charm and anticharm particles in the same event, we learn about the charm quark production mechanism as well as the hadronization process. Finally we present new results on D^0 distributions versus x_F and p_T^2 from approximately 100,000 $D^0 \to K\pi, K\pi\pi\pi$ decays.

INTRODUCTION

Hadroproduction of charm is factorizable into three parts as shown in Fig. 1. The first part is composed of the parton distribution functions (PDF's) which provide information about the flavor and momentum content of the partons. Specifically, $f_i^A(x_A, Q^2)$ is the probability of finding parton type i inside hadron A with momentum fraction x_A. These PDF's are generally derived from deep inelastic scattering data and prompt photon or lepton data. The interaction of parton i and parton j to produce a charm quark with four-momentum p_c is governed by the short distance (high Q^2) QCD interaction $\hat{\sigma}_{ij}(p_c, Q^2)$. Since this interaction takes place at a scale on the order of the charm quark mass ($\sim$1.5 GeV) which is above the QCD scale $\Lambda_{QCD} \sim 0.3$ GeV, this process should be calculable by perturbative QCD but perhaps not too reliably since 1.5 GeV $\not\gg$ 0.3 GeV. The third and final part of the production involves the fragmentation of the charm quarks into charm hadrons. This occurs at the QCD scale and is therefore incalculable by perturbative QCD. In addition, since the charm quarks are tied by color strings to the remnants of the beam and target hadrons, the simple Peterson fragmentation prescription is not expected to work well. A more involved fragmentation scheme such as the Lund string fragmentation model may be able to model these effects.

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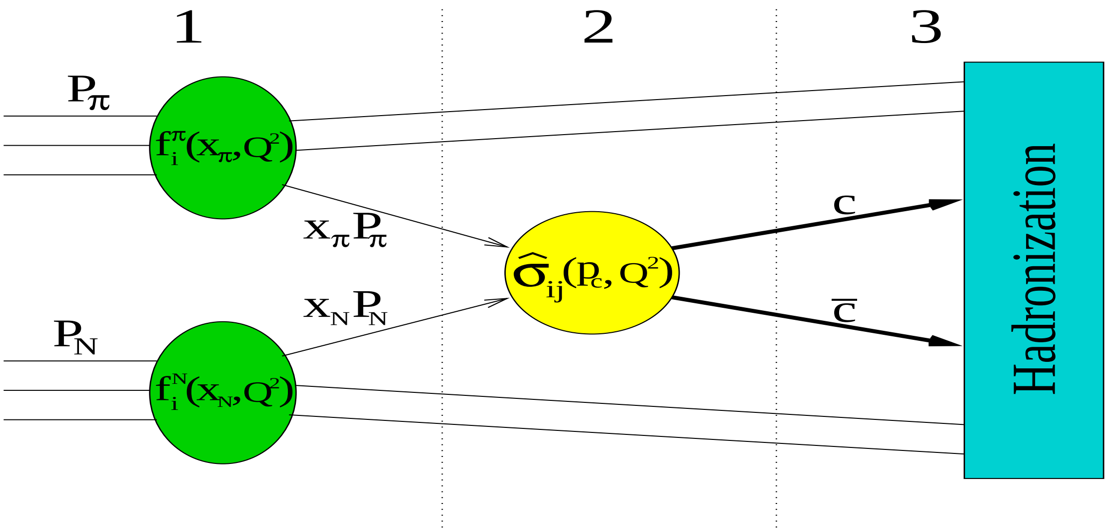

FIGURE 1. A schematic view of charm production from π^--N interactions.

By measuring various charm production properties we hope to arrive at a coherent picture of charm production and perhaps test QCD or, at least our knowledge of QCD. The goal of the E791 experiment was a high precision measurement of production and decay properties of charm particles. The E791 experiment was built upon the previous Tagged Photon Laboratory (TPL) experiments, E516, E691, and E769. The 500 GeV π^- beam was tracked with 8 planes of PWC's and 6 planes of silicon strip detectors and impinged on one platinum and four diamond targets. The downstream spectrometer, depicted in Fig 2, consisted of 17 planes of silicon strip detectors for vertexing and tracking along with 35 planes of drift chambers, 2 PWC planes and 2 analysis magnets for tracking and momentum measurement. Two threshold Čerenkov counters, an electromagnetic calorimeter, a hadronic calorimeter, and a muon wall provided particle identification. The trigger required a beam particle, a hadronic interaction, and a loose transverse energy requirement. The E791 experiment wrote 2×10^{10} events to 24,000 8 mm tapes during the 1991 fixed-target run. From this data set we have fully reconstructed more than 200,000 charm decays.

ASYMMETRIES

The asymmetries measured here are the production asymmetries of a particle versus its antiparticle as a function of some kinematic variables. Specifically, we measure $A \equiv \frac{\sigma_X - \sigma_{\overline{X}}}{\sigma_X + \sigma_{\overline{X}}}$ vs p_T^2 and $x_F \equiv \frac{p_L^*}{p_{L_{max}}^*}$. These asymmetries are quite interesting because they are expected to be nearly zero for charm quark production. Therefore, even the existence of an asymmetry gives information about the hadronization process, which is further elucidated by measuring the magnitude and kinematic dependence of the effect.

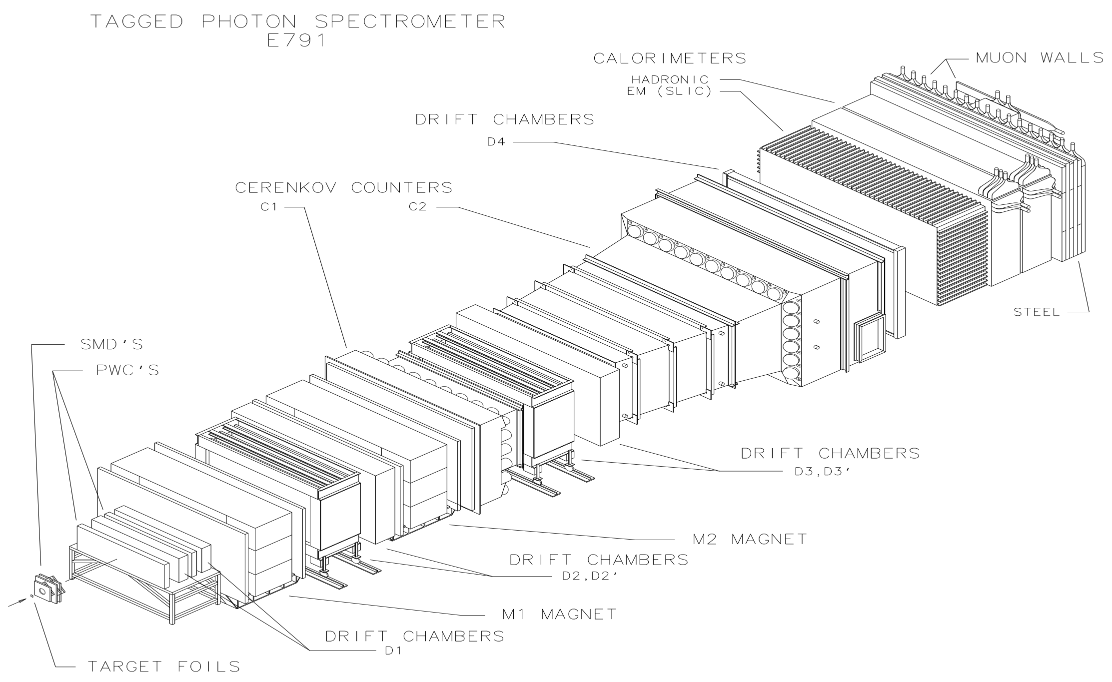

FIGURE 2. The E791 spectrometer.

A potential source of asymmetries comes from the fragmentation of the string between the charm quark and the beam/target fragments. As shown in Fig. 3, a $D^-(\bar{c}d)$ meson which has a d quark in common with the $\pi^-(\bar{u}d)$ beam can be formed from a coalescence of the π^- d quark and the $\bar{c}$ quark. Since the $D^+(c\bar{d})$ does not contain a quark in common with the beam, it cannot be produced the same way. Therefore, we might expect an excess of D^- mesons to D^+ mesons, especially at high x_F. This "leading particle effect" is clearly seen in the E791 data, as shown in Fig. 4 and reported in Ref. [1]. While the default version of Pythia predicts too much coalescence at low x_F, a modified ("tuned") version of Pythia provides

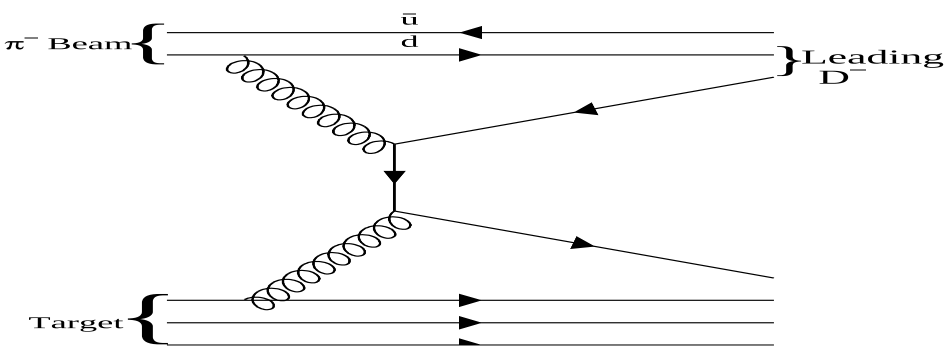

FIGURE 3. Coalescence of a valence d quark from the pion with the produced $\bar{c}$ quark leads to a high momentum $D^-(\bar{c}d)$.

good agreement with the data. The modifications to Pythia included increasing the average intrinsic k_t of the partons from 0.44 GeV/c to 1.00 GeV/c and increasing the charm quark mass from 1.35 GeV/c^2 to 1.70 GeV/c^2. This modified version of Pythia also appears to give the correct result for the p_T^2 asymmetry.

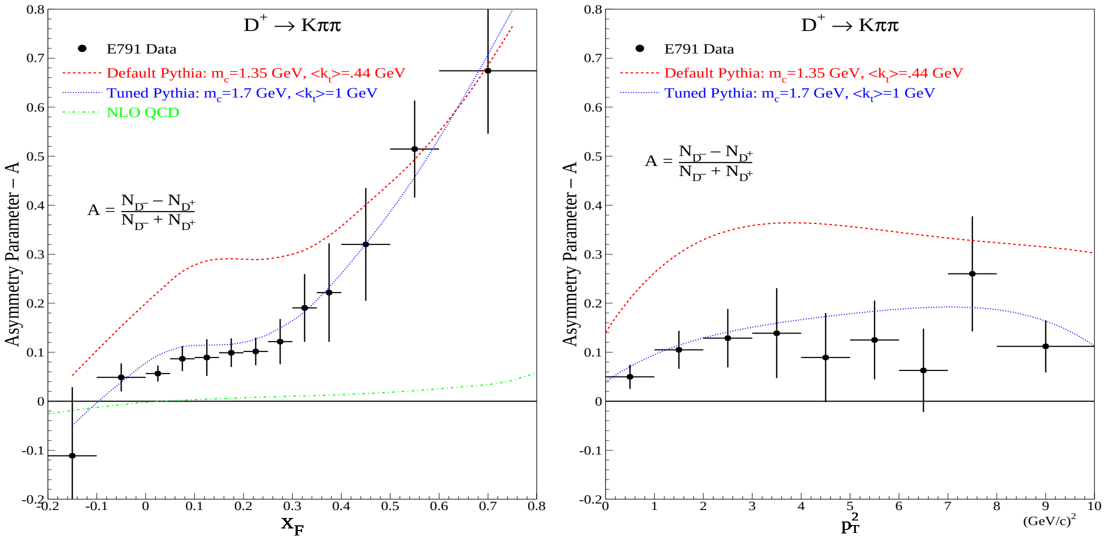

FIGURE 4. $D^{\pm}$ asymmetry versus x_F and p_T^2 compared to the default and "tuned" Pythia predictions as well as the next-to-leading order $c\bar{c}$ prediction.

Neither charge state of the $D_s(c\bar{s})$ meson has a quark in common with the beam or target hadrons. Therefore, we expect a flat, approximately zero, asymmetry. The data are consistent with this prediction as well as with the slight asymmetry predicted by the default Pythia program as seen in Fig. 5 and reported in Ref. [2].

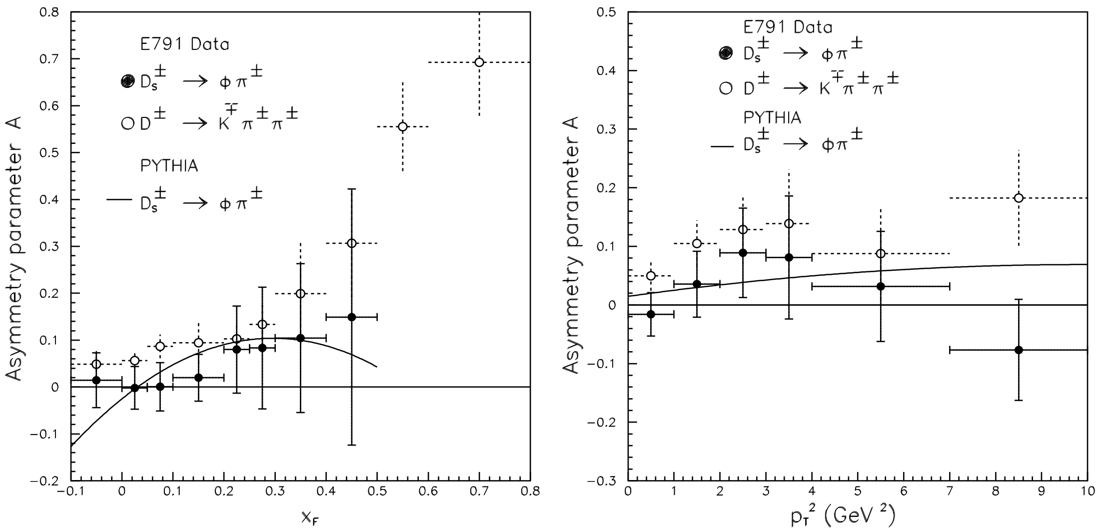

FIGURE 5. $D_s^{\pm}$ asymmetry versus x_F and p_T^2 compared to the default Pythia prediction.

Unlike the $D^{\pm}$ meson, the $\Lambda_c^{\pm}$ asymmetry is expected to be dominated by target, rather than beam, dragging. That is, the $\Lambda_c^+(udc)$ can come from a coalescence of a nucleon ud diquark and a c quark. This would give an increase in asymmetry as x_F decreases. The data shown in Fig. 6 are consistent with an increase at $x_F<0$, as predicted by the default Pythia program, and also consistent with a flat asymmetry. Clearly, more data are needed to determine the extent of the asymmetry.

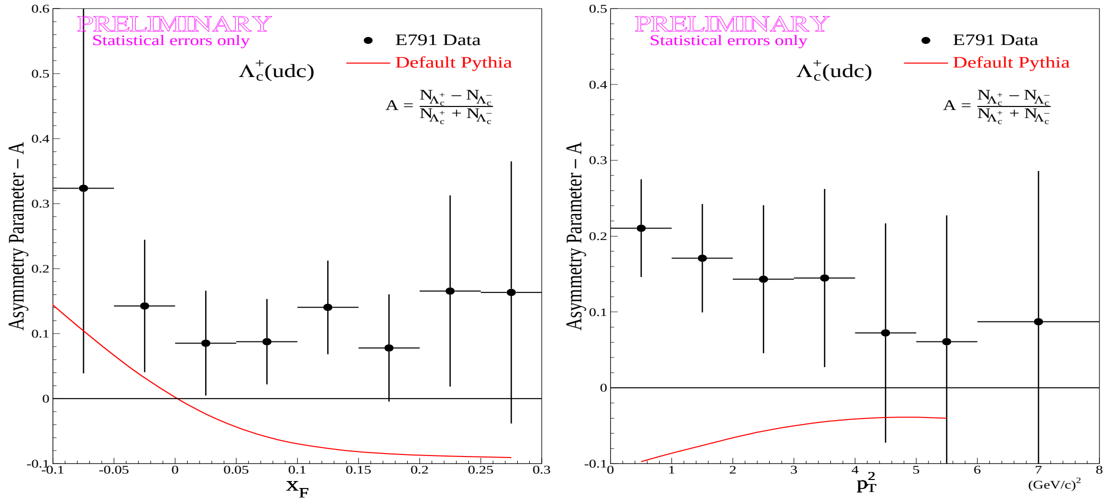

FIGURE 6. $\Lambda_c^{\pm}$ asymmetry versus x_F and p_T^2compared to the default Pythia prediction.

To look for this target dragging effect with higher statistics we can measure the asymmetry for the Λ, Ξ, and Ω hyperons. As seen in Fig. 7, the magnitude of the asymmetry at negative x_F clearly increases with the number of non-strange quarks in the produced baryon, that is, the number of quarks the hyperon has in common with the target nucleons. In addition, the Ξ asymmetry increases at positive x_F relative to the Λ asymmetry; perhaps due to dragging by the $\pi^-(\bar{u}d)$ beam.

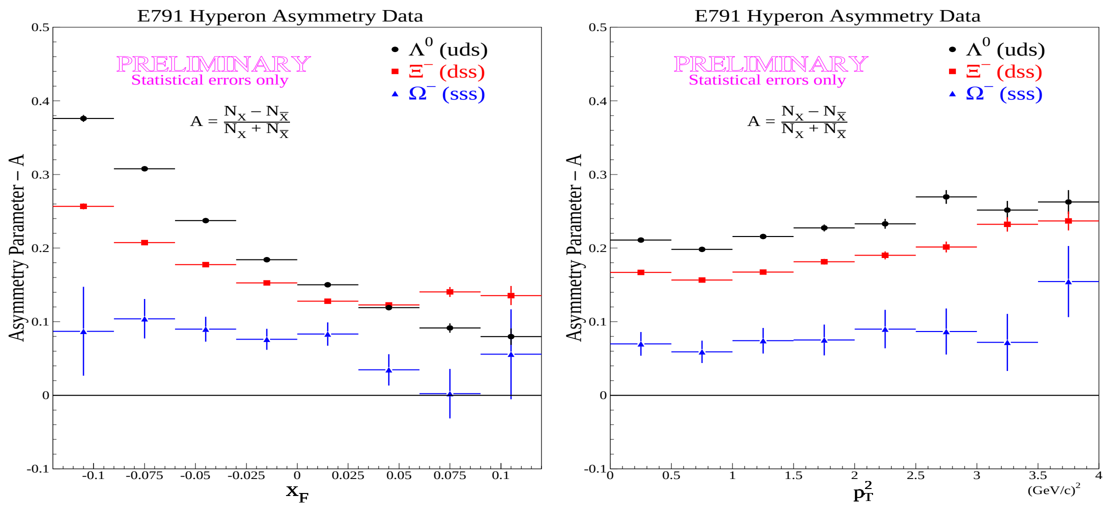

FIGURE 7. Hyperon asymmetry versus x_F and p_T^2.

CHARM-PAIR CORRELATIONS

Charm-pair correlations allow one to measure aspects of the charm quark production as well as the hadronization. The correlations are obtained from events in which both the charm and anticharm particles are reconstructed. We can construct transverse correlations such as $\Delta\phi$, $\Delta p_t^2 \equiv |p_{t,D}^2 - p_{t,\overline{D}}^2|$, and $p_{t,D\overline{D}}^2 \equiv |\vec{p}_{t,D} + \vec{p}_{t,\overline{D}}|^2$. These correlations are sensitive to the charm quark production mechanism and relatively insensitive to hadronization effects. The longitudinal correlations such as Δx_F are quite sensitive to hadronization effects and less so to the charm quark production.

The E791 analysis finds 791±44 fully reconstructed charm-pair events which, as shown in Table 1, is an order of magnitude more than any other hadroproduction experiment . The scatter plot of events as well as the function used to fit the data are shown in Fig. 8.

TABLE 1. Summary of fully-reconstructed and partially-reconstructed charm-pair samples from hadroproduction and photoproduction fixed-target experiments.

Expt	Energy	Beam	Target	Number of Pairs			
E791 [3]	500 GeV	π^-	Pt, C	791	fully		
NA27 [12]	360 GeV	π^-	H_2	12	fully	53	partially
WA92 [7]	350 GeV	π^-	Cu			475	partially
WA75 [8]	350 GeV	π^-	emulsion			177	partially
NA32 [9] [10]	230 GeV	π^-	Cu	20	fully	642	partially
E653 [11]	800 GeV	p	emulsion			35	partially
NA27 [6]	400 GeV	p	H_2	17	fully	107	partially
E687 [13]	200 GeV	γ	Be	325	fully	4534	partially
NA14 [14]	100 GeV	γ	Si	22	fully		

We compare the data to results from a next-to-leading order (NLO) calculation by Mangano, Nason, and Ridolfi (MNR) [4] and Pythia [5] using the default parameters for both. Some of the results are shown in Fig. 9; full details can be found in Ref. [3]. In leading order perturbative QCD, $\Delta\phi$ is predicted to be a delta function at 180°. While NLO terms smear the distribution, it is clear this is not enough to agree with the data. Adding intrinsic k_t to the NLO prediction helps improve agreement. While Pythia only uses leading order matrix elements in the cross section calculation, the intrinsic k_t and parton showers smear the $\Delta\phi$ distribution even more than the NLO prediction, although still not enough to account for the data. The $p_{t,D\overline{D}}^2$ distributions show similar discrepancies between theory and data. The Δp_t^2 distributions, however, are consistent between data and theory. For all three transverse variables shown, the Pythia hadronization has little effect. For the longitudinal correlations, however, this is not the case. The Δx_F distributions are approximately the same between the two $c\overline{c}$ predictions and come close to matching the data. After hadronization, however, the agreement is much

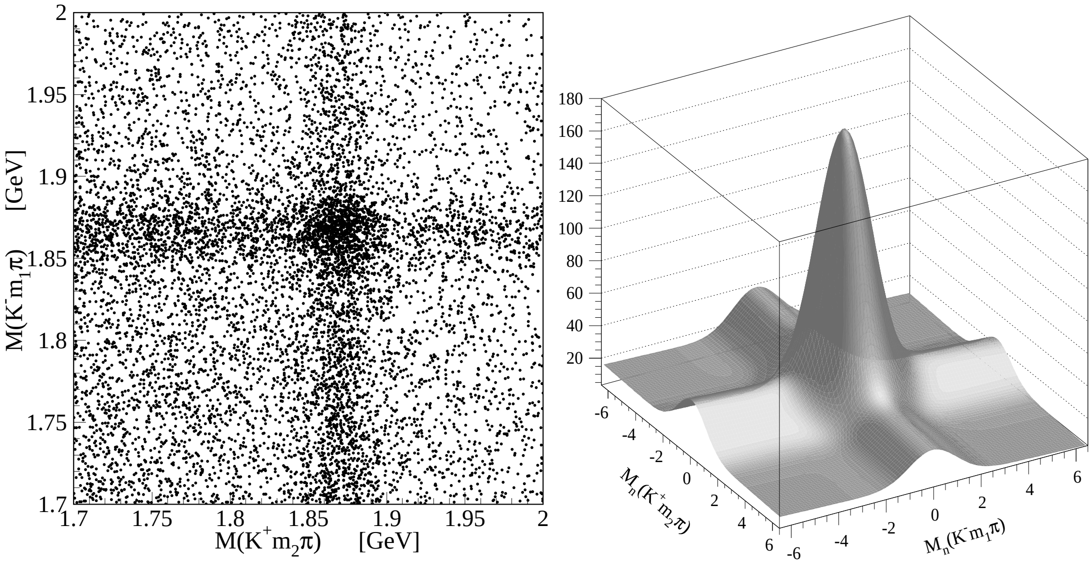

FIGURE 8. Scatter plot of the D-candidate mass versus the $\overline{D}$-candidate mass for the final unweighted charm-pair sample (left) and the function that maximizes the joint probability of the unweighted charm-pair candidates (right).

worse. The beam/target dragging in Pythia pulls the D mesons too far apart, creating the disagreement. Therefore, while we need the hadronization to explain the asymmetry data, it creates discrepancies in the longitudinal correlations of the charm and anticharm particles.

DIFFERENTIAL CROSS SECTIONS

The differential cross sections are cross sections measured as a function of kinematic variables such as x_F and p_T^2. The shapes of these distributions are sensitive to both the charm quark production and the subsequent hadronization. Figure 10 shows preliminary results for x_F and p_T^2 distributions from $\sim$100,000 $D^0 \to K\pi, K\pi\pi\pi$ events. The high statistics from this open geometry experiment clearly shows the x_F turnover point is above zero. This is expected since the pion partons are generally harder than the nucleon partons and therefore the parton center-of-mass is boosted forward relative to the hadron center-of-mass (where x_F is measured). The high statistics also allow a good p_T^2 measurement out to 18 $(\mathrm{GeV/c})^2$. A comparison to predictions from the MNR [4] NLO calculation for charm quarks and a Pythia prediction for D^0 mesons is also shown in Fig. 10. The default parameters are used for both and the normalization adjusted to provide the best fit to the data. For the x_F and p_T^2 distributions, the NLO charm quark prediction is much closer to the data than the Pythia D^0 meson prediction. This implies a cancelation of non-perturbative effects such as intrinsic k_t and fragmentation. Fragmentation will soften the p_T^2 spectrum while intrinsic k_t will counter

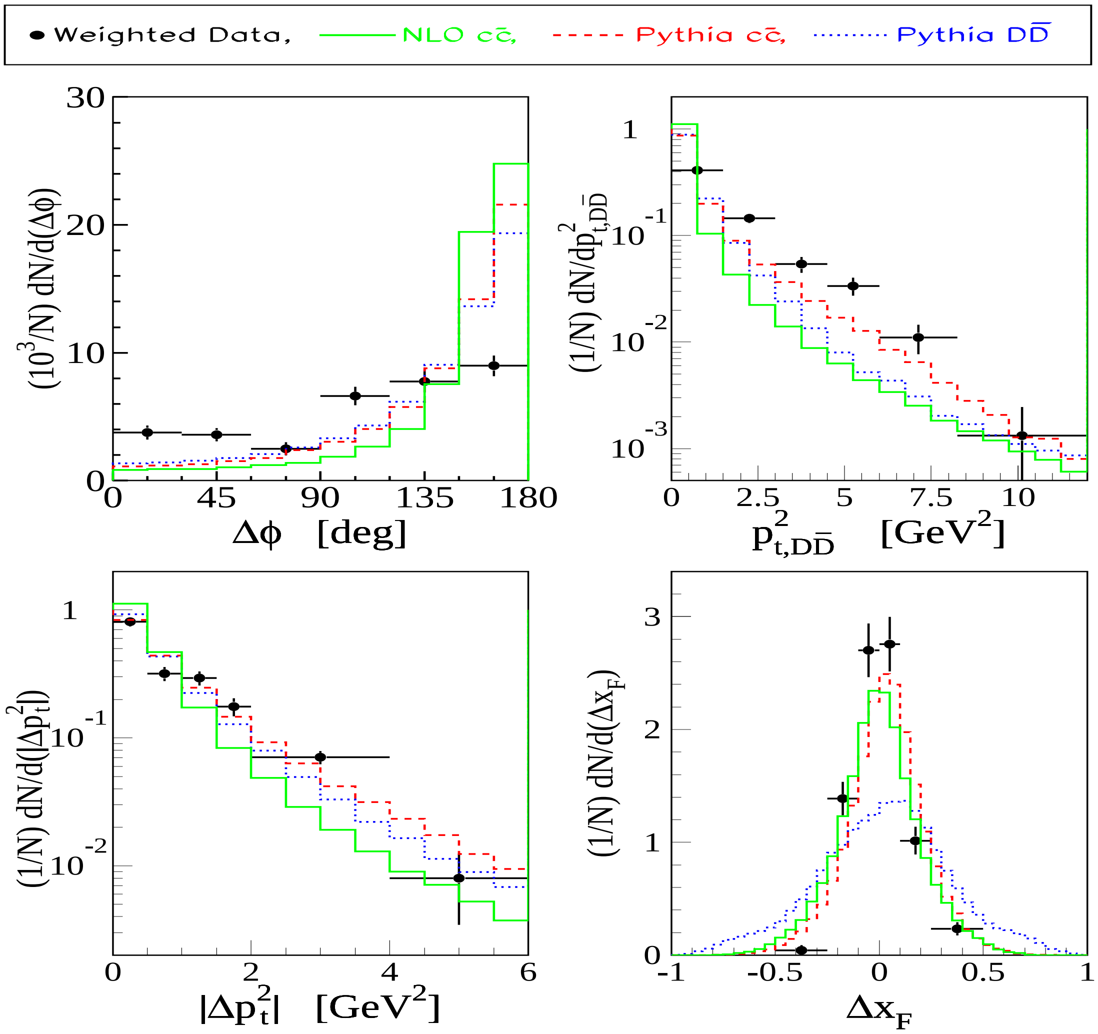

FIGURE 9. Charm-pair correlation results versus theoretical predictions from next-to-leading order $c\bar{c}$ calculations, Pythia $c\bar{c}$ results, and Pythia $D\overline{D}$ results.

that trend. Pythia hadronization appears to soften the p_T^2 spectrum too much. In addition, the excess of events in the Pythia x_F spectrum at $x_F > 0.2$ is probably due to too much beam dragging as has been seen in the $D^{\pm}$ asymmetry and charm-pairs Δx_F data.

CONCLUSIONS

E791 has provided, and will continue to provide, many results on charm hadroproduction. Large theoretical uncertainties imply that no single result, or even single experiment, can uniquely determine the physics of charm production. A synthesis of the results from E791 and other experiments may give a coherent picture.

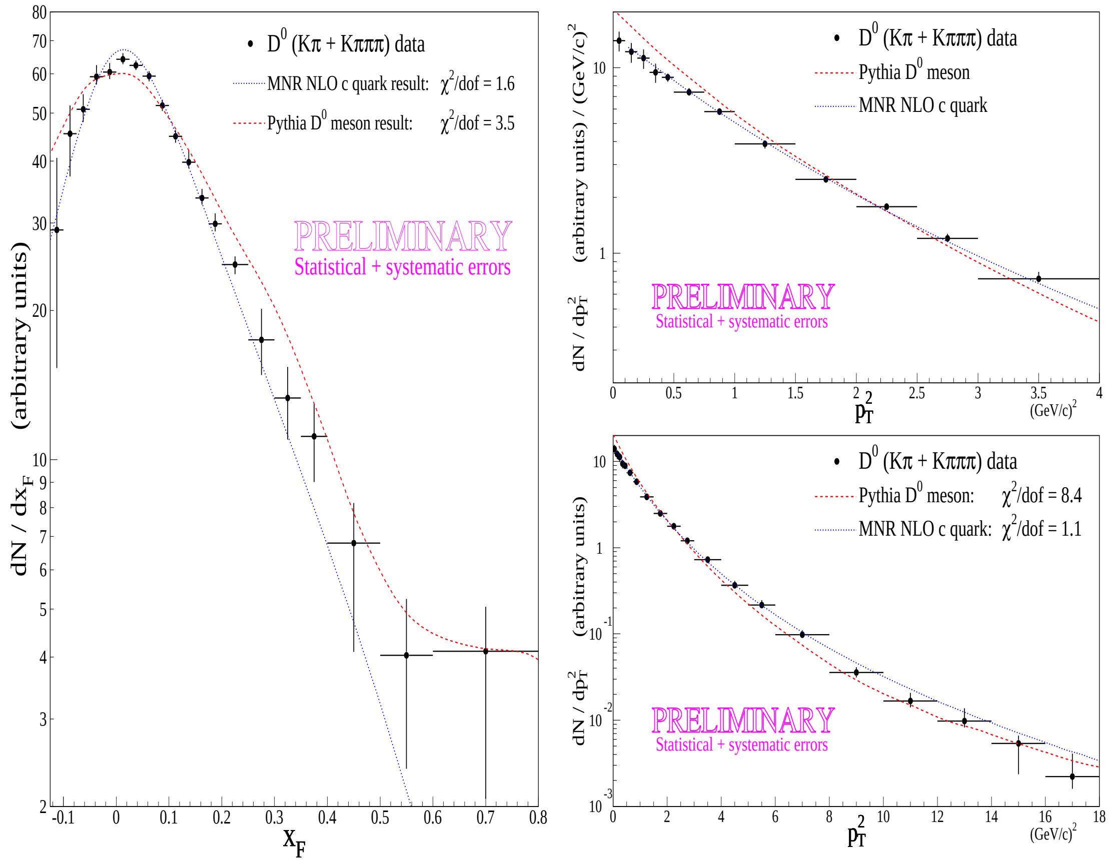

FIGURE 10. D^0 x_F and p_T^2 distributions compared to NLO c quark and Pythia D^0 predictions.

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