Fermi National Accelerator Laboratory

FERMILAB-Conf-94/365-E

E-687

Recent Results from Fermilab E-687: Charm Particle Decays, Liftimes and Photoproduction Dynamics: A Compilation of Results Presented at DPF 1994

The E687 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1994

Presented at the *Eighth Meeting of the Division of Particles and Fields of the American Phyiscal Society (DPF '94)*, Albuquerque, New Mexico, August 2-6, 1994

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RECENT RESULTS ON THE SEMILEPTONIC DECAY $D^0 \to K^- \mu^+ \nu_\mu$

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ABSTRACT

High statistics results on the decay $D^0 \to K^- \mu^+ \nu_\mu$(+c.c.) will be presented. The results include the relative branching fraction of $D^0 \to K^- \mu^+ \nu_\mu$ to $D^0 \to K^- \pi^+$, a measurement of the pole dependence of the f_+ form factor and a determination of $f_+(0)$.

1. Introduction

The next generation of fixed target charm experiments will have high precision, high statistics, low background measurements of semileptonic D decays. To take full advantage of this bounty, the analysis of the decay $D^0 \to K^- \mu^+ \nu_\mu$ from data taken during the 1990 and 1991 runs of Fermilab experiment E687 is used to test the possibility of relaxing the D^* tag requirement to increase statistics. The result is a better measurement of the ratio $\frac{BR(D^0 \to K^- \mu^+ \nu_\mu)}{BR(D^0 \to K^- \pi^+)}$ and the pole mass(from the single pole form of the f_+) than was realized when the analysis utilized a D^* tag.

2. Motivation

Using the expression for the full rate,[1]

$$\frac{d\Gamma}{dE_K} = \frac{G_F^2}{4\pi^3} |V_{cs}|^2 \left|f_+(q^2)\right|^2 P_K \left(\frac{W_0 - E_K}{F_0}\right)^2 \left[\frac{1}{3} m_D P_K^2 + \frac{m_l^2}{8m_D}(m_D^2 + m_K^2 + 2m_D E_K) + \frac{1}{3} m_l^2 \frac{P_K^2}{F_0} + \frac{1}{4} m_l^2 \frac{m_D^2 - m_K^2}{m_D} Re\left(\frac{f_-(q^2)}{f_+(q^2)}\right) + \frac{1}{4} m_l^2 F_0 \left|\frac{f_-(q^2)}{f_+(q^2)}\right|^2\right],$$

$$W_0 = \frac{m_D^2 + m_K^2 - m_l^2}{2m_D}, F_0 = W_0 - E_K + \frac{m_l^2}{m_D}, \tag{1}$$

and the single pole representation of the form factor, (other forms are possible)

$$f_{+,-}(q^2) = f_{+,-}(0)/(1 - q^2/m_{pole}^2) \tag{2}$$

we see that the semi–muonic channel must be measured if f_- is large. The best measurement presently available of the $\frac{BR(D^0 \to K^- l^+ \nu_l)}{BR(D^0 \to K^- \pi^+)}$ is from CLEO[2] and is dominated by the semi–electronic mode. Our measurement will also roughly double the available statistics now available for measurements of the ratio $\frac{BR(D^0 \to K^- l^+ \nu_l)}{BR(D^0 \to K^- \pi^+)}$, m_{pole} and $f_+(0)$.

*Representing the E687 Collaboration

3. Data and Analysis

3.1. Data Selection

The E687 spectrometer is described elsewhere.[3] To find a D^0, we select Kμ candidates by choosing kaons that the Čerenkov system identifies as a definite kaon or kaon/proton ambiguous. This kaon is combined with an opposite charge muon identified as a muon by the inner muon system of the E687 spectrometer. Typically, $\sim 1.0\%$ of all pions or kaons are identified as muons due to pattern recognition failures, the decay of the pion or the decay of the kaon. The kaon and the muon must form a vertex with a confidence level of 5% or better and have an invariant mass less than 1.855 GeV/c^2 to reduce contamination from $D^0 \to K^-\pi^+$. The remaining tracks in the event are used to find primary vertex candidates. The highest multiplicity primary vertex candidate with a significance of separation (l/σ) from the secondary Kμ candidate of 4.5 or greater and confidence level of fit 1% or greater is retained. To estimate the D^0 momentum, following Ref. 4, we assume the D^0 travels from the primary to the secondary; then boost the Kμ candidate to a frame where $(\bar{P}_\mu + \bar{P}_K)\cdot \check{l} = 0$ ($\check{l}$ is the D^0 decay direction) and determine the amount of momentum parallel to the D^0 carried by the missing neutrino. In the boosted frame, we require that $E_\nu > 0$, $(\bar{P}_\nu \cdot \check{l})^2 = (E_\nu^2 - P_{K\mu}^2) > -.7$ $(GeV/c^2)^2$, and for those events with $-.7 < (E_\nu^2 - P_{K\mu}^2) < 0$ we set $(E_\nu^2 - P_{K\mu}^2) = 0$. Hence, $(\bar{P}_\nu \cdot \check{l}) = \pm\sqrt{E_\nu^2 - P_{K\mu}^2} = \pm\bar{P}_D$, and one simply boosts the solutions into the lab frame to estimate the D^0 momentum. We resolve the kinematic ambiguity by choosing the lower D^0 momentum solution since it has the best E_k(hence q^2) resolution in the region of highest m_{pole} information density. A fit is then performed that takes microvertex tracks not assigned to the primary or the secondary vertex and gives a confidence level that any of these tracks are consistent with being in the secondary vertex. We require this confidence level to be $< 1\%$. To reduce backgrounds from muon misidentification, we further require that the $K\mu$ invariant mass be larger than 0.95 GeV/c^2, the $K\mu$ momentum be greater than 35 GeV and the muon momentum be greater than 15 GeV.

3.2. Fit

The emphasis in the fit is to include as much of the background as we understand. The largest source of background, muon misidentification, is estimated by redoing the $k\mu$ analysis without the requirement of muon identification and reweighting the event based on the probability that the particle could be misidentified. The backgrounds $D^0 \to K^{*-}\mu^+\nu_\mu$, $D^+ \to K^0\mu^+\nu_\mu$ and $D_s^+ \to \phi\mu^+\nu_\mu$ are generated with our Monte Carlo and given weights relative to $BR(D^0 \to K^-\mu^+\nu_\mu)$ based on production and measured branching ratios. The remainder of the background is simulated using events from the data where the K and the μ have the same charge. Of the components in the signal: $D^0 \to K^-\mu^+\nu_\mu$ accounts for 64.3% of the signal, muon misidentification 18.5%, $D^0 \to K^{*-}\mu^+\nu_\mu$ 7.6%, $D^+ \to K^0\mu^+\nu_\mu$ 7.1%, $D_s^+ \to \phi\mu^+\nu_\mu$ 0.8% and other backgrounds(from $Q(K) = Q(\mu)$) 1.7%.

To fit the data, we construct a likelihood function,

$$\mathcal{L} = \prod_{bins_i} \frac{n_i^{s_i} e^{-n_i}}{s_i!} \tag{3}$$

where

$$s_i = number\ of\ events\ in\ bin_i \tag{4}$$

$$\begin{aligned} n_i \ &= Yield \times \tfrac{[(K^-\mu^+\nu_\mu MC_i)+f_1\times(K^{*-}\mu^+\nu_\mu MC_i)+f_2\times((D^+\to)K^{*0}\mu^+MC_i)+f_3\times((D_s^+\to)\phi\mu^+MC_i)]}{(1+f_1+f_2+f_3)} \\ &+ number\ of\ events\ from\ misid\ in\ bin_i \\ &+ BKYield \times (background(from\ same\ sign\ data)\ in\ bin_i) \end{aligned} \tag{5}$$

and each fraction(f_i) multiplying a normalized Monte Carlo shape is determined by

$$f_1 \ = \frac{Efficiency(D^0\to K^{*-}(\to K^-\pi^0)\mu^+\nu_\mu)}{Efficiency(D^0\to K^-\mu^+\nu_\mu)} \times \frac{BR(D^0\to K^{*-}\mu^+\nu_\mu)}{BR(D^0\to K^-\mu^+\nu_\mu)} \tag{6}$$

$$f_2 \ = \frac{Efficiency(D^+\to K^{*0}(\to K^-\pi^+)\mu^+\nu_\mu)}{Efficiency(D^0\to K^-\mu^+\nu_\mu)} \times \frac{BR(D^0\to K^{*-}\mu^+\nu_\mu)}{BR(D^0\to K^-\mu^+\nu_\mu)} \times \frac{\Gamma(D^+\to K^{*0}\mu^+\nu_\mu)}{\Gamma(D^0\to K^{*+}\mu^+\nu_\mu)} \times \frac{\sigma_{D^+}}{\sigma_{D^0}} \times \frac{\tau_{D^+}}{\tau_{D^0}} \tag{7}$$

$$f_3 \ = \frac{Efficiency(C\bar{C}\to D_s^+\to\phi(\to K^-K^+)\mu^+\nu_\mu)}{Efficiency(C\bar{C}\to D^0\to K^-\mu^+\nu_\mu)} \tag{8}$$

where we account for the change in efficiency for different pole masses via,

$$Efficiency(D^0 \to K^-\mu^+\nu_\mu)\ _{bin_i} \Rightarrow Efficiency(D^0 \to K^-\mu^+\nu_\mu)_{bin_i} \times$$

$$\left[\sum_{in\ bin_i}^{\#events} \left(\frac{M_{fit}^2(q^2, E_\mu)}{M_{gen}^2(q^2, E_\mu)}\right)\right] \times \left(\frac{\int_{q^2_{low}}^{q^2_{hi}} \int_{E_{\mu low}}^{E_{\mu hi}} f_+^2(q^2, m_{pole_0}) M_{gen}^2(q^2, E_\mu) dq^2 dE_{mu}}{\int_{q^2_{low}}^{q^2_{hi}} \int_{E_{\mu low}}^{E_{\mu hi}} f_+^2(q^2, m_{pole}) M_{fit}^2(q^2, E_\mu) dq^2 dE_{mu}}\right) \tag{9}$$

and we allow the yield, background and pole mass to vary in the fit.

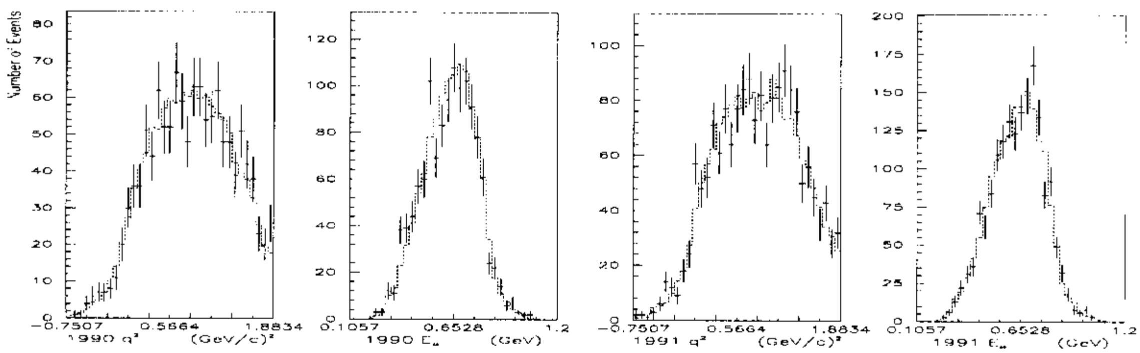

Figure 1.Fit overlayed to projections of the 1990 and 1991 signals.

The fit yields 823.6 ± 31.2 $D^0 \to K^-\mu^+\nu_\mu$ events for 1990 data, 1038.2 ± 37.4 $D^0 \to K^-\mu^+\nu_\mu$ events for 1991 data and a pole mass of $1.98^{+0.12}_{-0.10}$. Subsequent studies using simulated data sets show that the fit underestimates the error on all the parameters by 4%, and we inflate the returned errors by this amount in the final result. We also find that the likelihood from the fit to the data lies within 2σ of the centroid of the spread of likelihoods returned from fitting the simulated data sets. The result of the fit in projections for the 1990 and 1991 data is shown in Fig. 1.

3.3. Systematic Studies

Systematic error in the final result is due to uncertainty in the muon (mis)identification, the ratio $BR(D^0 \to K^{*-}\mu^+\nu_\mu)/BR(D^0 \to K^-\mu^+\nu_\mu)$, the ratio of production between D^0 and D^+ and the amount of Monte Carlo used for establishing efficiencies. To investigate the stability of the signal, we look at the variation with l/σ, $M(K\mu)$, confidence level of the fit to the $K\mu$ vertex, momentum of the $K\mu$ pair, momentum of the μ, choice of D momentum solution and 1990 and 1991 data sets. We also take all microvertex tracks not in the $K\mu$ vertex and vary the confidence level that any of these tracks are consistent with being in the $K\mu$ vertex.(note that this cut is more powerful than that used for the data selection process). Of these stability tests, we find the largest contributions to the systematic error coming from the choice of D momentum solution and the momentum behavior of the $K\mu$ pair(1991 data yield only). We also analyzed a subset of the non–tagged signal for the case where the D^0 is consistent with the hypothesis that it was produced from a D^{*+}. The results from this tagged data indicate statistical departures of less than 1σ for all parameters we measure with the non–tagged data. All sources of systematic error are added in quadrature.

3.4. Preliminary Results

In Table 1. we combine the results of an analysis of the mode $D^0 \to K^-\pi^+$ (where the π was limited to the acceptance of the muon system) for the ratio of branching ratios with the results of the fit and the systematic studies.

Table 1. Preliminary results from the non–tagged signal.

Measured Quantity	Value	Statistical Error	Systematic Error
$\frac{BR(D^0 \to K^-\mu^+\nu_\mu)}{BR(D^0 \to K^-\pi^+)}$	0.860	0.028	$^{+0.042}_{-0.039}$
Pole Mass M_{pole}	1.98	$^{+0.13}_{-0.10}$	$^{+0.04}_{-0.10}$
$f_+(0)$	0.730	$^{+0.020}_{-0.021}$	$^{+0.029}_{-0.033}$

Our results agree to within 2σ with the recent CLEO[2] measurement, but we are unable to rule out a significant f_- contribution to the semi–muonic branching fraction. Since $\left(\frac{E687\ BR(D^0 \to K^-\mu^+\nu_\mu)}{CLEO\ BR(D^0 \to K^-l^+\nu_l)}\right) = \left(\frac{0.86\pm0.05}{0.98\pm0.05}\right) = 0.88 \pm 0.07$, it will take the next generation of charm experiments to show whether there is a significant difference between the semi–electronic and the semi–muonic modes.

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Charmed Mesons

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CHARMED MESONS

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ABSTRACT

Charmed meson decays into hadronic final states have been extensively studied in the E687 photoproduction experiment at Fermilab. Multi-meson-decay modes offer a remarkable chance to address some of the main issues in charm physics. Results on the D^0, D^+ and D_s 3-body amplitude analysis have direct implications on the role of the different decay mechanisms. In addition a study of 4 and 5 body decays into kaons and pions has been carried out; the relative branching ratios are presented.

1. Three-body decays

A detailed Dalitz plot study has been performed on the decays of charmed mesons into three-body final states. The phenomenological amplitude used to fit the data is a sum of Breit-Wigner terms with appropriate angular factors and a constant term to represent the assumed uniform non-resonant contribution.

1.1. $K\pi\pi$ results

The $K\pi\pi$ Dalitz plot analysis has already been completed.[1] The $I = 1/2$ and $3/2$ amplitudes have been computed using the branching fractions obtained from this analysis in the modes $D^0 \rightarrow K^{*-}\pi^+, D^0 \rightarrow \bar{K}^{*0}\pi^0$and $D^+ \rightarrow \bar{K}^{*0}\pi^+$. A ratio $|A_{1/2}|/|A_{3/2}| = 5.9 \pm .3 \pm .3$ and a phase shift $\delta_{1/2} - \delta_{3/2} = 95 \pm 16 \pm 21°$ have been measured; this angular difference indicates the importance of final-state interactions in charm decays.

1.2. $KK\pi$ preliminary results

Fig. 1 shows the D^+ and $D_s^+ \rightarrow K^-K^+\pi^+$ signals along with their Dalitz plots. In the D_s case the reflection from the $D^+ \rightarrow K^-\pi^+\pi^+$ has been removed by rejecting events if they are consistent with a D^+ when reconstructed as $K^-\pi^+\pi^+$. The resulting D_s Dalitz plot (Fig. 1) shows clearly that the $KK\pi$ decay is dominated by the $\phi\pi$ and the $\bar{K}^{*0}K$ channels. The non-ϕ and non-$\bar{K}^{*0}$ events may be attributed either to the

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non-resonant or to the $f_0(975)\pi$ channel. Indeed the D_s into 3-pion data (Fig. 3) reveal the presence of the scalar $f_0(975)$ also decaying into a KK state.

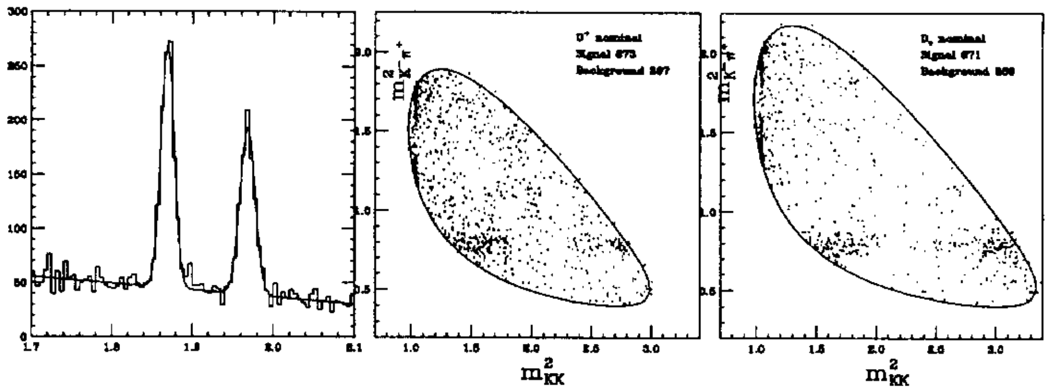

Fig. 1: D^+ and $D_s^+ \to K^-K^+\pi^+$ signals and Dalitz plots.

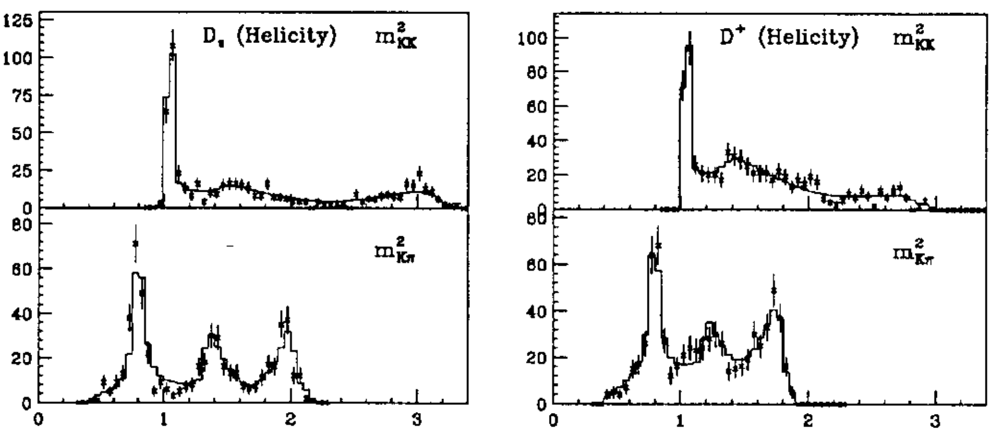

Fig. 2: D_s^+ and D^+ Dalitz plot projections and fit.

The parametrization and the effect of the $f_0(975)$ amplitude in the analysis is still problematic. On the other hand the "out-of-target"* sample shows a blur of events near the ϕ Zemach zero, which might be due to the $f_0(975)$. For the time being, preliminary results are reported as obtained with a 3-amplitude fit consisting only of $\phi, \bar{K}^{*0}$ and non-resonant amplitudes. Two differently selected samples of data (skims) have been analyzed with two different formalisms (Zemach and Helicity); in Fig. 2 the Dalitz projections and their fit are shown as obtained via the helicity approach. The quoted results are evaluated as an average of the analyses and should be considered very preliminary. The systematic errors have been estimated from fluctuations of the results of the different analyses. Results for the D_s fit fractions and phases are shown in Table

*A sample of events has been selected requiring the decay to be downstream of the experimental target. This very clean sample serves as an important check of the systematic errors caused by background fluctuations and model assumptions

I. An analogous model has been applied to D^+ (Fig. 2) and the corresponding results reported in the same Table I. In this case all the different analyses give very consistent results, with the exception of the $\phi/\bar{K}^{*0}$ phase that shows a certain shift in the out-of-target sample. This uncertainty is quoted as a systematic error. †

Table I: $D_s$and D^+ preliminary results

fit fractions and Phases	D_s	D^+
non-res	$.082 \pm .041 \pm .073$	$.401 \pm .025 \pm .018$
ϕ	$.437 \pm .039 \pm .062$	$.334 \pm .018 \pm .027$
$\bar{K}^{*0}$	$.584 \pm .040 \pm .060$	$.302 \pm .024 \pm .018$
non-resonant Phase	$-177 \pm 20 \pm 11°$	$96 \pm 7 \pm 11°$
ϕ Phase	$121 \pm 11 \pm 17°$	$162 \pm 10 \pm 41°$
$\bar{K}^{*0}$ Phase	0 (fixed)	0 (fixed)

1.3. $\pi\pi\pi$ preliminary results

The $\pi\pi\pi$ data sample was selected using the out-of-target cut already mentioned because of the huge background. Although the statistics is low,

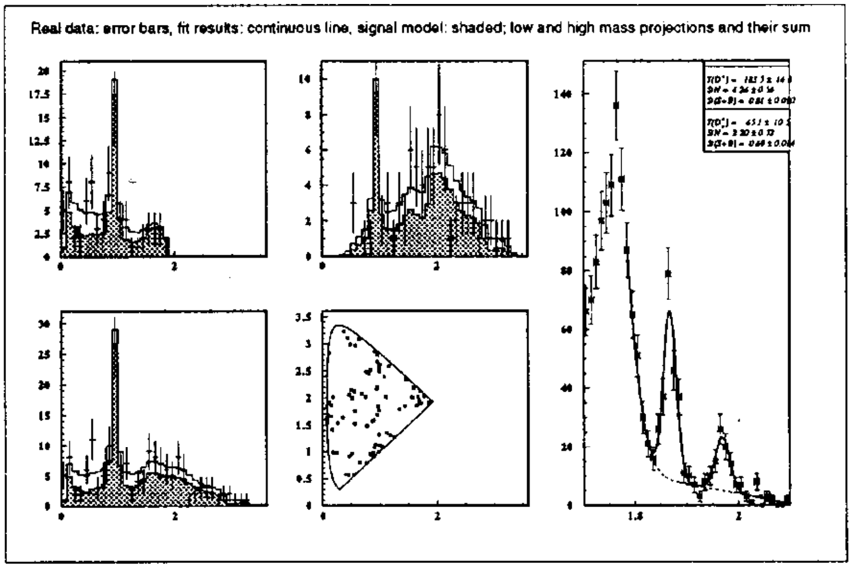

Fig. 3: D_s Dalitz plot and projections and $\pi\pi\pi$ invariant mass distribution.

the very good signal-to-noise ratio makes the analysis promising (Fig. 3). In this case, because of Bose symmetry, the data are represented by a folded Dalitz plot in $(m^2_{\pi\pi})_{high}$ and $(m^2_{\pi\pi})_{low}$. The model includes the $\rho(770)$, scalar $f_0(975)$, spin-2 $f_2(1270)$ and a flat non-resonant term. Again, as in the $KK\pi$ decay, there are remarkable differences in the fit predictions among the various $f_0(975)$ models. The analysis is still

†In this $K^-K^+\pi^+$ analysis, the helicity angle is defined to be the angle between the K^- and the resonance in the resonance rest frame.

in progress and only a very preliminary fit for the D_s is shown is Fig. 3. There is an indication that the decay is dominated by the $f_0(975)$ and f_2 channels.

2. Four and Five-body decays

The $D^0 \rightarrow 4\pi$, $D^0 \rightarrow 2K2\pi$ and $D^0 \rightarrow 3K\pi$ decays have been studied. The branching ratios relative to $D^0 \rightarrow K3\pi$ are reported in Table II.

Table II: Four-body decays of D^0

B.R.	E687	Previous results
$\frac{\Gamma(D^0 \rightarrow 4\pi)}{\Gamma(D^0 \rightarrow K3\pi)}$	$.097 \pm .006 \pm .002$	$.096 \pm .018 \pm .007 (E691)$ $.102 \pm .013 (CLEO)$
$\frac{\Gamma(D^0 \rightarrow 2K2\pi)}{\Gamma(D^0 \rightarrow K3\pi)}$	$.034 \pm .004 \pm .002$	$.028^{+.008}_{-.007}$ (E691) $.0314 \pm .010$ (CLEO) $.041 \pm .007 \pm .005$ (ARGUS)
$\frac{\Gamma(D^0 \rightarrow 3K\pi)}{\Gamma(D^0 \rightarrow K3\pi)}$	$.0028 \pm .007 \pm .002$	

These results constitute a considerable improvement over previous measurements.

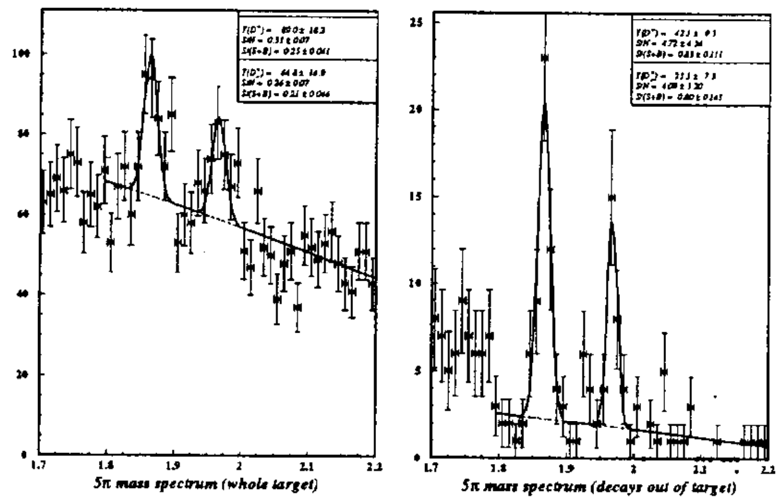

Fig. 4: D^+ and $D_s \rightarrow 5\pi$ signals with and without the out-of-target cut.

The first significant evidence of the $D^+, D_s \rightarrow 5\pi$ has been observed. The signals are shown in Fig. 4 with and without the out-of-target cut.

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Observation of the Decay $\Omega_c^0 \rightarrow \Sigma^+ K^- K^- \pi^+$

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OBSERVATION OF THE DECAY $\Omega_c{}^0 \to \Sigma^+ K^- K^- \pi^+$

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ABSTRACT

We report on the observation of a new decay mode of the $\Omega_c{}^0$, $\Omega_c{}^0 \to \Sigma^+ K^- K^- \pi^+$, where Σ^+ decays into either $p\pi^0$ and $n\pi^+$. We observe a clear signal of 42.4 ± 9.0 events and we give a new measurement of the mass.

1. Introduction

At present the published evidence for the doubly strange charmed baryon Ω_c^0 is not strong. Three Ω_c^0 events were reported by WA62[1] in the decay channel $\Xi^- K^- \pi^+ \pi^+$ and 6.5 ± 3.2 events were reported by ARGUS[2] for $\Omega_c^0 \to \Omega^- \pi^+ \pi^+ \pi^-$. The best published evidence so far are results from ARGUS[3] with 12.2 ± 4.5 events of $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$ at a mass of $2719 \pm 7.0 \pm 2.5$ MeV/c^2 and our results published in an earlier paper on $\Omega_c^0 \to \Omega^- \pi^+$[4] with with 10.3 ± 3.9 events at a mass of $2705.9 \pm 3.3 \pm 2.0$ MeV/c^2. Both these signals are about 2.7 standard deviations in statistical significance. In a recent preliminary analysis,[5] the CLEO collaboration finds no evidence for $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$, and reports a 90% confidence level upper limit on the cross-section $\times$ branching ratio of 0.40 pb, which is much lower than the value of $2.41 \pm 0.90 \pm 0.30$ pb measured by ARGUS. There is clearly a need for further confirmation of the Ω_c^0 and an improvement in the determination of its mass. In this paper we present further evidence for the Ω_c^0 in a new decay mode $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$ (the charge conjugate state is implied when a decay mode of a specific charge is stated) and give a new measurement of its mass. The data have been collected by Fermilab high energy photoproduction experiment E687.[6]

2. $\Sigma^+ K^- K^- \pi^+$ candidates selection

The Σ^+ hyperons are reconstructed through both the decays modes $\Sigma^+ \to p\pi^0$, and $\Sigma^+ \to n\pi^+$.[7] The Ω_c^0 decays were reconstructed using the standard E687 candidate driven vertex algorithm.[6] The decay secondaries, other than the Σ^+ hyperons, must be reconstructed in both the SSD and MWPC, and the two sets of track parameters have to agree within measurement errors. The K^- must be identified by the Čerenkov counters as kaon definite or K/p ambiguous, and the pion must not be identified as electron, kaon or proton definite or K/p ambiguous. The four microstrip tracks of the $\Sigma^+ K^- K^- \pi^+$ combination are required to form a (secondary decay) vertex with

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a confidence level (CLD) greater than 3%. The candidate Ω_c^0 "track" must form a primary vertex with at least one other microstrip track with a confidence level (CLP) larger than 3%. We eliminate fake decay secondaries that were actually produced in the primary interaction vertex by requiring that the confidence level for any of the four $\Sigma^+K^-K^-\pi^+$ tracks to individually extrapolate back to the primary vertex is less than 85%. In addition, the confidence level that other SSD tracks, not already assigned to the primary or secondary vertices, point back to the secondary vertex is required to be less than 0.1%. This cut is designed to eliminate higher multiplicity decays and fake decay vertices caused by secondary interactions. Since it is possible for the secondary vertex to be reconstructed upstream of the primary vertex because of finite resolution and due to fake vertices, we require that the secondary decay vertex be reconstructed downstream of the primary vertex. Based on Monte Carlo studies of the momentum spectrum of this Ω_c^0 decay, the momentum of the $\Sigma^+K^-K^-\pi^+$ combination is required to be greater than 50 GeV/c.
Figures 1(a) and 1(b) show separately the $\Sigma^+K^-K^-\pi^+$ invariant mass plots for the two decay modes of the Σ^+, $\Sigma^+ \to p\pi^0$ and $\Sigma^+ \to n\pi^+$ respectively. The cuts used were as described above. A peak in both plots at a mass of about 2.7 GeV/c^2 is clearly evident and remains even with a large variety of different event selection criteria.

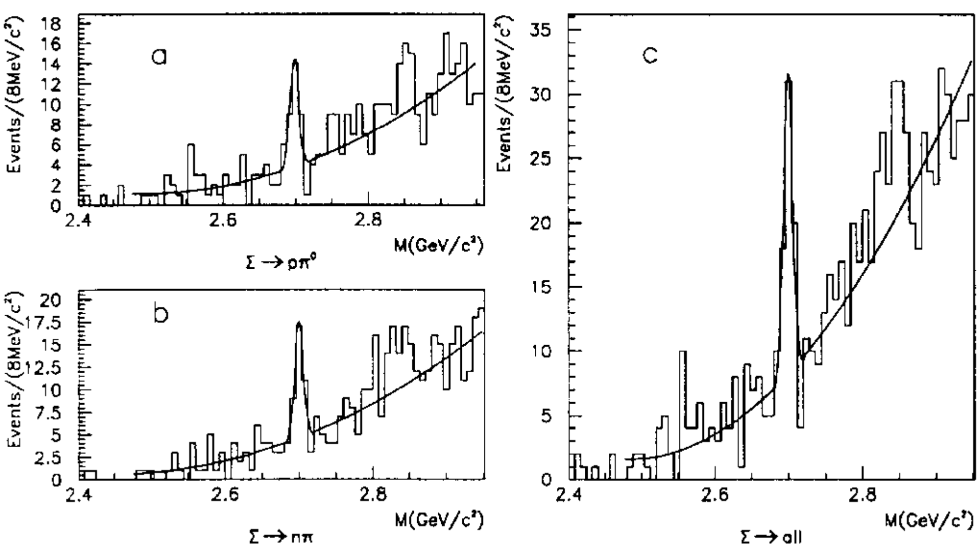

Fig. 1: $\Sigma^+K^-K^-\pi^+$ invariant mass: (a) for $\Sigma^+ \to p\pi^0$ decay mode, (b) for $\Sigma^+ \to n\pi^+$ decay mode, (c) for both decay modes of Σ^+.

The fits shown are to a Gaussian peak over a quadratic background. The fitted mass and width of the peak for the $p\pi^0$ mode are 2699.7±2.5 MeV/c^2 and 5.5±1.3 MeV/c^2 respectively, and for the $n\pi^+$ mode they are 2700.4±2.0 MeV/c^2 and 5.7±1.3 MeV/c^2. The two masses agree well with each other. Figure 1(c) shows the total $\Sigma^+K^-K^-\pi^+$ invariant mass plot using both Σ^+ decay modes. The fit to this mass distribution gives a yield of 42.4±9.0 events at a mass of 2699.9±1.5 MeV/c^2. The fitted width is 5.9±1.0 MeV/c^2, which is consistent with the experimental mass resolution. For the mass measurement we have investigated the effect of events containing a two-fold ambiguity in the Σ^+ momentum[7]: these events make up less than about 30% of the total. Any two-fold ambiguity leads to two candidate combinations with different $\Sigma^+K^-K^-\pi^+$ invariant masses. This was studied in a Monte Carlo analysis and also in data by using different methods of resolving the two-fold ambiguity. No significant shift in the measured mass was seen and we assign an uncertainty of 0.2 MeV/c^2 associated with the two-fold ambiguity. We have also investigated the overestimate of the true number of signal events due to the two-fold ambiguity. We estimated this effect to be less than 8%. According to Monte Carlo analyses we assign a systematic uncertainty of 2.0 MeV/c^2 on our absolute mass scale for this mass measurement. No systematic shifts associated with our choice of binning, fitting function, fitting method and choice of selection criteria have been observed, but, since their study was limited by statistics, we conservatively assign an upper limit of 1.5 MeV/c^2 in the systematic uncertainty in the mass. Adding the different systematic uncertainties incoherently we obtain a final mass measurement for the Ω_c^0 of 2699.9±1.5(stat)±2.5(syst) MeV/c^2.

3. Conclusions

In summary, we report an observation of 42.4±9.0 events in a new decay mode of the $\Omega_c^0 \rightarrow \Sigma^+K^-K^-\pi^+$ at a mass of 2699.9±1.5(stat.)±2.5(syst.) MeV/c^2. This strengthens the evidence for the existence of the Ω_c^0, and at a mass lower than that given by the ARGUS measurements but consistent with our previous measurement using the decay mode $\Omega_c^0 \rightarrow \Omega^-\pi^+$.

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The Physics of Charm Lifetimes

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THE PHYSICS OF CHARM LIFETIMES

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ABSTRACT

Charm particle lifetimes provide a laboratory for the study of inclusive charm decays. Recent charm lifetime results from Fermilab photoproduction experiment E687 are presented and the physics impact of these results is discussed.

1. Introduction

There is growing interest in the application of Heavy Quark Effective Theory to weak decays of charm and beauty hadrons.[1] This treatment constitutes an expansion in inverse powers of the heavy quark mass, and thus leads to a systematic procedure for including non-perturbative effects if the heavy quark mass is large enough. Although this is not the case for charm, a $1/m_c$ expansion may still be useful. However, rather than using this method to make predictions for weak decays of charm, we can use experimental measurements on charm decays to define the validity of the method and help discriminate between "choices" that arise in its application.[2] Recent charm lifetime results will be presented and it will be shown that we have now entered the stage where these measurements can tell us how QCD should work at the charm mass scale.

2. Lifetime Measurements

Data collected by Fermilab photoproduction experiment E687 have been used to measure the lifetimes of the D^0, D^+, D_s^+, Λ_c^+, Ξ_c^+ and Ξ_c^0 charm hadrons. The E687 detector is described in detail elsewhere.[3]

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The following decay modes were used in the lifetime analyses: $D^0 \rightarrow K^-\pi^+$; $D^+ \rightarrow K^-\pi^+\pi^+$; $D_s^+ \rightarrow \phi\pi^+$; $\Lambda_c^+ \rightarrow pK^-\pi^+$; $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$; and $\Xi_c^0 \rightarrow \Xi^-\pi^+$. For the D^0 lifetime analysis, both directly produced D^0 mesons and ones produced via $D^{*+} \rightarrow D^0\pi^+$ were used. The decay length was used in the lifetime analyses. To avoid using large acceptance corrections at short proper times, the reduced proper time was used. This amounts to "starting the clock" at a later time, instead of using the absolute time. The lifetime resolution is typically 0.05-0.06 ps depending on the decay mode. The lifetimes were determined using a binned maximum likelihood method, where events from the mass sidebands were used to model the background lifetime distributions. Extensive studies were made to investigate possible systematic effects associated with backgrounds, the fit method and acceptance uncertainties. The lifetime measurements are shown in Table 1. The 1992 world averaged lifetimes are also shown for comparison.[4] Details of the different lifetime measurements are described in detail elsewhere.[5]

Table 1. Lifetime measurements from E687 and Particle Data Group 1992 world averages. The mean of these two are also given together with the total percentage error on the mean.

	Lifetimes in 10^{-12} sec.		
Particle	E687	PDG'92	Mean (% error)
D^0	$0.413\pm0.004\pm0.003$	0.420 ± 0.008	0.415 ± 0.004 (1%)
D^+	$1.048\pm0.015\pm0.011$	1.066 ± 0.023	1.055 ± 0.015 (1.4%)
D_s^+	$0.475\pm0.020\pm0.007$	0.450 ± 0.030	0.466 ± 0.017 (3.6%)
Λ_c^+	$0.215\pm0.016\pm0.008$	$0.191^{+0.015}_{-0.012}$	0.200 ± 0.011 (5.5%)
Ξ_c^+	$0.41^{+0.11}_{-0.08}\pm0.02$	$0.30^{+0.10}_{-0.06}$	0.35 ± 0.06 (17%)
Ξ_c^0	$0.101^{+0.025}_{-0.017}\pm0.005$	$0.082^{+0.059}_{-0.030}$	$0.097^{+0.023}_{-0.015}$ (20%)

It is interesting to compare the lifetimes of the different charm particles. The lifetime ratios $\frac{\tau(D^+)}{\tau(D^0)} = 2.54 \pm 0.04$ and $\frac{\tau(D^0)}{\tau(\Lambda_c^+)} = 2.08 \pm 0.12$ are conclusively different from unity. The ratios $\frac{\tau(D_s^+)}{\tau(D^0)} = 1.12 \pm 0.04$, $\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)} = 1.75 \pm 0.32$, $\frac{\tau(\Lambda_c^+)}{\tau(\Xi_c^0)} = 1.75 \pm 0.32$, and $\frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)} = 3.61 \pm 0.94$ are different from unity by about 2.5-3.0σ. A definite lifetime hierarchy is emerging but we still require better precision to to make this more conclusive. We also still need an accurate and precise measurement of the Ω_c^0 lifetime to complete the picture. At present the data shows the following lifetime hierarchy:

$$\tau(D^+) > \tau(D_s^+) > \tau(D^0) \sim \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0).$$

3. Theoretical Picture

Much progress has been made in the use of "heavy quark expansions" as a systematic procedure for including non-perturbative corrections to inclusive charm decays.[2,6–8]

The decay width of the charm hadron is given by:

$$\Gamma(H_c) = \Gamma_0 \left(1 + \frac{A_2}{m_c^2} + \frac{A_3}{m_c^3} + ...\right).$$

Higher order $(1/m_c^4)$ terms have not been calculated but they are expected to play a role in charm decays. The A_2 term is different between mesons and baryons, and also it causes a 50% correction in the D meson inclusive semileptonic branching ratio (BR_{SL}).[7] In the spectator model with QCD radiative corrections BR_{SL} is expected to be about 15%. With just the $1/m_c^2$ corrections, the D mesons should all have BR_{SL} about 8%. The usual spectator corrections due to W-exchange/W-annhilation (WX/WA) and Pauli Interference (PI) are contained in the $1/m_c^3$ term. This term is as large as the $1/m_c^2$ and normal spectator decay terms and are different between the different mesons. This picture fits in well with the charm meson lifetimes and BR_{SL}. The D^+ lifetime and BR_{SL} is increased due to PI with WX in D^0 playing a small part. WX is both helicity and color suppressed and its contribution is difficult to calculate reliably. However the difference between the D^0 and D_s^+ lifetimes can give information on the size of WX/WA contributions in charm meson decays.[8]

Table 2. Charm baryon lifetime hierarchies from different authors.

Blok and Shifman[2] using F_D	$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$
using f_D	$\tau(\Omega_c^0) > \tau(\Xi_c^+)$
Voloshin and Shifman[9]	$\tau(\Xi_c^+) \approx \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$
Guberina, Rückl and Trampetić[10]	$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) \approx \tau(\Omega_c^0)$
Cheng[11]	$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) \geq \tau(\Omega_c^0)$
Gupta and Sarmar[12]	$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Xi_c^0) \geq \tau(\Lambda_c^+)$

The lifetime hierarchy for charm baryons has been calculated by a number of authors.[2,9-12] Some of these are shown in Table 2. Gupta and Sarmar[12] use a purely phenomenological analysis without considering PI. Blok and Shifman[2] are the only ones to include $1/m_c^2$ terms and not drop non-leading $1/N_c$ terms. Only Blok and Shifman, and Voloshin and Shifman[9] take hybrid logs into account. These partly take into account soft gluon radiative corrections.[2] Voloshin and Shifman use values of C_+, C_- calculated at $\Lambda_{QCD} \sim 100$ MeV, whereas the others use $\Lambda_{QCD} \sim$250-300 MeV. In calculations of the WX/WA and PI terms using the NQM, $|\psi(0)|$ can be related to the decay constant of the D meson, f_D. However, since f_D can also be expanded in $1/m_c$, $f_D = F_D[1 + (a_1/m_c) + ...]$, one should use F_D to be consistent. In fact Blok and Shifman have to use f_D for mesons and F_D for baryons in order that their lifetimes match data. The Ω_c^0 has a spin correlation with the spectator quarks like the D mesons but unlike the other charm baryons. This gives rise to a spin $1/m_c^2$ term which has been included only by Blok and Shifman. Because of the spin correlation for Ω_c^0, Blok and Shifman also try to use f_D for the Ω_c^0. Guberina, Rückl and Trampetić[10] use the "real world values" of f_D and $(M_{\Sigma_c^+} - M_{\Lambda_c^+})$ that appear in $|\psi(0)|$. Cheng[11] includes

Cabibbo suppressed WX terms for Ξ_c^+ and Ω_c^0, and uses a semileptonic width of half that used by Guberina, Rückl and Trampetić.

It can be seen that although a heavy quark expansion provides a systematic procedure for the inclusion of non-perturbative corrections, the realm of its validity and the exact implementation are not yet clear. However it appears that experimental measurements of the charm lifetimes can provide information on this.

4. Summary and Conclusions

Recent measurements of the lifetimes of D^0, D^+, D_s^+, Λ_c^+, Ξ_c^+ and Ξ_c^0 charm hadrons have been presented. All the measurements are comparable in precision and accuracy with the Particle Data Group 1992 world averages. Taken together, a definite lifetime hierarchy is emergying:

$$\tau(D^+) > \tau(D_s^+) > \tau(D^0) \sim \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0).$$

This is still at the 2.5–3.0σ level, so more precise measurements are needed to determine the hierarchy more conclusively. There exists a systematic procedure for the inclusion of non-perturbative corrections to inclusive charm decays. However its realm of validity and the exact implementation are not yet clear. A conclusive lifetime hierarchy based on experimental measurements should help define the correct implementation and hopefully in the process educate us on applications of QCD at the charm scale.

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Photoproduction of Charmed Hadrons

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PHOTOPRODUCTION OF CHARMED HADRONS

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ABSTRACT

Photoproduction data can be used to test QCD production mechanisms. In this paper we present results on the single-inclusive p_t^2 distributions of charm mesons and baryons, correlations between fully reconstructed charm pairs, and production asymmetries between charm and anticharm particles.

1. Introduction

Distributions such as the semi-inclusive p_t^2 spectra of photoproduced charmed hadrons as well as correlations between fully reconstructed $D\overline{D}$ pairs can be used to test QCD production mechanisms. In particular, the data may be compared to the next-to-leading order (NLO) single-inclusive cross sections[1] and the more recent NLO calculation for doubly-differential distributions.[2] Nonperturbative effects such as fragmentation also play an important role; one gauge of such effects is the production asymmetry between charm and anticharm particles.

The results presented here are from data collected by the Fermilab high energy photoproduction experiment E687 (average photon energy $\approx$ 200 GeV) during the 1990-91 fixed-target run at Fermilab. The data sample for this analysis consists of approximately 55000 fully reconstructed charm particles in the following decay topologies: $D^+ \rightarrow K^-\pi^+\pi^+$, $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ (both D^0 modes reconstructed with and without a D^{*+} tag), $D_s^+ \rightarrow K^-K^+\pi^+$, $\Lambda_c^+ \rightarrow pK^-\pi^+$, together with their charged conjugates.

2. Inclusive p_t^2 Distribution

In figure 1 are shown the observed p_t^2 spectra for the D^+ and Λ_c^+ states. The distribution was fit to the the form $dN/dp_t^2 = Aexp(ap_t^2 + bp_t^4)$. In Table 1 the data are compared to a Monte Carlo simulation in which the charm quarks are produced through the photon-gluon fusion mechanism at leading order in QCD and are decayed using the Lund model of string fragmentation.[4] Also shown is the prediction from the NLO calculation of FMNR[2] for photoproduced charm quarks at our beam energy. The

*For a complete list of co-authors, see H.W.K. Cheung, *"The Physics of Charm Lifetimes"*, these proceedings.

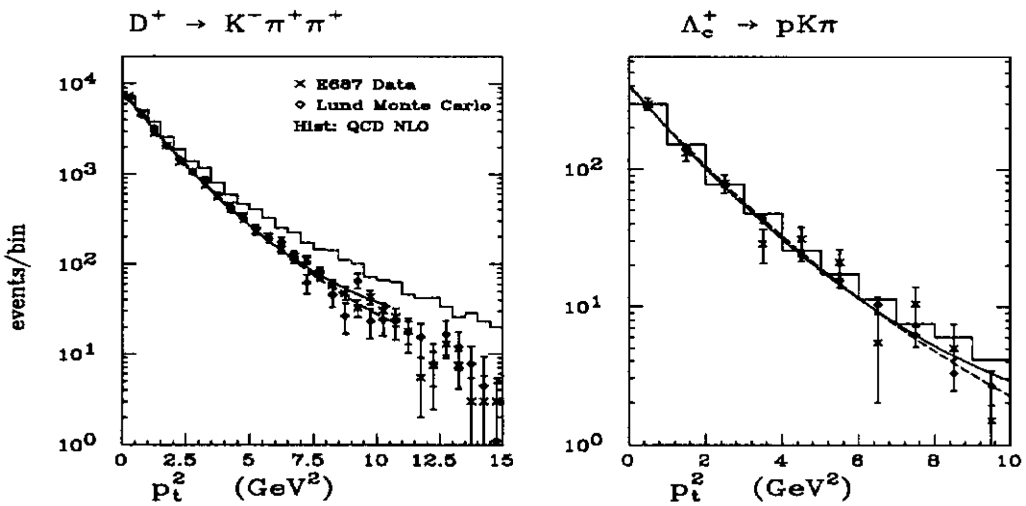

Fig. 1. The inclusive p_t^2 distribution from the E687 experiment (crosses) compared to Monte Carlo (diamonds) and to the NLO calculation for charm quarks from FMNR[2] (solid histogram).

significant disagreement with our data indicates that nonperturbative effects play an important role for D decay but less so for Λ_c decays. The FMNR authors have studied the inclusion of nonperturbative effects by supplementing their NLO result with a fragmentation function (which softens the p_t^2 distribution considerably) and by adding an intrinsic k_t component to the incoming partons. After inclusion of these effects the agreement with our data (Table 1) is considerably improved.

Table 1. Fits to p_t^2 distribution for photoproduced charm decays: NLO QCD theory[2], E687 data, and Monte Carlo simulations based on LO QCD and the Lund fragmentation model.

	a	b
QCD NLO	-0.656	0.021
+ frag + $< k_t^2 >= 1$ GeV^2	-0.947	0.035
$D^+ \to K\pi\pi$	-0.84 ± 0.02	0.030 ± 0.002
Lund Monte Carlo	-0.79 ± 0.02	0.023 ± 0.002
$\Lambda_c^+ \to pK\pi$	-0.75 ± 0.09	0.025 ± 0.011
Lund Monte Carlo	-0.70 ± 0.03	0.018 ± 0.004

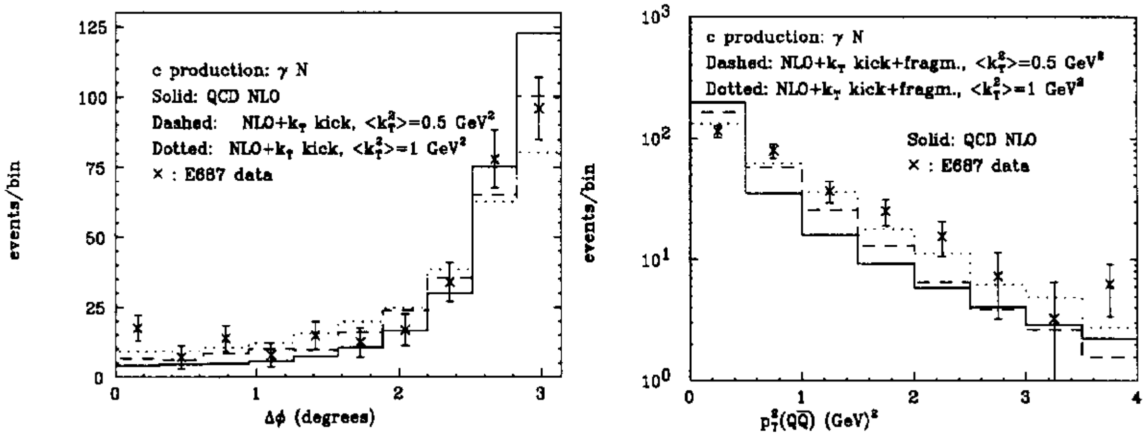

Fig. 2. The $\Delta\phi$ and p_t^2 distributions of the $D\overline{D}$ pair (E687 data) compared to the NLO prediction of FMNR[2] with and without the inclusion of nonperturbative effects. (Figure from Ref. 2.)

3. Charm Pairs

Correlations between two fully reconstructed D's can also be used to test QCD production models. The acoplanarity angle $\Delta\phi$ is the azimuthal angle between the D and $\overline{D}$ momentum vectors in the plane transverse to the photon direction. At leading order it is π radians. The p_t^2 of the $D\overline{D}$ pair is expected to be 0 at leading order. In Fig. 2 our sample[3] of 325 ± 23 fully reconstructed $D\overline{D}$ pairs is compared to the NLO QCD predictions.[2] Again, when the NLO result is supplemented with a fragmentation model and an intrinsic k_t kick the agreement with our data is considerably improved.

4. Production Asymmetries

At leading order in QCD, charm and anticharm quarks are produced symmetrically through the photon-gluon fusion mechanism. As the charm quarks fragment into colorless charmed hadrons, soft gluons are exchanged and thus nonperturbative effects may induce an asymmetry between charmed and anticharmed species. For example, in the Lund string fragmentation model[4] the struck gluon leaves the target nucleon in a color octet state which can be divided into a color antitriplet diquark and triplet quark, both of which are color connected to the charm quarks participating in the hard interaction. Since the color triplet charm quark must on average be closer in rapidity to the diquark, a condition which would favor charm baryon production as well as soften the D momentum spectrum, the model predicts a small enhancement of $\overline{D}$ meson production over D which should decrease with increasing beam energy.

In Fig. 3 we plot preliminary measurements of the production asymmetry, defined

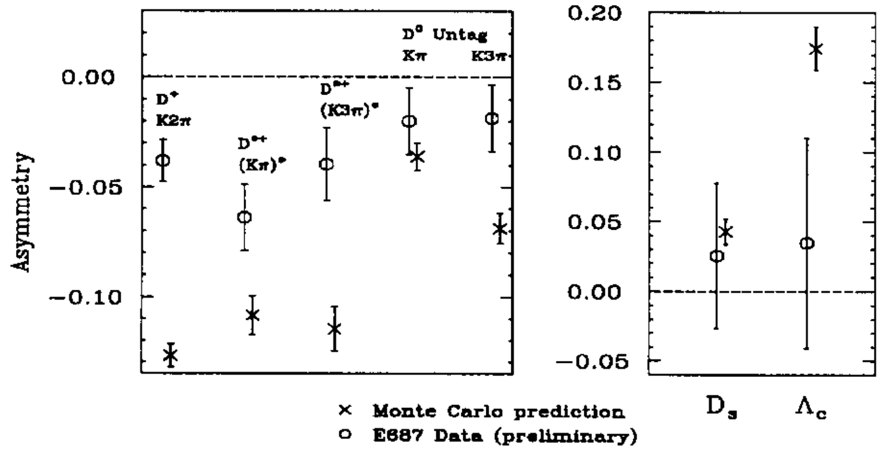

Fig. 3. The production asymmetry α (see text for definition) for D, D_s and Λ_c.

as $\alpha = \frac{N_D - N_{\overline{D}}}{N_D + N_{\overline{D}}}$. Also shown are Monte Carlo predictions based on the Lund Model. We observe small negative asymmetries for each of the D decay modes and small (but not statistically significant) positive asymmetries for both D_s and Λ_c decays. In general the measured asymmetries are much smaller than the Lund Model predictions.

5. Conclusions

We find that NLO calculations combined with nonperturbative models can yield a satisfactory description of our data. The $\Delta\phi$ ($D\overline{D}$ acoplanarity) is consistent with NLO supplemented with dressing and an intrinsic k_t kick of $\approx .5$ GeV^2. The inclusive p_t^2 distribution requires a larger k_t kick ($\approx$ 1-2 GeV^2) to overcome fragmentation effects. E687 observes a small enhancement of $\overline{D}$ over D production in the kinematic region $E_\gamma \approx 200$ GeV. Our preliminary result for the asymmetry averaged over D meson states is $\alpha = -3.7 \pm 0.6\%$. We note that no asymmetry is expected in leading order perturbative QCD. The asymmetry is smaller than Lund fragmentation model predictions and exhibits a much less severe kinematic dependence. Finally, at our energies we observe no significant excess of D_s^+ over D_s^- or Λ_c^+ over Λ_c^-.

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