A study of kinematical correlations between charmed particles produced in π -Cu interactions at $\sqrt{s} = 26$ GeV

The BEATRICE Collaboration

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Abstract

A sample of 475 events, in which two charmed-particle decays are observed, is analyzed to determine distributions of two-particle kinematic variables. One charmed particle with $x_F > 0$ is fully reconstructed and the other is at least partially reconstructed. The distributions of $\Delta\phi$ and p_T^2 are compared with a next-to-leading order QCD calculation.

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1 Introduction

Hadroproduction of heavy quarks is an important testing ground for Quantum Chromodynamics (QCD). Recent perturbative calculations to next-to-leading order (NLO), *i.e.* $O(\alpha_s^3)$, are believed to be of sufficient accuracy that useful comparisons can be made between experimental data and theoretical predictions [1]. For charm production, however, the mass is not sufficiently large for higher order perturbative effects to be negligible, thus significant discrepancies with experimental results might still exist. The observed experimental correlations between charmed particles provide a test of the NLO QCD calculations.

In this letter we report measurements of correlation variables which relate kinematic quantities for two charmed particles produced in a single event by experiment WA92. We have previously reported results on the azimuthal angle $\Delta\phi$ between charmed particles [2]. Now we improve our previous analysis in three ways. First, we include measurements of kinematic correlation variables, in addition to the topological variable $\Delta\phi$. Second, we use the full statistics of the experiment, increasing the sample size by approximately a factor of 5; third, we include the corrections due to an improved study of the acceptance of the detector.

The measurement of $\Delta\phi$ does not require knowledge of the magnitudes of the two charmed-particle momenta; however, this information is required for other kinematic correlation variables and must be either measured or estimated. The variables we have measured, in addition to $\Delta\phi$, include the invariant mass $M(D\bar{D})$, the rapidity difference $\Delta y = y(D) - y(\bar{D})$, the Feynman x difference $\Delta x_F = x_F(D) - x_F(\bar{D})$, the Feynman x of the $D\bar{D}$ system, and the square of the transverse momentum of the $D\bar{D}$ pair $p_T^2(D\bar{D})$, where p_T is relative to the incident beam particle direction. These variables are useful in subsequent comparisons with the predictions of charm production models.

Data were collected using a 350 GeV/c π^- beam incident on a 2 mm copper target in the CERN Ω Spectrometer. WA92 was conceived as a fixed-target beauty hadroproduction experiment, so the apparatus was designed to study short-lived particles. The main features of the experimental hardware are a fast online secondary vertex trigger and a high precision silicon microstrip detector array which provides excellent track visualization. The trigger, although designed to select beauty decays, also has significant efficiency for charm decays, which permits the present measurement. The silicon tracking array is divided into a Decay Detector (DkD) consisting of 17 planes of 10 μm pitch silicon microstrips covering the first 2.5 cm downstream of the target, followed by a Vertex Detector (VxD) consisting of 12 planes of 25 μm pitch and 5 planes of 50 μm pitch. The DkD has analogue readout so that secondary interactions in the detector material may be identified by their large energy deposits. Cuts on the recorded pulse heights in the vicinity of secondary vertices reduce by $\sim 91\%$ the number of vertices due to secondary interactions in the material of the DkD. More details of the description and performance of the experimental apparatus can be found in Refs. [3, 4]. The experiment collected data in 1992 and 1993 with a total luminosity of 8.1 nb^{-1} .

2 Event selection

Events are selected in which one charmed particle is fully reconstructed, while reconstruction of the decay vertex is all that is required for the second. Requiring both charmed particles to be fully reconstructed would reduce the sample size by a factor ~ 45 (*i.e.* to ~ 10 events). This factor is consistent with charm branching fractions and with our ac-

ceptance and reconstruction efficiency. Due to detector acceptance, all fully reconstructed charmed particle decays have a positive value of Feynman x ; the partially reconstructed decays may have either positive or negative x_F . Only events with two secondary vertices within 6 cm of the target are considered. The reconstructed positions of the secondary vertices are required to be outside of the target and to be separated from the primary vertex by at least 6σ (1.2 mm on average), where σ is the r.m.s. precision in the vertex separation. In addition, they are required to be separated from each other by at least $100\mu\text{m}$ in the plane transverse to the beam direction. Since our vertex reconstruction has a transverse accuracy of $\sigma \sim 3\text{--}10\mu\text{m}$, this last requirement excludes with high probability events in which a single vertex is split into two vertices by reconstruction errors.

As the fully reconstructed charm vertex must be physically compatible with a Cabibbo favoured decay $D \rightarrow Kn\pi$ ($n = 1, 2, 3$), its total charge is required to be 0 or ± 1 and its total momentum vector is required to point to the primary vertex within $30\mu\text{m}$. At this stage no cut is applied on the charmed candidate's invariant mass, except that 2-prong vertices compatible with K^0 or Λ^0 decays are rejected.

Softer cuts are applied to the second vertex. Any pairs of tracks belonging to it which have opposite charge and whose momentum sum points to the primary vertex within $60\mu\text{m}$ must be incompatible with K^0 or Λ^0 decays. e^+e^- pairs from photon conversions are automatically excluded as they would be detected as a single track in the silicon microstrip detectors which are located in a zone of weak magnetic field. The invariant mass of the vertex, assuming pion mass for all particles, must be less than $1.9\text{ GeV}/c^2$. There is no requirement on the vertex charge, on the number of tracks, nor on pointing to the primary vertex.

From the events which satisfy the previous requirements, 690 (2251) in the 1992 (1993) data, we extract two samples: the signal sample if the mass of the fully reconstructed vertex in the hypothesis $D \rightarrow Kn\pi$ equals the D mass $\pm 15\text{ MeV}/c^2$; and a side-band sample if the invariant mass M is in the region $1.69 < M < 1.78\text{ GeV}/c^2$ or $1.96 < M < 2.05\text{ GeV}/c^2$. The range and width of the side-bands has been chosen to allow the subtraction of a linear background distribution and at the same time to minimize the statistical error of this subtraction. There are 123 (441) events in the signal sample and 129 (407) events in the side-band sample for the 1992 (1993) data. Since our apparatus cannot distinguish between π and K , mass assignments for 2- and 4-prong vertices are ambiguous. All combinations are considered equally. Thus it is possible for a 2-prong vertex, for example, to be used twice — once in the signal sample and once, with the opposite mass assumptions, in the side-band sample. As the width of the side-bands is 6 times the width of the signal region, all combinations in the side-bands are given weight $1/6$. The 1992 and 1993 experimental setups were slightly different so the two data sets were analyzed independently. They were found to be compatible, so only the combined results are presented.

3 Momentum estimator

As previously noted, the momenta of the charmed particles is not needed for the measurement of $\Delta\phi$; however, it is required for the determination of the other correlation variables. Thus it is necessary to have an estimator for the momentum of the partially reconstructed vertex which takes into account the unseen decay products. We use a combination of two methods that are based on different physical considerations. The first method consists in closing the charm decay by adding a missing particle, assumed to have

Figure 1: *Error of the momentum estimator described in Section 3. The difference between the reconstructed and the simulated charm momentum is displayed as a function of the simulated momentum. The vertical error bars represent the r.m.s. width of the reconstructed momentum distribution.*

a pion mass. Requiring the vertex to have the charm mass and requiring that its total momentum vector point to the primary vertex, a second order equation is obtained with two possible solutions for the charm momentum. We choose the lower of the two charm momentum solutions since the apparatus has no acceptance for low-momentum charged particles (below $\sim 1 \text{ GeV}/c$) and, therefore, there is a greater probability that a missing particle makes a small contribution to the total momentum. The second method has been used by other experiments [10, 11] and is based on the assumption that in the rest frame of the charmed particle the unseen momentum is emitted on average in a direction perpendicular to the charm laboratory momentum. The Lorentz boost γ_D from the charm rest frame to the laboratory frame is then given by

$$\gamma_D = \frac{E_{vis}}{\sqrt{M_{vis}^2 + p_{T_{vis}}^2}}$$

where E_{vis} is the visible energy, $p_{T_{vis}}$ is the visible transverse momentum, and M_{vis} is the mass of the visible system, calculated assigning the pion mass to all the detected particles. The charm momentum can be deduced imposing the charm mass:

$$p_D = \beta_D \gamma_D M_D.$$

A comparison between these two methods and the simulation indicates that both methods give useful and independent information; however the first method systematically underestimates the momentum while the second method systematically overestimates it. The

best estimator for the charm momentum is a weighted average of the results of the two methods. The optimal weights are acceptance dependent; for our experimental setup equal weights give a good result. Finally, a 10% correction compensates for the underestimation of the visible mass due to the assignments of pion masses to kaons, yielding an accuracy of

$$\sigma_p/p = 0.012 + 3.2 \cdot 10^{-4}p$$

where p is in GeV/ c (see Fig. 1). The resulting fractional errors on the correlation variables are well below 10% over most of the range of their measurements. Obviously, if the secondary vertex momentum sum points to the primary vertex and the visible mass is compatible with the D mass, neither of the two methods is applied, and the visible momentum is used.

Figure 2: *Invariant mass distributions for: a) data; b) simulated $c\bar{c}$ events.*

4 Background subtraction and acceptances

The invariant mass distribution for the fully reconstructed vertex is shown in Fig. 2a. Fitting the data mass distributions with a Gaussian peak above a linear background, we find that the background in the signal region is $\sim 15\%$ for both the 1992 and 1993 data sets.

The main contribution to the background is from poorly reconstructed vertices in charm events and has been estimated using a Monte Carlo simulation. The $c\bar{c}$ events were produced by a combination of Pythia 5.4 [5] for leading order QCD generation of the initial $c\bar{c}$ quark pair, Jetset 7.3 [6] for their hadronization, and Fluka [7] for nuclear effects in the target; detector responses were simulated with Geant 3.21 [8] interfaced with Fluka and Jetset 7.4 [9] as described in ref. [4]. Monte Carlo events were selected by the

same criteria as those applied to the data; the resulting distribution is shown in Fig. 2b. Comparison of the data and Monte Carlo distributions shows that the charm events with reconstruction errors account for all the background in this mass interval.

Background distributions of each of the correlation variables were obtained from the side-band data sample. The signal sample was then corrected by subtracting the background distributions.

Acceptance corrections for each of the variables being studied were determined from simulated $D \rightarrow Kn\pi$ decays with $x_F > 0$. Events were generated separately for each decay channel and for both the 1992 and 1993 configurations. Comparisons of the simulated and reconstructed values show that the experimental precision in each variable is smaller than the bin sizes in Figs. 3 and 4, therefore acceptance corrections were evaluated by dividing each distribution of reconstructed events by the corresponding distribution of generated events. The distributions of real events shown in Figs. 3 and 4 include these acceptance corrections.

Figure 3: $\Delta\phi$ and $p_T^2(D\bar{D})$ distributions. The lines show for comparison the results of the NLO QCD calculation for $\langle k_T^2 \rangle = 1 \text{ GeV}^2/c^2$ (solid) and $\langle k_T^2 \rangle = 2 \text{ GeV}^2/c^2$ (dashed).

5 Results

Figs. 3 and 4 show the distributions of the charm correlation variables after background subtraction and acceptance correction. The distributions observed are similar in shape to those of other experiments [10]–[21], and in statistics to the previous highest statistics experiment [18]. Table 1 reports the mean values found by the present analysis for all measured correlation variables. As we can distinguish D^+/D^0 mesons from $D^-/\bar{D}^0$,

Figure 4: *Distributions of a) $D\bar{D}$ invariant mass, b) rapidity difference between D^+/D^0 and $D^-/\bar{D}^0$, c) Feynman- x difference between D^+/D^0 and $D^-/\bar{D}^0$, d) Feynman- x of the $D\bar{D}$ system.*

Table 1: *Mean values and r.m.s. of the correlation variables.*

$\langle \Delta\phi \rangle$	$102.4 \pm 3.6 \text{ degrees}$
$\langle p_T^2 \rangle$	$1.90 \pm 0.17 \text{ GeV}^2/c^2$
$\langle M(D\bar{D}) \rangle$	$5.02 \pm 0.16 \text{ GeV}/c^2$
$\langle \Delta y \rangle$	-0.18 ± 0.09
$\sigma(\Delta y)$	1.37 ± 0.06
$\langle \Delta x_F \rangle$	-0.072 ± 0.031
$\sigma(\Delta x_F)$	0.30 ± 0.02
$\langle x_F(D\bar{D}) \rangle$	0.23 ± 0.03

we present the difference distributions Δx_F and Δy as “charm minus anticharm”. The asymmetry in these distributions is thought to result from asymmetry in quark contents of the beam and target particle.

The $\Delta\phi$ and p_T^2 distributions are plotted in Fig. 3 along with the results of a model based on a NLO QCD calculation [22] which includes non-perturbative effects such as hadronization and initial transverse momentum of the incident partons [23].

The theoretical curves are calculated using $m_c = 1.5 \text{ GeV}/c^2$, $\mu_R = \sqrt{m_c^2 + p_T^2}$, $\mu_F = 2\mu_R$, $\Lambda_{QCD}^5 = 140 \text{ MeV}$, the SMRS $\pi 2$ [24] and MRSD- [25] parton distribution functions (respectively for the beam and target particle) and the Peterson fragmentation function [26]. In this model the combined effects of inaccuracies in the hadronization model, higher order QCD, and Fermi motion of the partons within the incident hadrons are incorporated into an intrinsic transverse momentum k_T of the initial partons relative to the incident beam particle direction. Predictions are displayed for $\langle k_T^2 \rangle = 1 \text{ GeV}^2/c^2$ and $\langle k_T^2 \rangle = 2 \text{ GeV}^2/c^2$.

Comparison of the data and theoretical calculations suggests that a value of $\langle k_T^2 \rangle$ between 1 and 2 GeV^2/c^2 would be compatible with both distributions, although the p_T^2 distribution favours a larger value of $\langle k_T^2 \rangle$ than the $\Delta\phi$ distribution. Inaccuracies in the hadronization model (for example, in this particular model, the lack of any contribution to transverse momentum from the fragmentation process) are incorporated into $\langle k_T^2 \rangle$, which may explain the large values of $\langle k_T^2 \rangle$ needed to describe the data. Hadronization is expected to have less influence on $\Delta\phi$ than on p_T^2 , which may account for the apparent difference in the values of $\langle k_T^2 \rangle$ favoured by the two distributions. Other possible contributory factors include the inadequacy of the NLO QCD expansion for quark masses of the order of m_c and nuclear effects in the target which can modify the direction of flight of the outgoing D meson with respect to the c quark direction.

The distributions of correlation variables presented in Fig. 4 involve the longitudinal momenta of the charmed particles. These depend essentially on the details and parameterization of the hadronization process, rather than being a feature of the NLO QCD calculations. Within the context of this model, no meaningful prediction is available for comparison with the data.

6 Conclusions

This paper presents correlations observed in the WA92 experiment between two charmed particles produced in π^- -Cu interactions at $\sqrt{s} = 26 \text{ GeV}$, where one of the charmed particles, which is fully reconstructed, has positive x_F . The distributions observed are similar in shape and statistics to the previous highest statistics experiment. A

comparison has been made between the $\Delta\phi$ and p_T^2 distributions observed and a model based on NLO QCD. It is found that qualitative agreement between the data and the model requires the introduction of an intrinsic transverse momentum k_T with $\langle k_T^2 \rangle$ between 1 and 2 GeV²/c².

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References

- [1] M. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B373 (1992) 295.
- [2] M. Adamovich et al., BEATRICE Coll., Phys. Lett. B348 (1995) 256.
- [3] M. Adinolfi et al., BEATRICE Coll., Nucl. Instr. Meth. A329 (1993) 117.
- [4] M. Adamovich et al., BEATRICE Coll., to be published in Nucl. Instr. Meth. A.
- [5] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 46 (1987) 43.
- [6] T. Sjöstrand and M. Bengtsson, Comput. Phys. Commun. 43 (1987) 367.
- [7] A. Fassò et al., Proc. IV International Conference on Calorimetry and their Applications, La Biodola, Italy (World Scientific, 1994) 493.
- [8] GEANT Detector Description and Simulation Tool, CERN Program Library Long Writeup W5013 (1994).
- [9] T. Sjöstrand, Comput. Phys. Commun. 82 (1994) 74.
- [10] M. Aguilar-Benitez et al., LEBC-EHS Coll., Phys. Lett. B161 (1985) 400.
- [11] K. Kodama et al., E653 Coll., Phys. Lett. B263 (1991) 579.
- [12] M. Aguilar-Benitez et al., LEBC-EHS Coll., Z. Phys. C40 (1988) 321.
- [13] M. Aguilar-Benitez et al., LEBC-EHS Coll., Phys. Lett. B164 (1985) 404.
- [14] K. Kodama et al., E653 Coll., Phys. Lett. B263 (1991) 573.
- [15] K. Kodama et al., E653 Coll., Phys. Lett. B284 (1992) 461.
- [16] S. Barlag et al., ACCMOR Coll., Z. Phys. C39 (1988) 451.
- [17] S. Barlag et al., ACCMOR Coll., Z. Phys. C49 (1991) 555.
- [18] S. Barlag et al., ACCMOR Coll., Phys. Lett. B302 (1993) 112.
- [19] S. Aoki et al., WA75 Coll., Progr. Theor. Phys. 87 (1992) 1315.
- [20] S. Aoki et al., WA75 Coll., Phys. Lett. B209 (1988) 113.
- [21] J.A. Alves et al., E769 Coll., Phys. Rev. Lett. 69 (1992) 31.
- [22] M. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B405 (1993) 507.
- [23] S. Frixione, M. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B412 (1994) 225.
- [24] P.J. Sutton, A.D. Martin, R.G. Roberts, W.J. Stirling, Phys. Rev. D45 (1992) 2349.
- [25] A.D. Martin, R.G. Roberts, W.J. Stirling, Phys. Rev. D43 (1991) 3648.
- [26] C. Peterson, D. Schlatter, I. Schmitt, P. Zerwas, Phys. Rev. D27 (1983) 105.