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**Charm Production Physics from  
Fermilab Fixed-Target Experiments**

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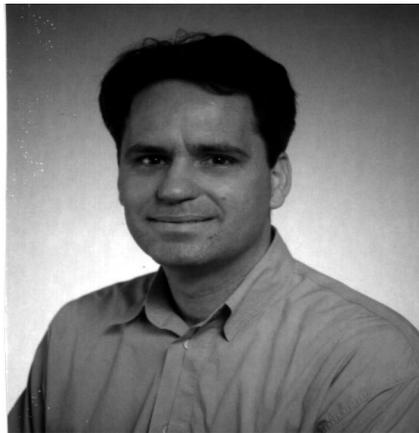
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## CHARM PRODUCTION PHYSICS FROM FERMILAB FIXED-TARGET EXPERIMENTS

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### ABSTRACT

Recent analyses of charm quark production mechanisms from Fermilab fixed-target experiments are summarized. Measurements of single inclusive differential cross sections for hadroproduced and photoproduced  $D$  mesons are compared to next-to-leading order QCD calculations. New data from hadroproduction and previous photoproduction measurements of charm meson pair correlations are compared to NLO calculations and also to parton shower Monte Carlo models. Nonperturbative effects, such as intrinsic  $k_t$  and fragmentation, are seen to play an important role in most of these comparisons. Results on charm production asymmetries in both hadroproduction and photoproduction are summarized.

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## 1. Introduction

Recent data from fixed-target experiments at Fermilab are being analyzed to investigate QCD production mechanisms for charm quarks. The measurements, such as single inclusive cross sections, correlated (pair) cross sections, and charm particle/antiparticle production asymmetries test both perturbative and nonperturbative aspects of QCD. Because the mass of the charm quark is not very large compared to  $\Lambda_{QCD}$ , there is considerable uncertainty in the theoretical calculation for the total cross section at fixed-target energies. On the other hand the relatively low charm quark mass is why they are produced in abundance at fixed-target energies (as compared to  $b$  quarks for example) and their properties measured with high statistical precision. Furthermore there is considerably less theoretical uncertainty in the shapes of differential distributions, which have been computed at next-to-leading order for the single inclusive distributions [1, 2, 3, 4] and also for the double-differential distributions (heavy quark correlations) [5, 6]. Thus it is interesting to ask what can be learned about heavy quark production in the situation where the theory may be on less solid ground than one would like, yet large statistical data samples are available. At present much of the information on open charm production physics comes from the Fermilab fixed-target hadroproduction experiments E769, E791, E789, and the photoproduction experiment E687.

## 2. Single Inclusive Distributions

Shown in Fig. 1 are the single inclusive  $p_t^2$  distributions for  $D^+$  mesons produced in photon-hadron collisions ( $\langle E_\gamma \rangle \approx 200$  GeV) from E687 and in  $\pi^-$ -hadron collisions ( $E_{\pi^-} = 250$  GeV) from E769. In both experiments the decay mode was  $D^+ \rightarrow K^- \pi^+ \pi^+$ . Comparison to the NLO calculations from [5, 6] are made using a computer program supplied by the authors. For the photoproduction experiment, the photon is assumed to be point-like (resolved photon contributions are expected to be less than 5% at these energies) and the NLO corrections (computed to  $\mathcal{O}(\alpha_s^2)$ ) to the leading order photon-gluon fusion process [7] take into account gluon bremsstrahlung, photon-quark, and QCD compton diagrams. Similar corrections to the lowest order gluon-gluon fusion graph are computed to  $\mathcal{O}(\alpha_s^3)$  for the hadroproduction case. Inputs to the calculation are the parton density functions, renormalization and factorization scales, and the charm quark mass. A review which discusses these choices and resulting uncertainties is given in Ref. [8].

The NLO curves for charm quarks indicate good agreement for the hadroproduction data, while the prediction is significantly harder than the photoproduction result. The NLO calculations alone contain no provision for the fragmentation of the charm quarks, nor do they necessarily account for all of the intrinsic transverse momentum ( $k_t$ ) of the incoming partons. These two effects tend to work in opposite ways: since energy is lost when the charm quark fragments the  $D^+$  meson  $p_t^2$  is softened, while the intrinsic  $k_t$  smearing tends to harden

the  $p_t^2$  distribution. One interpretation of the data is that these two effects cancel for the hadroproduced charm, while in photoproduction the cancellation is less perfect.

The NLO calculations can however be augmented to take into account nonperturbative effects [8]. Arbitrary amounts of additional intrinsic transverse momentum can be added to the incoming partons, and the energy loss due to hadronization can be approximated with a fragmentation model such as from Peterson *et al.* [9]. The dashed curve shown in Fig. 1 for the photoproduction data is the result of augmenting the NLO calculation for the charm quarks with fragmentation and an intrinsic  $k_t$  for the target gluon of  $\langle k_t^2 \rangle = 1 \text{ GeV}^2$ . The result is a distribution too soft in  $p_t^2$ , though adding more intrinsic  $k_t$  can improve the agreement. However, it is not clear that the fault does not lie with the fragmentation model assumed. An ideal solution would be to combine the NLO calculation with a more phenomenologically advanced hadronization model such as HERWIG [11] or the Lund programs PYTHIA and JETSET [12]. At present there seems to be no clear notion of how to do this in a theoretically justifiable manner. It is interesting that at least for the photoproduction case a Monte Carlo prediction based on PYTHIA and JETSET, which together contain the leading order photon-gluon fusion matrix element combined with intrinsic gluon  $k_t$ , initial and final state parton showering, and string fragmentation, describe the data satisfactorily as shown by the solid curve of Fig. 1.

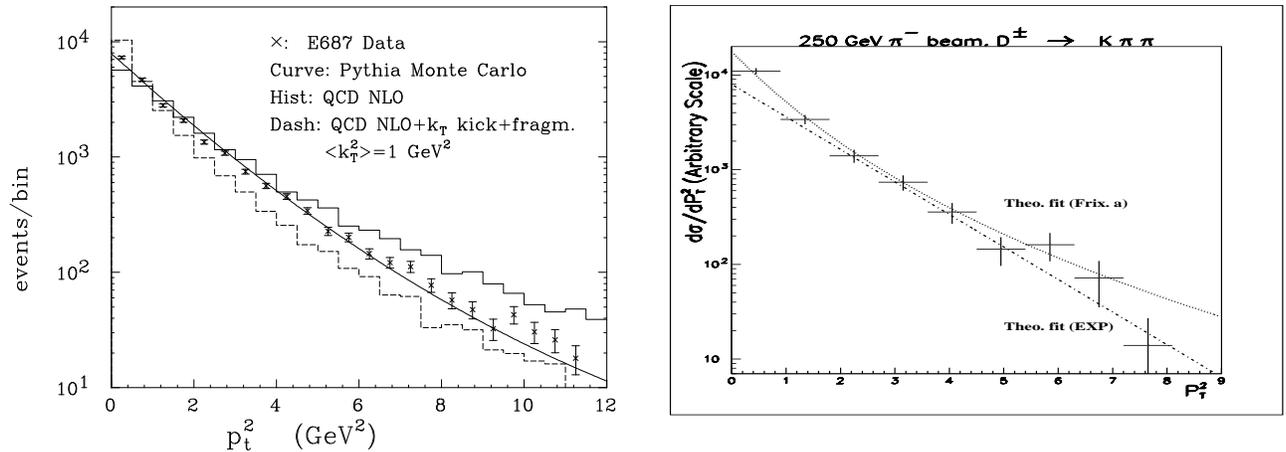


Figure 1: The  $p_t^2$  distribution for  $D^+ \rightarrow K^- \pi^+ \pi^+$  produced in photon-hadron collisions (E687, left), and  $\pi^-$  hadron collisions (E769, right). For the E769 data, the NLO prediction for charm quarks is the upper curve; the lower curve is a single exponential fit  $d\sigma/dp_t^2 = C e^{-b p_t^2}$ .

### 3. Correlated Charm Pair Distributions

Measurements of correlations between photoproduced charm meson pairs from E687 [10] have been compared to NLO QCD predictions in Ref.[8]. New preliminary measurements of charm meson pair correlations in hadroproduction have been made by E791. From their data sample of roughly 200 thousand reconstructed inclusive  $D$  meson signals they are able to

cleanly isolate about 640 fully reconstructed  $D\bar{D}$  pairs. The acoplanarity  $\Delta\phi$  is the azimuthal angle between the  $D$  and  $\bar{D}$  momentum vectors in the plane transverse to the incident beam direction. At leading order it is 180 degrees since the quarks are produced back-to-back. The  $p_t^2$  of the  $D\bar{D}$  pair is expected to be 0 at leading order since gluon radiation is neglected. In Fig. 2 the  $\Delta\phi$  distributions from the two experiments are compared to the NLO QCD predictions. For the photoproduction case the NLO prediction can be augmented by giving the target gluon an intrinsic  $k_t$  kick, while for the hadroproduction case both the beam and target gluons may receive an intrinsic  $k_t$  kick. Note that for both experiments the NLO calculation without any additional  $k_t$  kick predicts a  $\Delta\phi$  distribution more sharply peaked towards 180 degrees than observed in the data (but less peaked than PYTHIA predicts for the photoproduction case). By adding the fragmentation effect (which is small for the  $\Delta\phi$  distribution since the  $D$  meson keeps the same direction as the charm quark in this model) and intrinsic  $k_t$  kicks of  $\langle k_t^2 \rangle = 0.5 \text{ GeV}^2$  and  $k_t$  kick of  $\langle k_t^2 \rangle = 1 \text{ GeV}^2$  for photo- and hadroproduction respectively, the data are adequately described. That these two intrinsic  $k_t$  values differ is interesting and seems to suggest that the unaccounted for nonperturbative effects not directly related to fragmentation are larger in the hadroproduction case. However, a more unsettling issue may be that an intrinsic  $k_t$  kick of  $\langle k_t^2 \rangle = 2 \text{ GeV}^2$  is necessary to describe the hadroproduction data for the  $p_t^2$  of the  $D\bar{D}$  pair distribution (figure not shown). Two different  $k_t$  kicks were also necessary to simultaneously describe both  $\Delta\phi$  and  $p_t^2(D\bar{D})$  in the photoproduction case [8, 10]. Since the  $p_t^2(D\bar{D})$  distribution is sensitive to fragmentation (analogously to the single inclusive  $p_t^2$  distribution) this unsatisfactory situation could again be the result of assuming a simplified hadronization model.

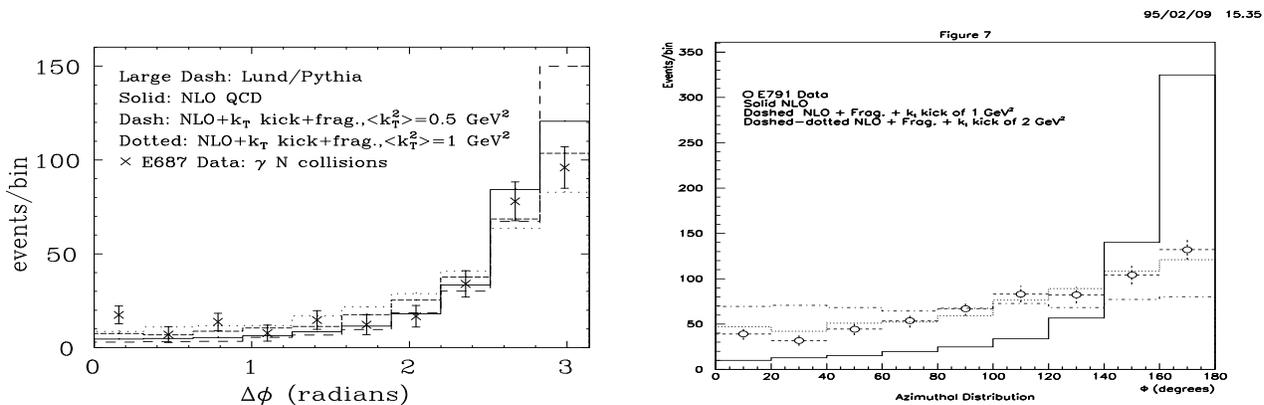


Figure 2: The  $\Delta\phi$  distributions for  $D\bar{D}$  pairs from E687 photoproduction data (left) and from preliminary E791 hadroproduction  $D\bar{D}$  data (o, right). The solid histograms are the QCD NLO predictions without an intrinsic  $k_t$  kick. For E687 the dashed histogram is for  $\langle k_t^2 \rangle = 0.5 \text{ GeV}^2$  and the dotted is for  $\langle k_t^2 \rangle = 1 \text{ GeV}^2$ . For E791, the dashed is for  $\langle k_t^2 \rangle = 1 \text{ GeV}^2$  and the dash-dotted is for  $\langle k_t^2 \rangle = 2 \text{ GeV}^2$ .

#### 4. Production Asymmetries

At leading order in QCD, charm and anticharm quarks are produced symmetrically

through the photon-gluon or gluon-gluon fusion mechanisms. There are small asymmetries induced at NLO resulting from diagrams which depend on the quark content of the initial state. In hadroproduction an enhancement in the production of leading (a leading  $D$  meson has a valence quark in common with the incident beam hadron) over non-leading  $D$  mesons has been previously reported by the E769 [13] and WA82 [14] collaborations. Higher statistics hadroproduction data recorded at higher beam energy is now being analyzed by E791 [15]. The E791 sample for  $D^\pm$  mesons produced by a 500 GeV/c  $\pi^-$  beam impinging on a segmented target of various materials is shown in Fig. 3. The signal shown is based on roughly 1/2 the full E791 data sample. The asymmetry parameter is defined as the difference between the detected number of leading ( $D^-$  for a  $\pi^-$  beam) and non-leading mesons over the sum. In Fig. 3 this asymmetry is plotted as a function of  $x_F$  and compared to the prediction from Lund string fragmentation (PYTHIA plus JETSET were used) and to predictions based on the intrinsic charm model [16]. The data have not been corrected for acceptance but the corrections are expected to cancel in the ratio [15].

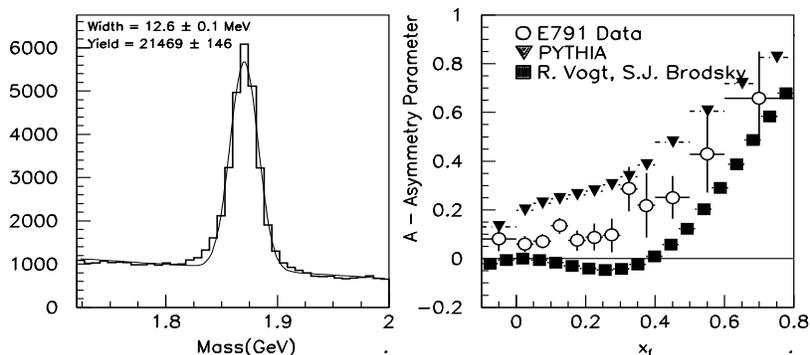


Figure 3: Preliminary  $D^+ \rightarrow K^- \pi^+ \pi^+$  signal and asymmetry from E791.

In the context of the Lund string fragmentation model[12] the struck gluon leaves the target nucleon in a color octet state which can be divided into a color antitriplet diquark and triplet monoquark, both of which are color connected to the charm quarks participating in the hard interaction. The simplest diagrams have the (non-leading) charm quark color connected to the target diquark while the (leading) anticharm quark may connect with the  $d$  from the beam  $\pi^-$ . The result is that leading particle is produced with more forward momentum than the non-leading particle, an effect sometimes referred to as “beam dragging”. The intrinsic charm asymmetry develops when a  $c\bar{c}$  pair is popped from the projectile and the quark identified as leading (the  $\bar{c}$  quark) dresses the valence  $d$  quark from the  $\pi^-$ . In certain kinematic regions, such as when the relative velocity between the quarks is small, this may be enhanced over other dressing mechanisms. Interestingly the data shown in Fig. 3 illustrate an enhancement at large  $x_f$  as do both models, and perhaps splits the difference between them. Further investigations in other kinematic projections such as  $p_t^2$  and using other charm species may help discriminate between these mechanisms which have very different

underlying origins.

Photoproduction asymmetries are also being investigated [17]. In the context of the Lund string fragmentation model the number of anticharm mesons are predicted to be enhanced in the forward region relative to the charm mesons since the charm quark dresses with the target diquark, which on average carries a larger fraction of the (backward moving in the CMS frame) target nucleon momentum. This “color-drag” asymmetry should decrease with increasing beam energy. Other sources of asymmetry such as that resulting from the associated production of  $\bar{D}$  mesons with (target associated) charm baryons are also possible, and may have an entirely different kinematic dependence.

The preliminary measurements for  $D^+$  from E687 are shown in Fig. 4 where the asymmetry is defined as  $N(D^+ - D^-)/N(D^+ + D^-)$ . The data, which have not been corrected for detector efficiency and acceptance, are compared to Lund model predictions which have been subjected to the same analysis cuts and apparatus acceptance conditions as the data. The default model prediction follows the same trend as the data but tends to over-predict the magnitude of the asymmetry. Investigations are being made to check the sensitivity of the predicted asymmetry to model parameters such as those controlling the energy partitioning of the target nucleon remnants. For example, the option which distributes the energy given to the target monoquark according to simple counting rules (in which case the monoquark receives a larger fraction of the nucleon momentum) results in a reduction of the asymmetry and is in better agreement with the data.

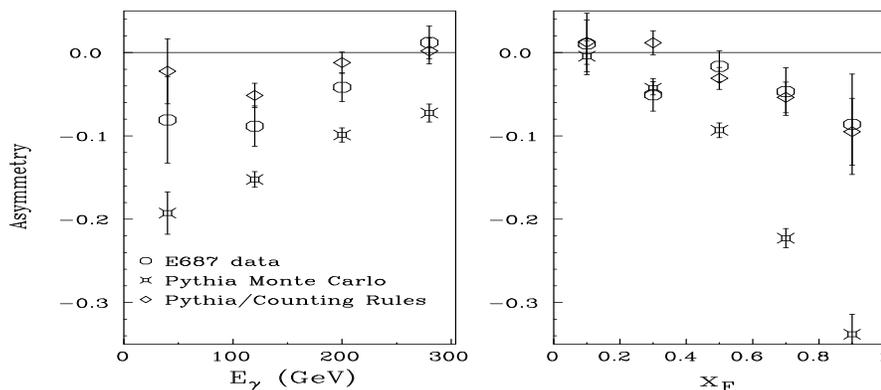


Figure 4: Preliminary asymmetry measurements for  $D^+ \rightarrow K^- \pi^+ \pi^+$  as a function of photon beam energy and x-Feynman from E687 ( $\circ$ ), default LUND/PYTHIA model predictions (crossed points) and the predictions with simple counting rules for energy partitioning ( $\diamond$ ).

## 5. Conclusion and Outlook

There are many topics I did not discuss including new measurements of hadroproduction total cross sections and cross section ratios for various charm species by experiment E769, and new results on the nuclear dependence of  $D^0$  meson production from the E789 collaboration [18]. The present generation of Fermilab fixed-target experiments are continuing to analyze their data and results should be forthcoming in the next year. A worthwhile

phenomenological challenge would be to obtain a justifiable method of combining next-to-leading order calculations with more advanced hadronization models. In the meantime the next generation of Fermilab fixed-target charm experiments (E831/FOCUS and E781/SELEX) are in the construction phase and will begin recording data in 1996.

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