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CHARM PRODUCTION ASYMMETRIES AT FERMILAB EXPERIMENTS

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ABSTRACT

I present asymmetries between the production of charm particles and anti-particles from Fermilab experiments, E687, E769 and E791. The results are shown as a function of x_F and p_t^2 for $D^{\pm}$ and $D_s^{\pm}$ mesons and for pion, kaon and photon beams and compared against current models. Results are also shown for a recent analysis of correlations between production of charm mesons and an associated pion.

1 Introduction

Fragmentation, the non-perturbative dressing of bare quarks into hadrons, is among the least understood aspects of quantum chromodynamics (QCD). While the results of the fragmentation process can not be predicted directly from perturbative QCD calculations, we can gain information on this process by looking at certain asymmetries in the production of particles and antiparticles. Along with being sensitive to fragmentation effects, these asymmetries can be largely free of experimental bias in the measurement process.

Early studies of charm particles showed evidence of a difference in particle and anti-particle production, even though no significant amount was predicted by next-to-leading-order (NLO) QCD calculations. Several models have been proposed to account for this difference, but until recently experiments have been limited by statistics. In this talk, I will present recent results on these asymmetries from three high-statistics Fermilab fixed target experiments, E687, E769 and E791 and so hope to provide a unique view into this interesting process.

2 Asymmetries from a charged beam

2.1 $D^{\pm}$

One form of production asymmetries is referred to as the leading-particle-effect where there is an enhancement of the forward production of charmed particles that contain a quark or anti-quark in common with the beam (leading particles) over those that do not (non-leading particles). Experiment E791 at Fermilab studied this effect using a 500 GeV/c π^- beam at the Tagged Particle Laboratory (TPL) [1]. In the case of E791's $\pi^-(d\bar{u})$ beam, the $D^-(d\bar{c})$ is leading and the $D^+(\bar{d}c)$ is non-leading.

A possible explanation of this asymmetry is given by the beam-dragging model in which forward momentum is added to the produced heavy quark if it combines with a remanent light quark from the incoming beam particle, forming a leading particle. This causes leading charmed particles to have a harder x_F spectrum 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 [2, 3].

A second class of models [4, 5, 6] 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 [4]. 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 remanent quarks, forming leading particles.

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:

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

Here, $\sigma_L(\sigma_{NL})$ is the production cross section for the leading (non-leading) particle being studied.

Figure 1(a) shows the E791 values of A compared to predictions based on

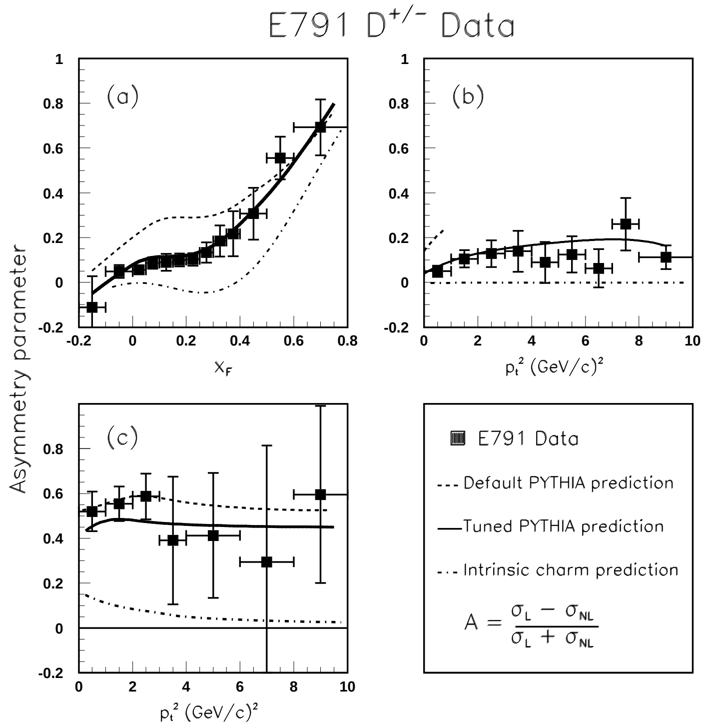

Figure 1: The $D^{\pm}$ asymmetry A for E791 data (points with error bars) and for three models. Figures (a) and (b) show A as a function of x_F and p_t^2 respectively with x_F between -0.2 and 0.8 and p_t^2 less than 10 $(\mathrm{GeV}/c)^2$. Figure (c) shows A as a function of p_t^2 for the high x_F region between 0.4 and 0.8. The tuned PYTHIA prediction [7] 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 $(1.0\ \mathrm{GeV}/c)^2$, 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 x_F between -0.2 and 0.8 and p_t^2 less than 10 $(\mathrm{GeV}/c)^2$.

two models as a function of x_F. 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 [7] that is consistent with our data is shown as the solid line in Fig. 1. 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 $(0.44\ \mathrm{GeV}/c)^2$ to $(1.0\ \mathrm{GeV}/c)^2$. This decreases the likelihood that the remanent 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 [8].

Figure 1(a) also compares E791 results to a recent prediction involving intrinsic charm by Vogt and Brodsky, specifically calculated for a 500 GeV/c π^- beam [4, 9]. 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 1(b) shows E791 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 ($\sim m_c^2$) [4]. 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. E791 shows 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. 1(c). Here, the intrinsic charm model predicts values of A that are too low to match the data. This is due to fragmentation assumptions used in the calculations which are not key to the intrinsic charm model. However, independent of this overall scale, the model predicts an increase in the value of A as p_t^2 goes to zero. E791 data show no indication of this increase.

2.2 Other Particles

$D^\pm$ are the most copiously produced mesons for which the leading and non-leading states can be studied without contamination of daughter particles from excited states. The current generation of higher statistics heavy quark experiments allows us to study this subject using other more rarely produced particles. Experiment E791 has also recently completed analysis of production asymmetries in $D_s^\pm$ mesons. Here, neither the $D_s^+(\bar{s}c)$ nor the $D_s^-(s\bar{c})$ have a quark in common with the incident $\pi-(d\bar{u})$. This would suggest that little or no asymmetry could exist between the two D_s mesons.

E791 produced a sample of 2447 mesons in the decay modes of $D_s \rightarrow \phi\pi$

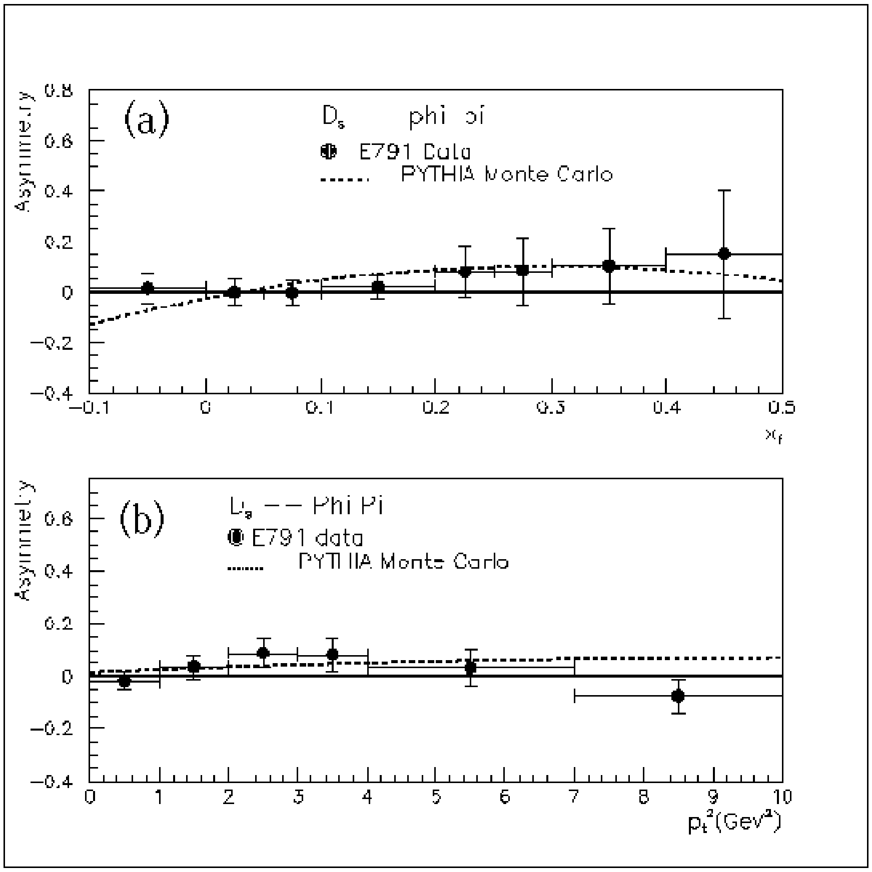

Figure 2: The $D_s^{\pm}$ asymmetry A for E791 data and for a tuned PYTHIA prediction [7]. E791 data has been corrected for acceptance.

with x_F in the range of -0.1 and 0.5 and p_t^2 less than 10.0GeV/c [10]. The asymmetry was quantified using eq(1) above with the D_s^- being arbitrarily tagged as the leading particle and the D_s^+ as non-leading. Figure 2(a) shows A as a function of x_F. A integrated over all x_F is consistent with zero, $0.006 \pm 0.025 \pm 0.002$ after a small correction for acceptance. Also shown on this plot is the prediction for PYTHIA tuned as described above. Figure 2(b) shows A as a function of p_t^2 plotted along with the prediction from the tuned PYTHIA.

In contrast to the pion beam of E791 where the D_s has no quarks in common with the incoming particle, Fermilab experiment E769 used 250 GeV/c $K+$ and $K-$ beams [11]. Here, the s quark or anti-quark in the incoming beam is in common with the strange quark or antiquark contained in the D_s. Table 1 shows E769 value for A for D_s and several other particles. While they are limited by statistics (100 D_s), the integrated value of A for $x_F > 0$ is larger than that seen by E791.

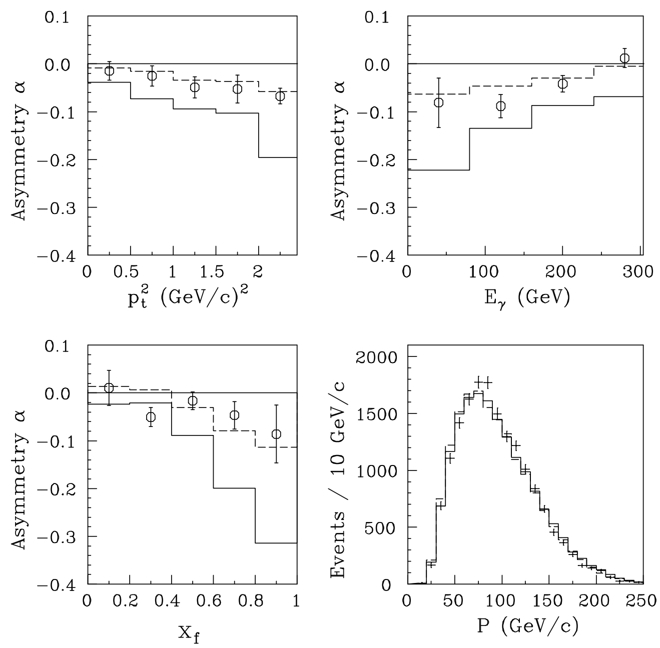

Figure 3: Kinematic variations of the production asymmetry α as a function of transverse momentum p_t^2), beam energy (E_γ) and Feynman x (x_F) for the decay mode $D^+ \to K^-\pi^+\pi^+$ from Fermilab experiment E687 (points with errors bars) and two Monte Carlo predictions discussed in the text (solid lines from Model 1, dashed line from Model 2). The lower right figure compares the predictions of the two models for D^+ momentum (P) to their data.

3 Asymmetries from photon beam

Asymmetries also occur in cases where there are no quarks in the incoming beam. Fermilab experiment E687 [12)] used a photon beam with an average $E \simeq 200$GeV to study the differences in production for charged D mesons and several other particles.

3.1 Inclusive Production

With a photon beam there are no quarks in the incoming beam; the difference in the fragmentation of particles and anti-particles comes from effects of the target.

As with the case of the π beam, the string model used in the LUND Monte Carlo software can provide an explanation of the asymmetries from the photon beam. The dominant process for the production of charm in this case is photon-gluon fusion. The emission of the struck gluon leaves the remanent quarks of the nucleon in a non-color-neutral state. In the LUND model, the quarks divide into

Table 1: Leading-particle asymmetries from Fermilab Experiment E769 (A, defined in text). Inequalities are given for 90% confidence level lower limits.

Beam	Particle	A
K	D_s	0.25 ± 0.11
	Λ_c	> 0.6
p	D^+	0.18 ± 0.05
	D^0	0.06 ± 0.06
	D^{*+}	0.36 ± 0.13
	Λ_c	> 0.6

a diquark pair and a single bachelor quark. During the fragmentation process, the model represents the color field as strings of uniform energy per unit length attaching the heavy quarks to the remanent quarks from the nucleon. Color restrictions require the $\bar{c}$ quark to be attached initially to the single bachelor quark while the c will be attached to the diquark pair. While the strings may break to form $q\bar{q}$ pairs, in some cases the heavy quarks may form a meson or baryon final state with these remanent quarks. As the remanent quarks are moving backwards in the center-of-mass frame, the LUND model predicts mesons containing the $\bar{c}$ quark will be produced in a less forward direction that those containing the c.

E687 compared their data to predictions of this model in detail. They found the asymmetries generated to be extremely sensitive to the kinematic region probed and to the assumed distribution for that fraction χ of the nucleon momentum carried by the bachelor quark [12]. They specifically compared their data to two different distributions for this fraction. "Model 1" is the default PYTHIA model which has the χ distribution sharply peaked towards small values,

$$\frac{dN}{d\chi} \sim \frac{(1-\chi)^3}{\chi}$$

. "Model 2" gives a greater fraction of the momentum to the bachelor quarks,

$$\frac{dN}{d\chi} \sim 2(1-\chi)$$

E687 expressed the difference production for each region of a variable by calculating [1]

$$\alpha \equiv \frac{N_c - N_{\bar{c}}}{N_c + N_{\bar{c}}}. \tag{2}$$

[1] Note that for $D^{\pm}$ mesons, this is the reserve of the definition of A used by E791 and E769

Table 2: Production asymmetry α (%) from Fermilab experiment E687 compared to two Monte Carlo predictions based on the Lund model.

Decay mode	E687 (This exp.)	Model 1	Model 2
$D^+ \to K^-\pi^+\pi^+$	-3.8 ± 0.9	-10.4 ± 0.4	-2.9 ± 0.3
$D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$	-6.4 ± 1.5	-9.2 ± 0.7	-2.4 ± 0.5
$D^{*+} \to D^0\pi^+ \to (K^-\pi^+\pi^+\pi^-)\pi^+$	-4.0 ± 1.7	-9.2 ± 0.8	-3.0 ± 0.5
$D^0 \to K^-\pi^+$ (no D^*-tag)	-2.0 ± 1.5	-5.1 ± 0.6	-1.6 ± 0.4
$D^0 \to K^-\pi^+\pi^+\pi^-$ (no D^*-tag)	-1.9 ± 1.5	-9.9 ± 0.5	-2.9 ± 0.4
$D_s^+ \to K^-K^+\pi^+$	2.5 ± 5.2	9.7 ± 1.7	2.5 ± 0.7
$\Lambda_c^+ \to pK^-\pi^+$	3.5 ± 7.6	21.5 ± 0.7	-7.7 ± 0.6

In fig. 3 α is shown for the E687 data and both models as a function of p_t^2, x_F and E_γ (beam energy). It is important to note that E687 data is shown uncorrected for acceptance. This is because Monte Carlo studies of their detector showed that their acceptance depended greatly upon the production model used. In order to compare to predictions from two different models on the same plot, the Monte Carlo events were subjected to simulations of their apparatus and photon beam. This made significant changes to particular values in some cases and is discussed more fully in their publication [12].

In each case shown in Fig. 3, the hard χ distribution Model 2 provides a good description of the kinematic variation shown while the default PYTHIA prediction Model 1 tends to over-emphasize the asymmetry. Table 2 gives the value of α integrated over all kinematic regions for several other particles and shows this same trend. While the two models have strikingly different predictions for productions asymmetries, very little difference is predicted for the momentum distributions as shown in the lower right graph of Fig. 3.

3.2 Asymmetries in Charmed Pairs

To further test the two models, E687 repeated their asymmetry measurements for charm candidates produced in association with a partially reconstructed $D^{*\pm}$. Here, a fully reconstructed charm meson is produced against a kinematically tagged soft pion of the correct charge from the decay $D^{*-} \to \pi\bar{D}^0$ where the daughter $\bar{D}^0$ is not reconstructed. The soft pion was kinematically tagged by scaling its momentum to that of the parent D^{*-} and noting that fully reconstructed $D\bar{D}$ pairs balance p_t^2 to within 4 $(\mathrm{GeV}/c)^2$ [14]. Background was accounted for by subtracting wrong-sign events.

Table 3 compares the E687 results for these events, again compared to the

Table 3: Observed production asymmetry α (%) for candidates produced in association with a $D^{*\pm}$ for Fermilab experiment E687.

$\gamma N \rightarrow$ (Decay mode) D^{*-}	E687 (This exp.)	Model 1	Model 2
$D^+ \rightarrow K^-\pi^+\pi^+$	-12 ± 5.1	-28 ± 4	-7.2 ± 1.6
$D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$	-9.6 ± 8.9	-25 ± 5	-3.4 ± 2.4
$D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+\pi^+\pi^-)\pi^+$	8.6 ± 14	12 ± 3.9	-10 ± 2.9
$D^0 \rightarrow K^-\pi^+$ (no D^*-tag)	5 ± 21	-30 ± 8.8	-6.5 ± 3.8
$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ (no D^*-tag)	-38 ± 16	-39 ± 7.2	-13 ± 3.2
$D_s^+ \rightarrow K^-K^+\pi^+$	51 ± 42	45 ± 6.9	5.5 ± 3.1

two PYTHIA models . Observation of a non-zero asymmetry in these $D^{-*}D$ events, which exclude any contribution from charm baryon production, would provide direct evidence for a kinematic cause. (This is as opposed to an asymmetry in D production caused by their production in association with baryons.) However, the weighted average of the five $D^{-*}D$ asymmetries of Table 3 is only 2.7σ different from zero. For the highest statistics mode $D^{-*}D^+$, their measurement is in good agreement with the prediction for Model 2 while it is only consistent with Model 1 at the 3σ level. This is in keeping with their previous results for inclusively produced D^+ events.

4 $D - \pi$ Correlations

The previous sections have discussed asymmetries in production which appear to have been caused by association of the produced charm quark with remanent quarks from either the beam or target nucleon. Fermilab experiment E791 studied the related correlations in charmed mesons and quarks pulled from the vacuum [13].

During fragmentation, correlations could be produced because $q\bar{q}$ pairs from the vacuum are neutral. For example, if a c quark combines with a $\bar{d}$ from such a pair to form a D^+, the remaining d is close by in phase space and is likely to become part of the closest pion, referred to as the "associated pion". Thus, $D^+\pi^-(D^-\pi^+)$ would be favored and $D^+\pi+(D^-\pi^-)$ would be disfavored. Similarly, $D^0\pi^+(\bar{D}^0\pi^-)$ would be favored and $D^0\pi^-(\bar{D}^0\pi^+)$ would be disfavored. Resonances produce the same favored associations. D^{*+} decays associate a π^+ with a D^0 while D^{*-} decays associate a π^- with a $\bar{D}^0$.

E791 studied this effect in fragmentation by comparing the association of the favored mode to the unfavored mode for several particles. "Association" of the D and π mesons was quantified by calculating Δm, the effective mass of the D

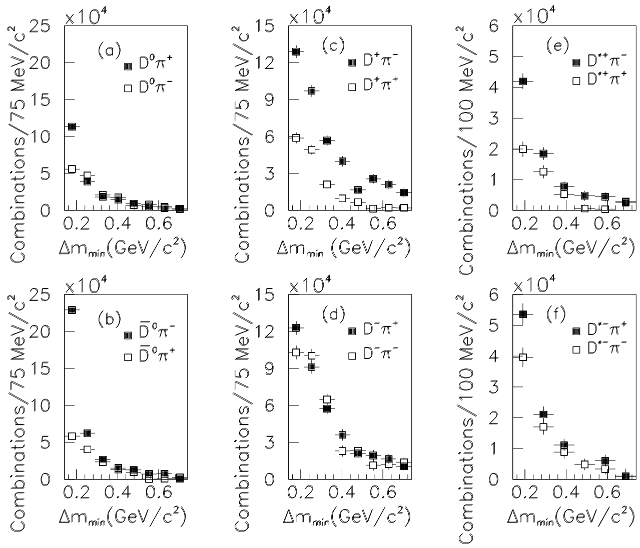

Figure 4: E791 data for Δm fully corrected for acceptance. The mode with expected production correlations in shown by black squares in each plot. The error bars are statistical only.

and π minus their rest mass. This correlation in production would be indicated by an increasing difference between the favored and unfavored modes as Δm goes to zero. For each D, the pion with the minimum Δm was was taken as the associated particle.

As resonances may increase the apparent correlation in some favored modes, the leading particle effect discussed earlier in this paper may also increase the apparent correlation in the forward direction for the *un*favored modes. In the case of E791 with with $\pi^-(d\bar{u})$ beam, a produced $\bar{c}$ may coalesce with a remanent d to form a D^-. The remaining $\bar{u}$ may tend to form π^- meson correlated in production direction with the D^-. So the study of this effect may be clearest in those events which do not involve a leading particle or a heavy meson which may result from a resonant decay.

Figure 4 shows the number of events in both modes for D^0, $\bar{D}^0$, D^+, D^-, D^{*-} and D^{*+} corrected for acceptance and detector resolution. The favored modes is shown by the black squares and the unfavored modes by the open squares. Plots

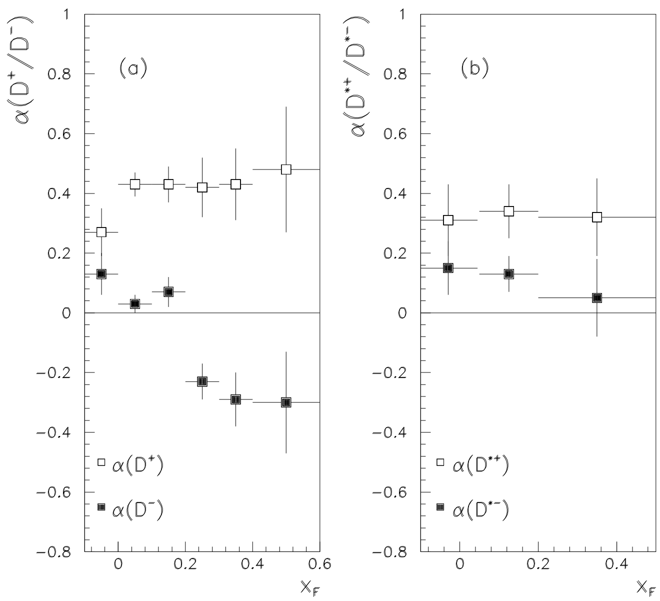

Figure 5: E791 data showing correlation in production between D mesons and the closest pion as a function of x_F. α is defined in eq (3). The mode with expected production correlation is shown in the black squares for both plots. The error bars correspond to statistical and systematic uncertainties added in quadrature.

(a) and (b) show the large difference between the modes in the lowest bin of Δm that is expected from the resonant decay of the $D^{*\pm}$ particles. In plots (d) and (f) both the unfavored and favored modes show increases in the lower bins with little difference between the two. This is explained in the previous paragraph as the unfavored modes involve the leading particles D^- and D^{*-}. But in plots (c) and (e), the heavy mesons are neither leading particles nor results of resonant decays. Here, the increasing difference in the two modes as $\Delta m \to 0$ is strong indication of the correlated production described above.

As a further test of their understanding of the correlated production, E791 studied the effect as a function of x_F for those events where the D and π appeared to be strongly correlated ($\Delta m < 0.74\mathrm{GeV}/c^2$). They defined the parameter $\alpha(D)$ as

$$\alpha(D) \equiv \frac{\sum N_i(D\pi^q) - \sum N_i(D\pi^{-q})}{\sum N_i(D\pi^q) + \sum N_i(D\pi^{-q})}. \tag{3}$$

where q = +, -, -, +, -, + for $D = D^0, \bar{D}^0, D^+, D^-, D^{*+}, D^{*-}$ respectively and $\sum N_i(D\pi^q)$ denotes the number of charmed mesons for which the selected pion has charge q. In the absence of correlations (no production difference) α is zero and in maximal correlated cases (large production difference) it is unity. Since the leading particle effect increases at higher x_F, the proposed model would show decreasing $\alpha(D)$ in the more forward direction for leading particles and constant $\alpha(D)$ for non-leading particles. Figure 5 shows $\alpha(D)$ plotted as a function of x_F for D^- (leading) and D^+(non-leading) mesons along with their excited states. Figure 5 shows strong indications of the decrease expected in $\alpha(D)$ for the leading particle (D^-). The excited states shown in fig. 5(b) are limited by statistics and x_F range and so no such statement can be made here.

5 Summary and the Future

In summary, the current set of experimental results are consistent with the standard model PYTHIA if reasonable changes are made to that model. This speaks well of our understanding of the fragmentation process. It would be more comforting if a single set of changes could be found which provides predictions consistent with both pion and photon beam simultaneously. This may be a worthwhile project once the final results are published from the 1990-1991 Fermilab fixed target run.

In the future, the fragmentation process will be studied using even higher statistics from more advanced detectors. Fermilab fixed target experiment E831 and E781 are taking data even as these proceedings are drafted. Their results are eagerly awaited.

6 Acknowledgements

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