**MEASUREMENTS OF CHARMED-MESON PRODUCTION
IN INTERACTIONS BETWEEN 350 GeV/c π^- PARTICLES AND NUCLEI**

Beatrice collaboration

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Abstract

Charmed-meson production by 350 GeV/c π^- particles incident on copper and tungsten targets has been studied in the WA92 experiment, performed at the CERN Ω' spectrometer. Results obtained are reported and discussed. Reconstruction of decays from the set $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow \phi \pi^+$ and charge conjugates has yielded a sample of 7280 ± 108 charmed mesons, produced with $x_F > 0$, $\langle x_F \rangle = 0.18$ and $\langle p_T^2 \rangle = 1.86$ (GeV/c)². Assuming a relationship $\sigma = \sigma_0 A^\alpha$ between the cross-section, σ , per nucleus of mass A and the nucleonic cross-section, σ_0 , the α value found for the detected charmed particles is $0.95 \pm 0.06 \pm 0.03$. Taking $\alpha = 1$, the measured cross-sections per nucleon for $x_F > 0$ production are $7.78 \pm 0.14 \pm 0.52$ μ barn for $D^0/\bar{D}^0$, $3.28 \pm 0.08 \pm 0.29$ μ barn for D^+/D^- and $1.29 \pm 0.16 \pm 0.33$ μ barn for D_s^+/D_s^- . Differential cross-sections with respect to x_F and p_T^2 have been determined for the various types of charmed meson, and particle-antiparticle asymmetries have been analysed.

PACS: 12.38.Qk; 13.85.Ni; 14.40.Lb; 25.80.Ls*Keywords:* charmed-meson hadroproduction; cross-section measurements; nuclear-mass dependence of cross-sections; x_F and p_T^2 distributions; particle-antiparticle asymmetries

1. INTRODUCTION

Particle production in hadron-hadron collisions can be viewed in quantum chromodynamics (QCD) as arising from interactions between the hadrons' partonic constituents. In the case of a parton-parton interaction where the modulus, Q , of the transferred four-momentum is large with respect to the relevant QCD scale parameter, Λ , perturbative quantum chromodynamics (PQCD) is applicable and the interaction's cross-section may be calculated via a power-series expansion in the strong coupling constant $\alpha_s(Q^2) \propto 1/\ln(Q^2/\Lambda^2)$. Partonic processes in which there is creation of a charmed quark, c , and associated antiquark, $\bar{c}$, have Q at least of the order of the charmed-quark mass, $m_c \sim 1.5 \text{ GeV}/c^2$, so that PQCD-based descriptions of such processes might be expected to be valid. Next-to-leading-order ($\mathcal{O}(\alpha_s^3)$) PQCD calculations of $c\bar{c}$ hadroproduction properties have been performed [1]. Being affected by the choices of renormalization scale and factorization scale, and by the lack of precise knowledge concerning parton-density functions, m_c and Λ , the numerical predictions are subject to considerable uncertainties.

The hadroproduction properties measured experimentally for charmed mesons can differ from those computed to $\mathcal{O}(\alpha_s^3)$ in PQCD for charmed quarks, because of effects that might be associated with the higher-order corrections to the perturbative calculations or with processes not treated in PQCD, for example the emission of low- Q^2 gluons by initial-state partons and the fragmentation of $c\bar{c}$ pairs into charmed hadrons. Several theoretical models that, to a greater or lesser extent, are intended to take into account such effects have been developed. In the parton-shower model [2] a single parton-parton interaction, via branchings of one parton into two or more partons, generates a cascade of partons and these may be caused to hadronize through mechanisms such as those of the Lund string model [3]. In the intrinsic-charm model [4] charmed-particle production brought about by the emergence of a $c\bar{c}$ pair from the parton sea of an interacting hadron is contemplated. In the intrinsic- k_T model [5,6] the momentum of an interacting parton is assigned a transverse component having a modulus, k_T , chosen in conformity with the probability-density function $P(k_T^2) = \langle k_T^2 \rangle^{-1} \exp(-k_T^2/\langle k_T^2 \rangle)$, with $\langle k_T^2 \rangle$ an input parameter of the model.

Comparisons [6-8] made between theoretical predictions and experimental data indicate that measurements of charmed-meson hadroproduction are largely consistent with the expectations of PQCD. As anticipated above however, there are features of the data that cannot be accounted for by PQCD alone. Additional experimental measurements serve to improve understanding of the relative importance in charmed-meson hadroproduction of processes not treated in PQCD and to provide tests of the applicability of the models put forward for their description.

This paper contains a presentation of results from CERN experiment WA92 on the production of charmed mesons by 350 GeV/ c π^- particles incident on copper (Cu) and tungsten (W) targets. An analysis of the full WA92 data set, comprising 1.37×10^8 triggers, has been performed and a sample of 7280 ± 108 charmed mesons, identified via reconstruction of the decays $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow \phi \pi^+$ and charge conjugates, has been extracted. Results are given on the total and differential cross-sections of the various charmed mesons and on the dependence of the cross-sections on the mass of the target nuclei. These results are compared with measurements from other experiments and with theoretical predictions.

2. WA92 EXPERIMENT

The WA92 experiment [9] was performed at the Ω' spectrometer [10], central to which is a superconducting dipole magnet that has a peak field strength of 1.8 T and a bending power of 7.2 Tm. Use was made of a beam of 350 GeV/ c π^- mesons (one 2.6 s spill of 4.2×10^6 particles every 14.4 s; 1.2% K^- contamination) from the CERN Super Proton Synchrotron, the beam particles being directed onto a target that was in the form of a 2-mm-thick metal disc. Data recording for the experiment took place in

1992, when 0.47×10^8 triggers with a Cu target and 0.37×10^8 triggers with a W target were accumulated, and, with a slightly modified setup, in 1993, when 0.53×10^8 triggers with a Cu target were collected. The experimental apparatus (Figure 1) and trigger are treated at length elsewhere [11] and here will be described only summarily. The reference system employed is a right-handed (x, y, z) Cartesian system that has its origin at the target centre, has its z -axis parallel to the direction of the spectrometer's magnetic-field vector and has its x -axis approximately coinciding with the line of flight of the beam particles.

Charged-particle tracking in the vicinity of the target, located 350 cm upstream of the mid-point of the spectrometer and in a region of low magnetic field, was accomplished using a series of silicon-microstrip detector (SMD) planes, grouped to form a Beam Hodoscope, a Decay Detector and a Vertex Detector. The Beam Hodoscope, which provided for reconstruction of the paths of incoming pions, extended over an interval of 80 cm upstream of the target and consisted of ten SMD planes, nine of $20 \mu\text{m}$ pitch and one of $50 \mu\text{m}$ pitch. Occupying the first 3 cm downstream of the target and optimised for tracking in the x - z projection, the Decay Detector comprised seventeen SMD planes, each having $10 \mu\text{m}$ pitch and $5.12 \times 5.12 \text{ mm}^2$ active area. Microstrips of the Decay-Detector planes had individually set thresholds and analogue readout. The Vertex Detector extended from $x = 6 \text{ cm}$ to $x = 63 \text{ cm}$ and consisted of seventeen SMD planes, twelve of $25 \mu\text{m}$ pitch and five of $50 \mu\text{m}$ pitch. Measurements of z coordinates were provided by six planes, measurements of y coordinates were provided by six planes in 1992 and by seven planes in 1993; information from the remaining planes enabled matching of the x - z and x - y projections.

Charged-particle tracking over the bulk of the spectrometer volume was performed using multiwire proportional chambers and drift chambers, the latter positioned downstream of the spectrometer magnet. The momentum-measurement accuracy, σ_p/p^2 , was $10^{-3} (\text{GeV}/c)^{-1}$ for particles tracked through the multiwire proportional chambers only and $3 \times 10^{-4} (\text{GeV}/c)^{-1}$ for particles tracked through both the multiwire proportional chambers and the drift chambers.

Downstream of the tracking detectors there was an electromagnetic calorimeter, followed by a muon filter. The electromagnetic calorimeter consisted of an active sampler, a shower-position detector, and the calorimeter proper, an array of 18×19 lead-glass blocks of surface area $14.35 \times 14.35 \text{ cm}^2$ and depth 47 cm (18.5 radiation lengths and 1.3 interaction lengths). The muon filter comprised two shielded detection zones, each of which contained three layers of 3×2 resistive-plate chambers, with two layers for measurement of z coordinates and one layer for measurement of y coordinates. Each of the resistive-plate chambers had readout electrodes segmented in strips of 31 mm pitch and covered an area of $2 \times 1 \text{ m}^2$.

Online event selection was performed using a multi-component trigger [11] that was optimized for collection of events in which there were decays of beauty hadrons ($b\bar{b}$ events) and, relative to unbiased inelastic interactions, also gave a small enrichment (3-6), albeit with comparatively low acceptance (5-10%), for events featuring charmed-particle production ($c\bar{c}$ events).

A trigger for beam particles and a trigger for interactions were formed using (Figure 2) six scintillation counters, denoted S1, S2, V1, S3, S4, V2, and a $300\text{-}\mu\text{m}$ -thick silicon-strip detector, to be referred to as the in-target (IT) counter. The counts from these two triggers are used in the determination (Section 5) of the total numbers of beam particles incident on target and so provide the absolute normalization for cross-section measurements (Section 6). Counters S1, S2 and V1 were positioned upstream of the target, counters S3 and S4 were 10 cm downstream of the Vertex Detector and counter V2, used in flagging non-interacting beam particles, was 6.5 m downstream of the target. Consisting of twenty-two active strips of area $10 \times 0.2 \text{ mm}^2$, affixed to the downstream side of the target and oriented so as to measure z coordinates, the IT counter registered a signal when the energy release in any strip was greater than $\sim 500 \text{ keV}$, this approximately corresponding to the energy deposition of five minimum-ionizing particles. The beam-particle trigger was defined by the coincidence $S1 \cdot S2 \cdot \overline{V1}$ and the interaction trigger was defined by the coincidence $S1 \cdot S2 \cdot \overline{V1} \cdot IT \cdot S3 \cdot S4 \cdot \overline{V2}$. By requiring the IT signal in the latter it was ensured that

>93% of triggered interactions took place in the target, most of the remainder being in the IT counter itself or in the Decay Detector.

A trigger for particles having a large momentum component, p_{yz} , in the plane transverse to the beam-particle direction was obtained utilizing one of the multiwire proportional chambers and two butterfly-shaped hodoscopes [12]. Being subject to deflection in the field of the spectrometer magnet, a charged particle originating in or close to the target could traverse the two hodoscopes, and satisfy the trigger, only if it had $p_{yz} \geq 0.6$ GeV and a pseudorapidity, η , in the interval $3 < \eta < 6$.

A transverse-energy trigger exploited information from the electromagnetic calorimeter. Given the energy, E , recorded in a calorimeter block that in x , y and z had the centre of its front surface displaced relative to the target centre by amounts Δx , Δy and Δz respectively, the transverse energy, E_{yz} , was estimated as: $E_{yz} = E [(\Delta y^2 + \Delta z^2)/(\Delta x^2 + \Delta y^2 + \Delta z^2)]^{1/2}$. Disregarding blocks in the calorimeter's central three rows, where the multiplicity of hadronic interactions was high, and blocks affected by noise at the calorimeter's borders, the transverse-energy trigger required that at least two blocks registered $E_{yz} \geq 0.65$ GeV.

A muon trigger was implemented using twin processors that, receiving data from those of the muon-filter's resistive-plate chambers that measured z coordinates and employing a coincidence-matrix logic, identified candidate muons consistent with an origin in the target.

A secondary-vertex trigger used custom-built hardware that processed signals from some of the silicon-based detectors. The z coordinate at which an interaction occurred was estimated from the coordinates of the hit strips recorded by two of the SMD planes of the Beam Hodoscope and, in 1993 only, by the IT counter. Working with the information given by the six Vertex-Detector planes that measured z coordinates, tracks were reconstructed in the xz projection and, in this projection, each track's impact parameter, IP_{z_T} , with respect to the estimated position of the interaction point was evaluated. A track was classified as primary if it had $IP_{z_T} \leq 100 \mu\text{m}$ or as secondary if it had $IP_{z_T} > 100 \mu\text{m}$. Only tracks having $IP_{z_T} \leq 1000 \mu\text{m}$ were searched for by the reconstruction algorithm. The secondary-vertex trigger required that three or more primary tracks and a given number of secondary tracks be identified.

An event was written to tape if it was selected by the interaction trigger and either the muon trigger flagged the presence of ≥ 2 muon candidates or the conditions imposed by any of the admitted combinations of the various triggers were satisfied (Table 1).

3. EVENT SIMULATION

Simulated minimum-bias interactions and simulated $c\bar{c}$ events are respectively used (Section 5) in the evaluation of the interaction-trigger's overall acceptance, needed for the absolute normalization of the data sample, and in the determination of the reconstruction efficiencies for the charmed-meson decays of interest. The possibility that some fraction of the charmed mesons isolated in the present analysis might derive from beauty-hadron decays is investigated through a consideration (Section 5) of simulated $b\bar{b}$ events.

Minimum-bias interactions have been generated using Fluka [13] as interfaced to Geant 3.21 [14]. Of special consequence for the simulation of the behaviour of the IT counter, the production of heavily ionizing particles as represented by Fluka is consistent with published data.

Events in which there is creation of a heavy quark, Q , and its antiquark, $\bar{Q}$, have been generated using the Lund packages Pythia 5.4 [15] and Jetset 7.3 [16] to model hard-scattering processes and using Fluka to include nuclear effects, the most important being the production of heavily ionizing particles, mentioned above. Employing a parton-shower approach in conjunction with PQCD calculations performed to leading order, Pythia simulated the production of a $Q\bar{Q}$ pair in a collision between a π^- having a fraction, ξ , of the beam-pion momentum and a nucleon. For the generation of $b\bar{b}$ events ξ was assigned a fixed value of $340/350 \approx 0.97$, whereas for the generation of $c\bar{c}$ events, after tuning to have approximate agreement with

WA82 data [17], ξ was distributed over the interval $0.27 \leq \xi \leq 1$ as $P(\xi) \propto \xi^5(1-\xi)$ and had a mean value of 0.75. Hadronization of the Q and $\bar{Q}$ was performed by Jetset, following the prescription of the Lund string model [3]. An interaction between a π^- and a target nucleus was then simulated by Fluka, the π^- having assigned to it the beam-particle momentum not carried away by the $Q\bar{Q}$ hadronization products. A complete event consisted of the particles created in the $Q\bar{Q}$ hadronization and the Fluka interaction products.

The passage of particles through the experimental apparatus and the detector responses have been simulated in detail using Geant 3.21, with particle decays and secondary interactions taken into account. Decays of particles not allowed for in the default Geant data tables, and including all hadrons containing b or c quarks, were defined by Jetset 7.4 [18], interfaced with Geant for this purpose. Particle masses, lifetimes and branching fractions were essentially those of the 1992 Review of Particle Properties [19], except that weakly decaying beauty hadrons were ascribed a lifetime of 1.52 ps. Detector inefficiencies and random noise were added in accordance with experimental measurements. Trigger responses for fully simulated events were arrived at through a close mimicking of the online event-selection procedures.

Comparisons between results for simulated minimum-bias interactions and data from the WA92 experiment have been made [11], and show that the simulation reproduced well the experimental trigger rates and the observed particle multiplicities and kinematics. Uncertainties in reconstructed track and vertex parameters for simulated events were consistent with the corresponding uncertainties for experimental data.

4. ANALYSIS PROCEDURE

Events collected during the 1992 data taking were subject to an offline filtering designed to reinforce the online trigger selection and to save on the total computing time needed for analysis. An event was immediately passed by the filter program if flagged by the muon trigger as containing ≥ 2 muon candidates. Otherwise, track reconstruction in the x - z projection was performed using information from the Beam Hodoscope and from the Vertex Detector. The (x, z) coordinates of an event's primary-interaction vertex were estimated from a consideration of track crossings and, remaining in the x - z projection, each track's impact parameter, IP_{z_F} , with respect to the vertex was calculated. Events containing < 2 tracks with $IP_{z_F} < 60 \mu\text{m}$ were rejected. An event selected by the secondary-vertex trigger was required to have ≥ 2 tracks with $IP_{z_F} \geq 80 \mu\text{m}$ if recorded with the Cu target, or ≥ 2 tracks with $IP_{z_F} \geq 96 \mu\text{m}$ if recorded with the W target. An event not selected by the secondary-vertex trigger was required to have ≥ 2 tracks with $IP_{z_F} \geq 60 \mu\text{m}$ or ≥ 1 track with $IP_{z_F} \geq 80 \mu\text{m}$. In the case of an event flagged by the muon trigger as containing a single muon candidate, it was additionally required that hits registered by the resistive-plate chambers of the muon filter could be associated with at least one of the tracks found in the Vertex Detector. The filter program passed 29% of the events recorded with the Cu target, retaining an estimated 70% of $c\bar{c}$ events, and passed 33% of the events recorded with the W target, retaining 81% of $c\bar{c}$ events.

The trigger used in 1993 having been more selective than the trigger used in 1992 (Table 1), filtering was not considered necessary for the events from the second year of data collection.

Full spatial reconstruction [11] of tracks and vertices and identification of photons, electrons and muons were undertaken for events from the 1992 data taking that were accepted by the filter program and for all events from the 1993 data taking. The uncertainties on the x , y and z coordinates of a vertex depended on the vertex topology and on whether the tracks fitted to the vertex were measured in both the Vertex Detector and the Decay Detector or only in the Vertex Detector, but were typically in the ranges 100-450 μm , 4-12 μm and 3-11 μm respectively.

The present analysis is based on a consideration of secondary vertices found in events where the track of the incoming pion was reconstructed in the Beam Hodoscope and attached to a primary vertex located inside the target. Denoting the x coordinates of the upstream and downstream edges of the target by x_{T1}

and x_{T2} respectively, an event that had a primary vertex at $x = x_P \pm \sigma_{x_P}$ and that was to be accepted in the analysis was subject to the constraints $x_{T1} - x_P \leq 3\sigma_{x_P}$, $x_{T2} - x_P \geq 0.5\sigma_{x_P}$. The lower tolerance allowed on $x_{T2} - x_P$ was designed to reject events where there was ambiguity as to whether the incoming pion interacted in the material of the target or in the silicon of the IT counter. Simulation studies indicated that after enforcement of the conditions on primary-vertex position, satisfied by $\sim 95\%$ of $c\bar{c}$ events where the primary interaction was truly in the target, the fraction of accepted $c\bar{c}$ events where the primary interaction took place in the IT counter or in an SMD plane was negligible.

If an event contained more than one secondary vertex then each was treated separately. A secondary vertex placed at $x = x_S \pm \sigma_{x_S}$, in the region covered by the Decay Detector and the Vertex Detector, and formed from two tracks with net associated charge 0 (V2 vertex), from three tracks with net associated charge ± 1 (C3 vertex), or from four tracks with net associated charge 0 (V4 vertex), was selected as a candidate decay vertex if certain criteria were satisfied. With the aim of excluding vertices to be attributed either to secondary interactions in the target or to reconstruction errors of a type common in regions of high track density, it was required that a candidate decay vertex be outside of the target: $x_S - x_{T2} \geq 1$ mm, $x_S - x_{T2} \geq 3\sigma_{x_S}$; and well separated from the primary vertex: $x_S - x_P \geq 8(\sigma_{x_P}^2 + \sigma_{x_S}^2)^{1/2}$. In order to discriminate against vertices produced by secondary interactions in the downstream SMD planes, it was required that, extrapolated back from the secondary vertex, the vector obtained by summing over the momenta associated with the secondary-vertex tracks have, in the x - z projection, an impact parameter of ≤ 20 μm with respect to the primary vertex. It was further required that the secondary-vertex coordinates be uncorrelated with the position of any large energy release registered in the Decay Detector, such an energy release usually resulting from nuclear break-up in an hadronic interaction. A V2 vertex was rejected if it could be regarded as being due to the decay of a K^0 or $\bar{K}^0$ ($\pi^+\pi^-$ mass between 0.460 GeV/c^2 and 0.518 GeV/c^2) or of a Λ^0 or $\bar{\Lambda}^0$ ($p^\pm\pi^\mp$ mass between 1.095 GeV/c^2 and 1.135 GeV/c^2).

The events containing the selected candidate decay vertices were divided into samples according to year of data taking and target material, and different decay channels were analysed separately, a distinction being maintained between particle decays and antiparticle decays. Physics results obtained for individual event samples and decay channels were combined when this was appropriate.

Invariant masses were calculated for the candidate decay vertices, where for a V2 vertex the hypothesised decay products were $K^\mp\pi^\pm$, for a V4 vertex the hypothesised decay products were $K^\mp\pi^\mp\pi^\pm\pi^\pm$ and for a C3 vertex the hypothesised decay products were $K^\mp K^\pm\pi^\pm$ if either combination of unlike-sign particles gave a $K^\mp K^\pm$ mass between 1.005 GeV/c^2 and 1.035 GeV/c^2 , so that the particles concerned could be interpreted as coming from the resonance decay $\phi \rightarrow K^-K^+$, or $K^\mp\pi^\pm\pi^\pm$ otherwise. Given that there was no pion or kaon identification, all permutations of mass assignments compatible with the charge constraints were admitted. In the centre-of-mass frame of primary interactions, the momentum component, p_T , with respect to the beam-pion direction, evaluated on an event-by-event basis, and the ratio, χ_F , of the momentum component along the beam-pion direction to the component's kinematically permitted maximum, were determined for each particle hypothesised as generating a candidate decay vertex, with the invariant mass computed for the vertex taken into account. Fractional uncertainties in the χ_F and p_T^2 values obtained were typically less than $\pm 3\%$. Data relating to the infrequent cases ($< 2\%$ of the statistics) where $\chi_F \leq 0$ was found were explicitly excluded from subsequent analysis.

Signals for the decays $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$ and their charge conjugates were seen as peaks in the distributions (Figure 3) of the calculated invariant masses. Representing a signal peak and its background by a Gaussian and an exponential respectively, binned maximum-likelihood fits of the invariant-mass spectra were performed, then the numbers of reconstructed decays (Table 2) and the quantities of background under the signal peaks were ascertained from the fit parameters. For the channels considered, the signals obtained correspond to the decays of a

total of 7280 ± 108 charmed mesons (84% produced in Cu, 16% produced in W) above a background of 3859 ± 77 entries. Results for the amounts of signal and background were the same, within uncertainties, if the background was modelled by a second-degree polynomial.

Given an invariant-mass distribution containing a peak fitted by a Gaussian of mean M and standard deviation σ_M , where σ_M was typically in the range 6-9 MeV/ c^2 , the interval $M \pm 3\sigma_M$ was defined as the signal region, a lower sideband was defined by the interval 1.71 GeV/ c^2 - 1.79 GeV/ c^2 and an upper sideband was defined by the interval 2.02 GeV/ c^2 - 2.10 GeV/ c^2 in the case that the hypothesised decay products were $K^\mp K^\pm \pi^\pm$, or by 1.94 GeV/ c^2 - 2.02 GeV/ c^2 otherwise. The distributions of $\mathcal{X}_F$ and p_T^2 relative to background entries in the signal region were obtained from entries in the sidebands, appropriately normalized. No appreciable difference was seen between distributions relative to entries in lower sidebands and distributions relative to entries in upper sidebands. From the $\mathcal{X}_F$ and p_T^2 distributions (Figure 4) obtained directly from the data, the measured signal is significantly above the level of the background for $\mathcal{X}_F < 0.7$ and for $p_T^2 < 18$ (GeV/ c)². The mean $\mathcal{X}_F$ and p_T^2 of the detected charmed mesons were $\langle \mathcal{X}_F \rangle = 0.18$ and $\langle p_T^2 \rangle = 1.86$ (GeV/ c)² respectively.

Taking into account the target material and year of data collection referred to, simulated events were processed in the same way as events recorded in the experiment.

5. ABSOLUTE NORMALIZATION AND ACCEPTANCES

The number, N_π , of beam particles incident on target during a given data-taking period has been evaluated from the counts, N_{int} , recorded by the interaction trigger as:

$$N_\pi = \frac{F_{tag} N_{int}}{\epsilon_{int}} \left(1 - \exp \left[- \frac{\Delta x \rho \sigma_{inel} N_A}{A} \right] \right)^{-1},$$

where A , ρ and σ_{inel} are the target-material's molar mass, density and inelastic π^- -nucleus cross-section respectively, Δx is the target thickness, F_{tag} is the fraction of triggered interactions that occur in the target, ϵ_{int} is the interaction-trigger acceptance for inelastic interactions in the target and N_A is the Avogadro constant. Uncertainties in the values obtained (Table 3) are dominated by the uncertainties in σ_{inel} and ϵ_{int} . The inelastic cross-sections used, 0.624 ± 0.019 barn per nucleus for Cu and 1.362 ± 0.088 barn per nucleus for W, are from measurements [20] appertaining to π^- particles of 280 GeV/ c but, from the observed slow evolution of the cross-section with π^- momentum over the momentum range 60 GeV/ c to 280 GeV/ c , can be expected to differ negligibly from the cross-sections for 350 GeV/ c π^- interactions. Values of F_{tag}/ϵ_{int} have been deduced from considerations of simulated minimum-bias events and have overall uncertainties of $\pm 4\%$, due mainly to the uncertainty in the proportion of interactions resulting in a total charged-particle multiplicity of ≤ 3 .

Direct measurements of the numbers of beam particles incident on target were provided by the counts of the beam-particle trigger (Table 3) but were disregarded in the analysis as their uncertainties, associated with indeterminacies in the noise levels and efficiencies of the trigger-defining scintillators and related electronics, and expected to be of the order of $\pm 5\%$, could not be reliably calculated. Most significantly, losses associated with scaler deadtimes (~ 10 ns per count), important when counting the high-rate ($\sim 1.6 \times 10^6$ s⁻¹) beam-particle triggers but not relevant to the counting of the lower-rate ($\sim 1.1 \times 10^4$ s⁻¹) interaction triggers, were not well known. The direct measurements nonetheless support the numbers derived from the counts of the interaction trigger.

Efficiencies for reconstructing decays of forward ($\mathcal{X}_F > 0$) charmed mesons have been obtained as functions of the decaying-particle's $\mathcal{X}_F$ (Figure 5) and p_T^2 (Figure 6) from a consideration of 1.4×10^6 fully simulated $c\bar{c}$ events, in each of which one of the decays of interest was forced to occur (other decays taking place according to branching fractions) and the particle that had its decay mode preselected was generated with $\mathcal{X}_F > 0$. In the channels analysed, the number of simulated decays corresponded to roughly twice the

number of decays present in the experimental data. As a function of χ_F , the reconstruction efficiencies are peaked in the interval 0.1-0.5. Events containing charmed mesons of higher χ_F are generally characterised, at the WA92 energy, by comparatively small particle multiplicities and were disfavoured in the online selection because the interaction trigger, with the effect of the IT counter predominating, and the high- p_{yz} -particle trigger, were both biased towards events with larger multiplicities. Efficiencies initially rise with charmed-meson p_T^2 because, the separation, in the y - z plane, of a charmed-meson's production and decay vertices tending to increase with the meson's p_T^2 , the decay-vertex-identification efficiency of the offline reconstruction program improved. The reduced efficiencies for charmed mesons of lower χ_F and for charmed mesons of higher p_T^2 were related to the geometrical acceptance of the apparatus.

As functions of a kinematic variable, q , by which decaying particles might be characterised, the number of reconstructed decays of a given type from forward particles and the associated decay-reconstruction efficiency will be denoted $N_R(q)$ and $\varepsilon_R(q)$ respectively. For the decay channels analysed, the form of $N_R(q)$ found experimentally and the form of $N_R(q)$ obtained for simulated events have been compared (Figure 7) for $q \equiv \chi_F$ and for $q \equiv p_T^2$. The χ_F dependence of the number of decays reconstructed for the experimental data and for simulated events is the same, within statistical uncertainties, for $\chi_F \leq 0.4$. At higher χ_F values the relative charmed-meson yield is overestimated in the simulation by up to a factor of 2, but as less than 10% of the forward charmed mesons have $\chi_F > 0.4$ the fraction of simulated charmed mesons that have χ_F generated incorrectly is extremely small. The form of $N_R(p_T^2)$ for the experimental data differs markedly from that for simulated events, but the largest differences are again for a region of phase space ($p_T^2 > 10 \text{ (GeV/c)}^2$) where the charmed-meson production rates are low. Since (Section 3, [11]) the simulation accurately represented the measured properties of minimum-bias interactions, the discrepancies noted here between simulation and experiment are to be understood as reflecting shortcomings of the model of charmed-meson production used in the generation of $c\bar{c}$ events.

Two methods of estimating the average efficiency for reconstructing a specified decay of a forward charmed meson have been considered. In the first case, the efficiency estimate, $\varepsilon_{tot}(\chi_F > 0)$, was the ratio of reconstructed decays to generated decays as given by the simulation, and so was subject to uncertainties relating to all imperfections of the $c\bar{c}$ event generator. In the second case, the efficiency estimate, $\varepsilon'_{tot}(\chi_F > 0)$, was obtained as:

$$\varepsilon'_{tot}(\chi_F > 0) = \frac{\int_0^{p_{Texp}^2} N_R(p_T^2) dp_T^2}{\int_0^{p_{Texp}^2} [N_R(p_T^2)/\varepsilon_R(p_T^2)] dp_T^2} ,$$

with p_{Texp}^2 , typically $\sim 20 \text{ (GeV/c)}^2$, the maximum p_T^2 for which the experiment had any sensitivity, $N_R(p_T^2)$ determined from experimental data and $\varepsilon_R(p_T^2)$ given by the simulation. Since the efficiencies that enter into the expression for $\varepsilon'_{tot}(\chi_F > 0)$ relate to individual p_T^2 values, $\varepsilon'_{tot}(\chi_F > 0)$ was approximately free of any error associated with inaccuracies in the p_T^2 spectrum of the simulated charmed mesons. As best estimates of the average reconstruction efficiencies (Table 4), the values adopted for the decays $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$ and their charge conjugates were those of the second method. These values were systematically higher than the corresponding values from the first method, $R_\varepsilon \equiv \varepsilon'_{tot}(\chi_F > 0)/\varepsilon_{tot}(\chi_F > 0)$ for the decays considered varying little with target material and decay topology and having a mean of $\langle R_\varepsilon \rangle = 1.03$. The reconstruction efficiencies used for the decays $D_s^+ \rightarrow \phi \pi^+$ and $D_s^- \rightarrow \phi \pi^-$, for which the form of $N_R(p_T^2)$ was poorly measured, were those of the first method multiplied by $\langle R_\varepsilon \rangle$. Contributions from charmed mesons with $p_T^2 > p_{Texp}^2$ were expected to be minute and have been neglected. Hypothesising that the (known) amount by which average decay-reconstruction efficiencies determined solely from the simulation needed to be corrected to allow for the inaccuracies in the p_T^2 spectrum of simulated charmed mesons was at least as great as the correction necessary to allow for all other inaccuracies in the modelling of charmed-meson production and decay in the simulation, the

magnitude of the systematic uncertainties in the best estimates of the average decay-reconstruction efficiencies was taken to be $\pm |\langle R_\varepsilon \rangle - 1| \approx \pm 3\%$. Additional uncertainties in the average efficiencies arise from the statistical uncertainties in $N_R(p_T^2)$ and in $\varepsilon_R(p_T^2)$, and have been taken into account (Table 4).

The analysis acceptance for charmed mesons from beauty-hadron decays has been evaluated using a sample of 75000 fully simulated $b\bar{b}$ events. For all data-taking configurations, charmed mesons from interactions are enriched with respect to charmed-mesons from beauty-hadron decays by more than a factor of 10. The enrichment is essentially due to the implied requirement (Section 4) that the reconstructed line of flight of a decaying particle should pass close to the interaction vertex. Given that the ratio of the beauty-hadron cross-section to the charmed-hadron cross-section is of the order of 0.001 at the WA92 energy, no charmed mesons from beauty decays are expected in the sample of charmed mesons used in the present study.

6. RESULTS AND DISCUSSION

6.1 Definitions

PQCD predictions to which reference will subsequently be made are based on next-to-leading-order calculations¹ where the values chosen for the charm-quark mass, m_c , the renormalization scale, μ_R , the factorization scale, μ_F , and the QCD scale parameter, Λ , were: $m_c = 1.5 \text{ GeV}/c^2$, $\mu_R = m_c$ for evaluation of total $c\bar{c}$ cross-sections, $\mu_R = (m_c^2 + p_T^2)^{1/2}$ for evaluation of differential cross-sections, $\mu_F = 2\mu_R$ and, for four active quark flavours, $\Lambda = 222 \text{ MeV}$. Use was made of the MRS235 [21] parton-density functions for nucleons and of the SMRS2 [22] parton-density functions for pions. The dependence of the $\mathcal{O}(\alpha_s^3)$ PQCD predictions on the values taken for m_c , μ_R , μ_F and Λ , and on the structure functions employed, has been analysed in detail elsewhere [5] and will be briefly noted when comparing theory and experiment.

Predictions from the Lund (Pythia/Jetset) event generator are with the generator as used in the WA92 event simulation (Section 3). All parameters of the Pythia and Jetset packages were set to their default values [18] and a total of 1.2×10^7 $c\bar{c}$ events was generated. As they are used in comparisons with acceptance-corrected data, these events were not processed by the detector-simulation program.

Throughout this section, unless otherwise indicated, the charmed-particle production properties considered relate to charmed particles with $x_F > 0$. Where a measurement is quoted with two uncertainties the first is statistical and the second is systematic.

6.2 Forward cross-sections and their nuclear-mass dependence

Charmed-meson forward production cross-sections have been determined from the numbers of reconstructed decays, the decay branching fractions and reconstruction efficiencies, and the numbers of π^- particles incident on target. The branching fractions used were those of the 1996 Review of Particle Properties [23]: $(3.83 \pm 0.12)\%$ for $D^0 \rightarrow K^- \pi^+$, $(7.50 \pm 0.40)\%$ for $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, $(9.10 \pm 0.60)\%$ for $D^+ \rightarrow K^- \pi^+ \pi^+$ and $(1.77 \pm 0.44)\%$ for $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$. Cross-section values obtained have statistical uncertainties that are dominated by uncertainties in the numbers of reconstructed decays, but also take into account the statistical components of the uncertainties in decay-reconstruction efficiencies. Systematic uncertainties in the cross-section determinations include uncertainties in the numbers of incoming π^- particles ($\pm 5.0\%$ uncertainty for data with Cu target, $\pm 7.5\%$ uncertainty for data with W target), uncertainties in decay branching fractions (uncertainties for $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$ of $\pm 3.1\%$, $\pm 5.3\%$, $\pm 6.5\%$ and $\pm 25\%$ respectively) and the estimated systematic uncertainty of $\pm 3\%$ in the efficiencies for decay reconstruction. Results derived from the data collected in 1992 with Cu target and results derived from the data collected in 1993 (Cu target

¹ The program used to perform the PQCD calculations is the work of M.L. Mangano, P. Nason and G. Ridolfi [5].

throughout) were in agreement within the experimental uncertainties, with no evidence of any systematic shifts, and have been combined. Similarly, D^0 and $\bar{D}^0$ cross-sections obtained from consideration of V2 vertices matched, and have been combined with, the corresponding cross-sections determined from consideration of V4 vertices. For various sets of charmed mesons, cross-sections for individual charmed particles have been summed to give the cross-section for production of any of a set's members. Final results on production cross-sections per nucleus, for Cu and W nuclei, have been tabulated (Table 5).

The particle-production cross-section, σ , per nucleus of mass A is usually taken to be related to the nucleonic cross-section, σ_0 , via a single parameter, α , as $\sigma = \sigma_0 A^\alpha$. Values of α for charmed-meson production have been computed from the measured nuclear cross-sections as:

$$\alpha = \frac{\ln(\sigma_{Cu}/\sigma_W)}{\ln(A_{Cu}/A_W)},$$

where subscripts identify the target material. When calculating the ratio σ_{Cu}/σ_W , the systematic uncertainties in σ_{Cu} mostly cancelled those in σ_W . The α values found have an estimated systematic uncertainty of $\pm 3\%$ that remains because of the dependence of σ_{Cu}/σ_W on the ratio of the inelastic π^- -Cu cross-section to the inelastic π^- -W cross-section.

The results obtained (Table 5), with $\alpha(\{D^0, \bar{D}^0\}) = 0.92 \pm 0.07 \pm 0.02$, $\alpha(\{D^+, D^-\}) = 0.95 \pm 0.07 \pm 0.03$, $\alpha(\{D_s^+, D_s^-\}) = 1.12 \pm 0.30 \pm 0.03$, are in good agreement with $\alpha(\text{charmed hadron})$ measurements from other experiments [24-26] (Table 6) in which charmed-meson decays were fully reconstructed, and are consistent with the $\alpha(\text{charmed hadron})$ value of ~ 1 expected in the framework of PQCD. By contrast, analyses of lepton yields in beam-dump experiments [27-29] have given values for $\alpha(\text{charmed hadron})$ in the range 0.75 to 0.83 (Table 6), close to the $\alpha(\text{any hadron})$ value of ~ 0.76 measured [20] for interacting π^- particles of 60-280 GeV/c, and to be compared with the $\alpha(\text{any hadron})$ value of $2/3$ that would be observed if nuclei behaved as totally absorbing spheres and all nuclei had the same, uniform density. The relative sensitivity to charmed particles produced at large x_F tended to be greater in the beam-dump experiments than in the other experiments referred to, so that the lower $\alpha(\text{charmed hadron})$ values found in the former class of experiments might be interpreted as indicating that $\alpha(\text{charmed hadron})$ becomes smaller as the x_F of the detected charmed particles is increased. It is a prediction of the intrinsic-charm model [4] that $\alpha(\text{charmed hadron})$ should vary from ~ 1 for charmed particles with $x_F \sim 0$ to < 0.8 for charmed particles of high x_F and low p_T^2 . Decreases with rises in the x_F of the particles considered have previously been measured in proton-nucleus interactions for $\alpha(\text{any hadron})$ [30] and for $\alpha(J/\psi)$ [31].

Values of $\alpha(\{D^0, \bar{D}^0, D^+, D^-\})$ as a function of x_F and p_T^2 have been determined (Figure 8) from cross-sections calculated for limited ranges of the x_F and p_T^2 variables. Results agree with, and in terms of statistical significance are comparable to, the data of E769 [25] and WA82 [26]. Although, within their large uncertainties, not incompatible with the forecasts of the intrinsic-charm model, the measurements provide no evidence of $\alpha(\{D^0, \bar{D}^0, D^+, D^-\})$ varying with x_F or p_T^2 . That $\alpha(\{\text{charmed hadron}\})$ is independent of the x_F and p_T^2 of the charmed particles considered will be an assumption for the remainder of this section.

Combining results relating to the data recorded with Cu target and results relating to data recorded with W target, cross-sections per nucleon for forward production of the assorted charmed mesons have been calculated (Table 5) for $\alpha(\{\text{charmed hadron}\}) = 1$.

The aggregate forward cross-section for D^0 , $\bar{D}^0$, D^+ , D^- , D_s^+ and D_s^- is measured to be $12.37 \pm 0.19 \pm 0.86 \mu\text{barn}$ per nucleon. For comparison, the cross-section per nucleon for forward production by a 350 GeV/c π^- of a c or $\bar{c}$ is given by the $\mathcal{O}(\alpha_s^3)$ PQCD calculations, with the inputs chosen (Subsection 6.1), to be $12.9 \mu\text{barn}$. (The $c\bar{c}$ cross-section – half the cross-section for c or $\bar{c}$ production integrated over all x_F – is calculated to be $10.3 \mu\text{barn}$ per nucleon). It should however be noted that

over the range of plausible inputs to the perturbative calculations the absolute value of the predicted $c\bar{c}$ cross-section varies by more than an order of magnitude [5].

Relatively small uncertainties affect the PQCD prediction of the scaling of the π^- -nucleon cross-section for charm-quark production with the π^- momentum. Taking into account such scaling, the present measurements of $\sigma_0(\{D^0, \bar{D}^0\}) = 7.78 \pm 0.14 \pm 0.52 \mu\text{barn}$ per nucleon, $\sigma_0(\{D^+, D^-\}) = 3.28 \pm 0.08 \pm 0.29 \mu\text{barn}$ per nucleon and $\sigma_0(\{D_s^+, D_s^-\}) = 1.29 \pm 0.16 \pm 0.33 \mu\text{barn}$ per nucleon are consistent with results from other experiments [32-36] (Figure 9), these encompassing diverse π^- momenta between 200 GeV/c and 600 GeV/c and a variety of target materials.

Values have been determined for certain ratios of cross-sections (Table 7). When such ratios are evaluated, the systematic uncertainties associated with the individual cross-sections treated mostly cancel. Vestigial systematic uncertainties are due to uncertainties in the magnitudes of decay branching fractions that enter into the cross-section calculations. The WA92 values

$$\sigma_0(\{D^+, D^-\})/\sigma_0(\{D^0, \bar{D}^0\}) = 0.423 \pm 0.012 \pm 0.030 \text{ and}$$

$\sigma_0(\{D_s^+, D_s^-\})/\sigma_0(\{D^0, \bar{D}^0, D^+, D^-\}) = 0.116 \pm 0.014 \pm 0.029$ are in reasonable agreement with measurements from other experiments [17,32-38] (Table 7). Over the range 200-600 GeV/c, there is then no indication that the relative production frequencies of the various charmed mesons has a dependence on the momentum of the interacting π^- . The Lund event generator, for interactions between 350 GeV/c π^- particles and nucleons, gives $\sigma_0(\{D^+, D^-\})/\sigma_0(\{D^0, \bar{D}^0\}) = 0.472$, reproducing the WA92 result to within $\sim 10\%$, but substantially underestimates the relative probability for $D_s^\pm$ production to occur, predicting $\sigma_0(\{D_s^+, D_s^-\})/\sigma_0(\{D^0, \bar{D}^0, D^+, D^-\}) = 0.077$. Differences found experimentally between meson cross-sections and corresponding anti-meson cross-sections are commented on below.

6.3 Differential cross-sections

The x_F and p_T^2 distributions relative to entries in the signal regions of the invariant-mass spectra dealt with have been corrected bin by bin for background and for signal acceptance, and have then been normalized to yield charmed-meson differential cross-sections.

For $D^0, \bar{D}^0, D^+$ and D^- taken collectively, the forms of the measured differential cross-sections with respect to x_F and p_T^2 (Figure 10) are essentially compatible with those calculated for charmed quarks in the framework of PQCD. The data indicate that the differential cross-section for charmed-meson production decreases more rapidly with x_F than is predicted by the Lund event generator and decreases less rapidly with p_T^2 .

Making comparisons between differential cross-sections measured for charmed mesons and differential cross-sections predicted for charmed quarks by PQCD is not entirely satisfactory. Although the forms of the differential cross-sections given by PQCD calculations do not have a great sensitivity to the calculations' inputs it might be expected that, if they are to represent the data, the calculated results should be modified to take into account hadronization and other processes for which $\mathcal{O}(\alpha_s^3)$ PQCD provides no treatment. Some attempt to allow for such processes in a computation of the charmed-particle differential cross-section with respect to p_T^2 has been made in the context of the intrinsic- k_T model [5,6]. Here, the effect of adding to the momentum of an interacting parton a transverse component, k_T , is incorporated into the $\mathcal{O}(\alpha_s^3)$ PQCD calculations and partonic cross-sections are convoluted with a fragmentation function of Peterson form [39]. For the present purposes, as advocated elsewhere [5,6], the defining parameter of the fragmentation function is assigned a value of 0.06. The shape of the measured p_T^2 spectrum relating to $D^0, \bar{D}^0, D^+$ and D^- collectively is approximately reproduced by the intrinsic- k_T model if $\langle k_T^2 \rangle$ is taken to be $1\text{-}2 (\text{GeV}/c)^2$ (Figure 11). A $\langle k_T^2 \rangle$ value of around $2 (\text{GeV}/c)^2$ was previously found to be required for the intrinsic- k_T model to reproduce the forms of the charmed-meson p_T^2 spectra recorded in experiments WA82 and E769 [6], and is also consistent with WA92 measurements of correlations between pairs of associated charmed hadrons [40].

For the charmed-particle differential cross-section with respect to x_F , predictions based on $\mathcal{O}(\alpha_s^3)$ PQCD calculations complemented by a treatment of hadronization are not currently available.

Distributions from hadroproduction experiments of charmed-meson differential cross-sections with respect to x_F and p_T^2 are traditionally fitted as:

$$\begin{aligned}\frac{d\sigma_0}{dx_F} &= C_1 (1 - |x_F|)^n, \\ \frac{d\sigma_0}{dp_T^2} &= C_2 \exp(-b p_T^2),\end{aligned}$$

where C_1 , n , C_2 and b are fit parameters. The fitted curves tend to represent the experimental data imperfectly and the fit results generally have a dependence on the x_F and p_T^2 ranges considered. Nonetheless, by examining n and b values obtained in two different experiments it is possible to have some indication of whether the charmed-meson x_F and p_T^2 spectra measured in one of the experiments are similar in form to the corresponding spectra measured in the other experiment. For $x_F < 0.8$ and $p_T^2 < 7 \text{ (GeV/c)}^2$, the distributions of differential cross-sections reported here for D^0 , $\bar{D}^0$, D^+ and D^- are fitted (Figure 10) by $n = 4.27 \pm 0.11$, $b = 0.85 \pm 0.02 \text{ (GeV/c)}^{-2}$. The uncertainties quoted are statistical only but dominate over systematic uncertainties. Over the same x_F and p_T^2 ranges, the Lund-event-generator distributions of differential cross-sections for D^0 , $\bar{D}^0$, D^+ and D^- are fitted by $n = 3.53$, $b = 1.03 \text{ (GeV/c)}^{-2}$ and the PQCD distributions of differential cross-sections for charmed quarks are fitted by $n = 3.99$, $b = 0.89 \text{ (GeV/c)}^{-2}$. The fact, noted previously, that the experimental distributions have a greater resemblance to the PQCD distributions than to the Lund-event-generator distributions is then reflected in the n and b values found. Values of n and b relative to PQCD calculations have a certain sensitivity to the m_c value adopted: varying the m_c value by $\pm 0.3 \text{ GeV/c}^2$ about the value of 1.5 GeV/c^2 chosen here, all other calculational inputs being kept the same, produces a variation of around $\pm 10\%$ in the value obtained for n and a variation of around $\pm 15\%$ in the value obtained for b .

In previous experiments, in which the interacting π^- particles have had momenta of between 200 GeV/c and 600 GeV/c , n values ranging from 2.5 to 4.3 and b values ranging from $0.76 \text{ (GeV/c)}^{-2}$ to $1.18 \text{ (GeV/c)}^{-2}$ have been measured [33-37,41-43] (Table 8) for D^0 , $\bar{D}^0$, D^+ and D^- collectively. Such n and b values are similar in magnitude to those obtained in the present experiment. According to PQCD, raising the momentum of the interacting π^- from 200 GeV/c to 600 GeV/c should increase n by about 30% and should decrease b by some 15%. The experimental results do not provide strong evidence that n and b have a dependence on the interacting- π^- momentum, but neither do they exclude such a dependence. It is noted that in comparing n and b values determined in different experiments some allowance needs to be made for the fact that the x_F and p_T^2 intervals fitted are not always the same. In the case of the present data it was found that n increased by 10% when the x_F interval fitted was changed from 0.0-0.8 to 0.1-0.7, and that b was reduced by 5% if the p_T^2 interval fitted was changed from 0-4 (GeV/c)^2 to 0-10 (GeV/c)^2 .

The x_F spectra (Figure 12) measured for different types of charmed meson are not quite uniform in shape. In particular, the x_F spectrum of the D^+ has, as a function of increasing x_F , a more rapid fall off than the x_F spectrum of the D^- . The Lund event generator comes near to reproducing the diverse forms of the D^+ and D^- x_F spectra, but for larger values of x_F tends to give an inexact representation of the relative production frequencies of D^0 and $\bar{D}^0$. The p_T^2 spectra (Figure 13) measured for different types of charmed meson all have a similar profile, close to that of the p_T^2 spectrum predicted for charmed quarks by $\mathcal{O}(\alpha_s^3)$ PQCD.

6.4 Particle-antiparticle asymmetries

Differences in the production characteristics of two particles X_1 and X_2 may be quantified in terms of a production asymmetry, $Asym(X_1, X_2)$, where if, with reference to a specified phase-space region, X_1 and X_2 have production rates R_{X_1} and R_{X_2} respectively then:

$$Asym(X_1, X_2) = \frac{R_{X_1} - R_{X_2}}{R_{X_1} + R_{X_2}}.$$

Asymmetries as functions of x_F and p_T^2 have been determined for D^- with respect to D^+ and for D^0 with respect to $\bar{D}^0$ (Figure 14).

The value measured for $Asym(D^-, D^+)$ is close to 0 for $x_F = 0$, is around 0.4 for $x_F = 0.5$ and approaches 1, although with a large uncertainty, over the interval $0.6 < x_F \leq 1.0$. In the present experiment, use having been made of a π^- ($\bar{u}d$) beam, a D^- ($\bar{c}d$) was a leading particle, meaning that it might contain a valence quark surrendered by a beam hadron, whereas a D^+ ($c\bar{d}$) was a non-leading particle. The increase of $Asym(D^-, D^+)$ with x_F then evidences an enhancement of leading-charmed-meson production at higher x_F values. The mean value of $Asym(D^-, D^+)$ over the region of positive x_F is 0.146 ± 0.023 , corresponding to $\sigma_0(D^-)/\sigma_0(D^+) = 1.34 \pm 0.06$. Both the observed variation of $Asym(D^-, D^+)$ as a function of x_F and (Table 7) the value obtained for $\sigma_0(D^-)/\sigma_0(D^+)$ are in good agreement with measurements from E769 [37,44] and WA82 [38]. The observed x_F dependence of $Asym(D^-, D^+)$ agrees also with the measurement from the high-statistics experiment E791 [45]. At larger x_F values and for an incoming π^- , $\mathcal{O}(\alpha_s^3)$ PQCD marginally favours $\bar{c}$ generation over c generation [1], but the effect is too small to account for the rise of $Asym(D^-, D^+)$ with x_F recorded experimentally. Enhanced production of leading charmed mesons is included in the Lund event generator as a hadronization phenomenon, associated with couplings between charmed quarks and beam-particle remnants. The Lund event generator overestimates the ratio of D^- mesons to D^+ mesons for forward production, predicting $\sigma_0(D^-)/\sigma_0(D^+) = 2.25$, but has $Asym(D^-, D^+)$ vary as a function of x_F in a manner that, after a global normalization to the measured value of $\sigma_0(D^-)/\sigma_0(D^+)$, accords well with the data (Figure 14 a)).

Whereas a D^- produced in the experiment could be classed unequivocally as a leading particle and a D^+ was always a non-leading particle, a D^0 would be leading if generated directly or in the decay of a D^{*0} but non-leading if generated in the decay of a D^{*+} . The fraction of the emitted D^0 mesons expected to have come from D^{*+} decays is about a third. Similarly, many $\bar{D}^0$ mesons, in themselves non-leading, will have come from decays of intrinsically leading D^{*-} mesons. Enhancements of the production of leading charmed mesons then have consequences for $Asym(D^0, \bar{D}^0)$ that differ from those for $Asym(D^-, D^+)$. The data (Figure 14 b)) indicate that if $Asym(D^0, \bar{D}^0)$ increases with x_F then it does so more gradually than $Asym(D^-, D^+)$ and, given the measurement uncertainties, are compatible with $Asym(D^0, \bar{D}^0)$ being independent of x_F . The mean value of $Asym(D^0, \bar{D}^0)$ over the region of positive x_F is -0.030 ± 0.022 , corresponding to $\sigma_0(D^0)/\sigma_0(\bar{D}^0) = 0.94 \pm 0.04$. This $\sigma_0(D^0)/\sigma_0(\bar{D}^0)$ value and the $\sigma_0(D^0)/\sigma_0(\bar{D}^0)$ values from E769 [37] and WA82 [17] are (Table 7) all less than 1, although in each case by no more than 1.5 standard deviations. Combining the three experimental results yields $\sigma_0(D^0)/\sigma_0(\bar{D}^0) = 0.93 \pm 0.03$. This is about 15% lower than is foreseen by the Lund event generator. Over the x_F range where the data of the present experiment are significant, the Lund event generator predicts an increase of $Asym(D^0, \bar{D}^0)$ with x_F that, after a global normalization to the measured value of $\sigma_0(D^0)/\sigma_0(\bar{D}^0)$, is consistent with observations (Figure 14 b)).

The measurements admit the possibility that, as suggested by the Lund event generator, $Asym(D^-, D^+)$ and $Asym(D^0, \bar{D}^0)$ are slowly varying functions of p_T^2 , but are also compatible with $Asym(D^-, D^+)$ and $Asym(D^0, \bar{D}^0)$ having no p_T^2 dependence (Figures 14 c), 14 d)). Similar results concerning the p_T^2 dependence of $Asym(D^-, D^+)$ have been obtained in experiments E769 [44] and E791 [45].

7. SUMMARY AND CONCLUSIONS

A study of charmed-meson hadroproduction has been performed in the WA92 experiment, in which a beam of 350 GeV/ c π^- particles was directed onto copper and tungsten targets. The experimental apparatus included a high-resolution imaging detector comprising 17 silicon-microstrip planes of 10 μm pitch. Using triggers for secondary vertices, for leptons and for particles having a large momentum component in the plane transverse to the π^- -beam direction, a total of 1.37×10^8 interactions was recorded. Reconstruction of decays from the set $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow \phi \pi^+$ and charge conjugates has yielded a sample of 7280 ± 108 charmed mesons, produced with $x_F > 0$, $\langle x_F \rangle = 0.18$ and $\langle p_T^2 \rangle = 1.86 \text{ (GeV}/c)^2$.

Assuming a relationship $\sigma = \sigma_0 A^\alpha$ between the cross-section, σ , per nucleus of mass A and the nucleonic cross-section, σ_0 , the α value found for the detected charmed particles is $0.95 \pm 0.06 \pm 0.03$, consistent with the value of ~ 1 expected within the framework of perturbative QCD. The value of α for charmed-meson production is not seen to depend significantly on the x_F and p_T^2 ranges considered, and values of α determined for different types of charmed meson are the same within uncertainties. Taking $\alpha = 1$, the measured cross-sections per nucleon for $x_F > 0$ production are $3.75 \pm 0.12 \pm 0.25 \text{ } \mu\text{barn}$ for D^0 , $4.01 \pm 0.12 \pm 0.27 \text{ } \mu\text{barn}$ for $\bar{D}^0$, $1.40 \pm 0.05 \pm 0.12 \text{ } \mu\text{barn}$ for D^+ , $1.88 \pm 0.06 \pm 0.17 \text{ } \mu\text{barn}$ for D^- , $0.59 \pm 0.10 \pm 0.15 \text{ } \mu\text{barn}$ for D_s^+ and $0.70 \pm 0.12 \pm 0.18 \text{ } \mu\text{barn}$ for D_s^- . With the standard parameterization of $d^2\sigma_0/dx_F dp_T^2 \propto (1 - |x_F|)^n \exp(-b p_T^2)$, fits to the x_F and p_T^2 spectra obtained for D^0 , $\bar{D}^0$, D^+ and D^- give $n = 4.27 \pm 0.11$ for $x_F < 0.8$ and $b = 0.85 \pm 0.02 \text{ (GeV}/c)^{-2}$ for $p_T^2 < 7 \text{ (GeV}/c)^2$. The p_T^2 spectrum for D^0 , $\bar{D}^0$, D^+ and D^- cannot be accurately represented by a single exponential over the full range encompassed by the data. Slight dissimilarities in form are noted between x_F spectra for different types of charmed meson. Measurements of particle-antiparticle asymmetries provide evidence for enhanced production of leading charmed mesons at higher x_F values, the asymmetry for (leading) D^- with respect to (non-leading) D^+ rising significantly with increasing x_F . The p_T^2 spectra obtained for different types of charmed meson all have a similar shape.

Comparisons of the present results with theoretical predictions tend to reinforce the view that charmed-meson hadroproduction can be described by perturbative QCD supplemented by a modelling of hadronization and other processes not allowed for in the perturbative calculations. The measurements in many cases improve on data from other experiments, with which there is generally good agreement. In particular, forward and differential cross-sections for charmed-meson production have been determined with higher accuracy than has been achieved previously and the p_T^2 range over which charmed-meson hadroproduction is measured, formerly limited to $p_T^2 < 14 \text{ (GeV}/c)^2$, has been extended to $20 \text{ (GeV}/c)^2$.

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Figure captions

- Figure 1:** Experimental setup (x - z projection), including target (T), silicon-microstrip detectors (SMD), multiwire proportional chambers (MW), drift chambers (D), butterfly-shaped hodoscopes (BH), electromagnetic calorimeter (EC) and muon filter comprising beam dump (BD) and resistive-plate chambers (RPC). Enlarged views show the arrangement of the SMD planes as Beam Hodoscope (BmH), in-target counter (IT), Decay Detector (DkD) and Vertex Detector (VxD).
- Figure 2:** Layout (x - y projection) of scintillation counters (S1, S2, V1, S3, S4, V2) and in-target counter (IT) used in defining the beam trigger ($S1 \cdot S2 \cdot \bar{V1}$) and the interaction trigger ($S1 \cdot S2 \cdot \bar{V1} \cdot IT \cdot S3 \cdot S4 \cdot \bar{V2}$). The positions of the target (T), Beam Hodoscope (BmH), Decay Detector (DkD) and Vertex Detector (VxD) are indicated. Distances marked are relative to the target centre.
- Figure 3:** Invariant-mass distributions for the accepted vertices, the peaks constituting signals for the decays a) $D^0 \rightarrow K^- \pi^+$, b) $D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$, c) $D^+ \rightarrow K^- \pi^+ \pi^+$, d) $D^+ \rightarrow \phi \pi^+$ (lower mass), $D_s^+ \rightarrow \phi \pi^+$ (higher mass) and their charge conjugates. Contributions from the 1992 data taking with W target (1992 W), from the 1992 data taking with Cu target (1992 Cu) and from the 1993 data taking (1993 Cu) are indicated.
- Figure 4:** Distributions of χ_F and p_T^2 obtained directly from the data (no acceptance correction), summed over all decay channels analysed. Combined signal and background distributions relate to entries in the signal regions of the invariant-mass spectra; background distributions relate to entries in the sidebands, appropriately normalized.
- Figure 5:** Decay-reconstruction efficiencies as a function of χ_F . A curve represents the average efficiency for the indicated decay and its charge conjugate. Efficiencies relative to the 1992 data taking with W target (1992 W), the 1992 data taking with Cu target (1992 Cu) and the 1993 data taking (1993 Cu) are shown separately.
- Figure 6:** Decay-reconstruction efficiencies as a function of p_T^2 for decaying particles with $\chi_F > 0$. A curve represents the average efficiency for the indicated decay and its charge conjugate. Efficiencies relative to the 1992 data taking with W target (1992 W), the 1992 data taking with Cu target (1992 Cu) and the 1993 data taking (1993 Cu) are shown separately.
- Figure 7:** Numbers of reconstructed decays as functions of χ_F and p_T^2 of decaying particle, summed over all decay channels analysed, as found for the experimental data and for simulated events, (backgrounds subtracted but no acceptance corrections). The sample of simulated decays is normalized to the number of decays in the experimental data.
- Figure 8:** Dependence of $\alpha(\{D^0, \bar{D}^0, D^+, D^-\})$ on a) χ_F and b) p_T^2 of charmed mesons considered.
- Figure 9:** Comparison of charmed-meson cross-sections per nucleon ($\chi_F > 0$ production) measured in the present experiment with other experimental results [32-36], relating to diverse π^- momenta and a variety of target materials. The cross-section per nucleon, σ_0 , has been taken to depend on the cross-section per nucleus, σ , in a material of nuclear mass A as $\sigma_0 = \sigma/A$. Cross-sections from previous experiments have been recalculated using current branching fractions [19]. The NA32 results [35] for 200 GeV/c π^- particles were increased by a corrective factor of $\times 1.15$, as required by later NA32 analyses [34]. Curves represent the PQCD predictions of inclusive $c\bar{c}$ cross-sections, normalized to the experimental points.

- Figure 10:** Differential cross-sections with respect to a) x_F and b) p_T^2 for D^0 , $\bar{D}^0$, D^+ and D^- collectively. Experimental data for the differential cross-section with respect to x_F have been fitted as $d\sigma_0/dx_F \propto (1 - |x_F|)^n$, with $n = 4.27 \pm 0.11$. Data for the differential cross-section with respect to p_T^2 have been fitted as $d\sigma_0/dp_T^2 \propto \exp(-b p_T^2)$, with $b = 0.85 \pm 0.02 \text{ (GeV}/c)^{-2}$, for $p_T^2 < 7 \text{ (GeV}/c)^2$. Predictions from the Lund event generator and from PQCD are normalized to the measured total cross-section for production of D^0 , $\bar{D}^0$, D^+ or D^- with $x_F > 0$.
- Figure 11:** Comparison of p_T^2 spectrum for D^0 , $\bar{D}^0$, D^+ and D^- with predictions of the intrinsic- k_T model, for various choices of $\langle k_T^2 \rangle$ and a fragmentation function of Peterson form.
- Figure 12:** Differential cross-sections with respect to x_F for different types of charmed particle, as indicated on plots. Each curve from the Lund event generator is normalized to the measured value of the relevant total cross-section for $x_F > 0$ production. The curve given by PQCD is normalized in a) to half the measured forward cross-section for production of D^0 or $\bar{D}^0$, is normalized in b) to half the measured forward cross-section for production of D^+ or D^- , and is normalized in c) to the measured forward cross-section for production of D_s^+ or D_s^- .
- Figure 13:** Differential cross-sections with respect to p_T^2 for different types of charmed particle, as indicated on plots. Each curve from the Lund event generator is normalized to the measured value of the relevant total cross-section for $x_F > 0$ production. The curve given by PQCD is normalized in a) to half the measured forward cross-section for production of D^0 or $\bar{D}^0$, is normalized in b) to half the measured forward cross-section for production of D^+ or D^- , and is normalized in c) to the measured forward cross-section for production of D_s^+ or D_s^- .
- Figure 14:** Production asymmetries as functions of x_F and p_T^2 for D^- with respect to D^+ and for D^0 with respect to $\bar{D}^0$. Each curve from the Lund event generator is normalized so as to give an average asymmetry for $x_F > 0$ equal to the relevant measured average.

Table 1 Online event-selection criteria and overall acceptances. An event was written to tape if it satisfied the interaction trigger and the conditions marked (•) in a column relevant to the data-taking period and target material. For example, an event flagged as containing 2 secondary particles, 1 particle with $p_{yz} \geq 0.6$ GeV/ c and no muons would have been recorded on tape during the data taking with Cu target (1992 and 1993) but would not have been recorded during the data taking with W target. Acceptances for inelastic interactions are based on experimental measurements; acceptances for $c\bar{c}$ events and $b\bar{b}$ events are determined from simulation.

Year of data taking	1992				1992				1993			
Target material	Cu				W				Cu			
High- p_{yz} -particle trigger: ≥ 1 particle with $p_{yz} \geq 0.6$ GeV/ c ≥ 2 particles with $p_{yz} \geq 0.6$ GeV/ c	•		•		•		•		•			
Transverse-energy trigger: ≥ 2 blocks with $E_{yz} \geq 0.65$ GeV										•		
Muon trigger: ≥ 1 muon ≥ 2 muons		•	•			•	•				•	
				•				•				•
Secondary-vertex trigger: ≥ 1 secondary track ($IP_{zT} > 100$ μm) ≥ 2 secondary tracks ($IP_{zT} > 100$ μm)	•	•			•	•			•		•	
Overall trigger acceptance for interactions in target:												
inelastic interactions	2.5%				1.8%				1.5%			
$c\bar{c}$ events	9.7%				5.3%				8.5%			
$b\bar{b}$ events	29.0%				20.8%				23.4%			

Table 2 Numbers of reconstructed decays.

Year of data taking	1992	1992	1993	1992 / 1993
Target material	Cu	W	Cu	Cu / W
$D^0 \rightarrow K^- \pi^+$	312 ± 22	198 ± 18	601 ± 29	1111 ± 41
$\bar{D}^0 \rightarrow K^+ \pi^-$	316 ± 22	206 ± 18	599 ± 28	1121 ± 40
$D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$	204 ± 22	129 ± 18	510 ± 32	843 ± 43
$\bar{D}^0 \rightarrow K^+ \pi^+ \pi^- \pi^-$	173 ± 18	95 ± 15	530 ± 32	798 ± 40
$D^+ \rightarrow K^- \pi^+ \pi^+$	330 ± 24	231 ± 18	866 ± 36	1427 ± 47
$D^- \rightarrow K^+ \pi^- \pi^-$	497 ± 28	315 ± 22	1060 ± 38	1872 ± 52
$D_s^+ \rightarrow \phi \pi^+$ $\quad \quad \quad \searrow K^- K^+$	12 ± 4	13 ± 3	27 ± 6	52 ± 8
$D_s^- \rightarrow \phi \pi^-$ $\quad \quad \quad \searrow K^- K^+$	14 ± 5	8 ± 4	34 ± 7	56 ± 9
All decays	1858 ± 56	1195 ± 45	4227 ± 81	7280 ± 108

Table 3 Numbers of beam particles incident on target, as derived from counts of interaction trigger and as measured directly by counts of beam-particle trigger. Uncertainties on values from the beam-particle trigger are expected to be of the order of $\pm 5\%$ but are not well determined.

Year of data taking	1992	1992	1993
Target material	Cu	W	Cu
Number of beam particles:			
from counts of interaction trigger	$(1.59 \pm 0.08) \times 10^{11}$	$(1.13 \pm 0.09) \times 10^{11}$	$(3.01 \pm 0.15) \times 10^{11}$
from counts of beam-particle trigger	1.59×10^{11}	1.15×10^{11}	3.01×10^{11}

Table 4 Efficiencies for reconstructing decays of particles with $x_F > 0$. The uncertainties include a statistical component and the estimated systematic uncertainty of $\pm 3\%$.

Year of data taking	1992	1992	1993
Target material	Cu	W	Cu
$D^0 \rightarrow K^- \pi^+$	$(1.19 \pm 0.06)\%$	$(0.55 \pm 0.04)\%$	$(1.34 \pm 0.06)\%$
$\bar{D}^0 \rightarrow K^+ \pi^-$	$(1.20 \pm 0.06)\%$	$(0.53 \pm 0.03)\%$	$(1.16 \pm 0.05)\%$
$D^0 \rightarrow K^- \pi^- \pi^+ \pi^+$	$(0.40 \pm 0.03)\%$	$(0.21 \pm 0.03)\%$	$(0.50 \pm 0.04)\%$
$\bar{D}^0 \rightarrow K^+ \pi^+ \pi^- \pi^-$	$(0.38 \pm 0.03)\%$	$(0.15 \pm 0.03)\%$	$(0.51 \pm 0.03)\%$
$D^+ \rightarrow K^- \pi^+ \pi^+$	$(1.61 \pm 0.07)\%$	$(0.72 \pm 0.06)\%$	$(2.02 \pm 0.07)\%$
$D^- \rightarrow K^+ \pi^- \pi^-$	$(1.51 \pm 0.06)\%$	$(0.73 \pm 0.06)\%$	$(1.97 \pm 0.07)\%$
$D_s^+ \rightarrow \phi \pi^+$			
$\hookrightarrow K^- K^+$	$(0.66 \pm 0.05)\%$	$(0.31 \pm 0.04)\%$	$(0.87 \pm 0.04)\%$
$D_s^- \rightarrow \phi \pi^-$			
$\hookrightarrow K^- K^+$	$(0.74 \pm 0.06)\%$	$(0.31 \pm 0.04)\%$	$(0.76 \pm 0.05)\%$

Table 5 Cross-sections measured for production of particles with $\mathcal{X}_F > 0$ and values obtained for the parameter, α , used to relate the cross-section per nucleus, σ , in a material of nuclear mass A and the cross-section per nucleon, σ_0 , as $\sigma = \sigma_0 A^\alpha$.

Particle(s) [$\mathcal{X}_F > 0$]	Production cross-section per nucleus [μbarn]		α	Production cross-section per nucleon [μbarn] for $\alpha = 1$
	Cu	W		
D^0	$242 \pm 9 \pm 16$	$643 \pm 61 \pm 56$	$0.92 \pm 0.10 \pm 0.03$	$3.75 \pm 0.12 \pm 0.25$
$\bar{D}^0$	$259 \pm 9 \pm 17$	$688 \pm 64 \pm 60$	$0.93 \pm 0.09 \pm 0.03$	$4.01 \pm 0.12 \pm 0.27$
$D^0, \bar{D}^0$	$501 \pm 12 \pm 33$	$1330 \pm 87 \pm 116$	$0.92 \pm 0.07 \pm 0.02$	$7.78 \pm 0.14 \pm 0.52$
D^+	$90 \pm 4 \pm 8$	$247 \pm 27 \pm 26$	$0.96 \pm 0.11 \pm 0.03$	$1.40 \pm 0.05 \pm 0.12$
D^-	$120 \pm 4 \pm 11$	$331 \pm 32 \pm 35$	$0.95 \pm 0.10 \pm 0.03$	$1.88 \pm 0.06 \pm 0.17$
D^+, D^-	$210 \pm 6 \pm 19$	$578 \pm 42 \pm 61$	$0.95 \pm 0.07 \pm 0.03$	$3.28 \pm 0.08 \pm 0.29$
D_s^+	$35 \pm 7 \pm 9$	$167 \pm 61 \pm 44$	$1.46 \pm 0.39 \pm 0.04$	$0.59 \pm 0.10 \pm 0.15$
D_s^-	$47 \pm 8 \pm 12$	$102 \pm 48 \pm 27$	$0.73 \pm 0.48 \pm 0.02$	$0.70 \pm 0.12 \pm 0.18$
D_s^+, D_s^-	$82 \pm 11 \pm 21$	$269 \pm 78 \pm 71$	$1.12 \pm 0.30 \pm 0.03$	$1.29 \pm 0.16 \pm 0.33$
$D^0, \bar{D}^0, D^+, D^-$	$711 \pm 13 \pm 47$	$1908 \pm 97 \pm 165$	$0.93 \pm 0.05 \pm 0.03$	$11.05 \pm 0.13 \pm 0.72$
$D^0, \bar{D}^0, D^+, D^-, D_s^+, D_s^-$	$793 \pm 17 \pm 55$	$2177 \pm 124 \pm 197$	$0.95 \pm 0.06 \pm 0.03$	$12.37 \pm 0.19 \pm 0.86$

Table 6 Comparison of WA92 α values with α values measured in previous experiments [24-29]. Where a measurement is shown with a single uncertainty, this includes statistical and systematic contributions. An indication of the $\mathcal{X}_F$ range of the charmed particles detected in each experiment is given.

	$\mathcal{X}_F$ coverage	$\alpha(\{D^0, \bar{D}^0\})$	$\alpha(\{D^+, D^-\})$	$\alpha(\{D^0, \bar{D}^0, D^+, D^-\})$	$\alpha(\{c, \bar{c}\})$
WA92: 350 GeV/c π^- on Cu, W	$\mathcal{X}_F > 0$ $\langle \mathcal{X}_F \rangle \approx 0.18$	$0.92 \pm 0.07 \pm 0.02$	$0.95 \pm 0.07 \pm 0.03$	$0.93 \pm 0.05 \pm 0.03$	
E789: 800 GeV/c p^+ on Be, Au [24]	$0 < \mathcal{X}_F < 0.08$ $\langle \mathcal{X}_F \rangle \approx 0.031$	$1.02 \pm 0.11 \pm 0.07$			
E769: 250 GeV/c $\pi^\pm$ on Be, Al, Cu, W [25]	$\mathcal{X}_F > 0$	$0.95 \pm 0.06 \pm 0.02$	$1.05 \pm 0.07 \pm 0.02$	$1.00 \pm 0.05 \pm 0.02$	
WA82: 340 GeV/c π^- on Si, Cu, W [26]	$\mathcal{X}_F > 0$ $\langle \mathcal{X}_F \rangle \approx 0.24$	0.98 ± 0.08	0.84 ± 0.08	0.92 ± 0.06	
WA78: 300 GeV/c p^+ on Al, Fe, U [27] from μ^+ yield: from μ^- yield:	$\mathcal{X}_F > 0.1$ $\langle \mathcal{X}_F \rangle \approx 0.23$				0.79 ± 0.12 0.76 ± 0.13
WA78: 320 GeV/c π^- on Al, Fe, U [28] from μ^+ yield: from μ^- yield:	$\mathcal{X}_F > 0.2$ $\langle \mathcal{X}_F \rangle \approx 0.27$				0.76 ± 0.08 0.83 ± 0.06
FNAL beam dump: 400 GeV/c p^+ on Be, Cu, W [29]	$\langle \mathcal{X}_F \rangle \approx 0.45$				0.75 ± 0.05
Average:		0.95 ± 0.04	0.95 ± 0.04	0.95 ± 0.03	

Table 7 Comparison of WA92 values for ratios of cross-sections with previous experimental values [17,32-38], recalculated taking into account current branching fractions [19], and with values from the Lund event generator. The uncertainties shown are statistical only. Systematic uncertainties are dominated by uncertainties in the magnitudes of decay branching fractions that enter into the cross-section calculations, and for the WA92 measurements are: $\pm 7\%$ for $\sigma_0(\{D^+, D^-\})/\sigma_0(\{D^0, \bar{D}^0\})$, $\pm 25\%$ for $\sigma_0(\{D_s^+, D_s^-\})/\sigma_0(\{D^0, \bar{D}^0, D^+, D^-\})$, negligible for $\sigma_0(D^-)/\sigma_0(D^+)$ and $\sigma_0(D^0)/\sigma_0(\bar{D}^0)$.

	$\frac{\sigma_0(\{D^+, D^-\})}{\sigma_0(\{D^0, \bar{D}^0\})}$	$\frac{\sigma_0(\{D_s^+, D_s^-\})}{\sigma_0(\{D^0, \bar{D}^0, D^+, D^-\})}$	$\frac{\sigma_0(D^-)}{\sigma_0(D^+)}$	$\frac{\sigma_0(D^0)}{\sigma_0(\bar{D}^0)}$
WA92: 350 GeV/c π^- on Cu, W	0.423 ± 0.012	0.116 ± 0.014	1.34 ± 0.06	0.94 ± 0.04
E769: 250 GeV/c π^- on Be, Al, Cu, W [32,37]	0.419 ± 0.043	0.167 ± 0.033	1.44 ± 0.18	0.89 ± 0.12
E769: 210 GeV/c π^- on Be, Al, Cu, W [32]	0.258 ± 0.058			
WA82: 340 GeV/c π^- on Si, Cu, W [17,38]			1.34 ± 0.13	0.91 ± 0.06
E653: 600 GeV/c π^- on emulsion [33]	0.393 ± 0.032			
NA32: 230 GeV/c π^- on Cu [34]	0.422 ± 0.033	0.158 ± 0.029		
NA32: 200 GeV/c π^- on Si [35]	$0.439^{+0.123}_{-0.094}$			
NA27: 360 GeV/c π^- on H [36]	0.564 ± 0.171			
Experimental average:	0.415 ± 0.010	0.129 ± 0.012	1.35 ± 0.05	0.93 ± 0.03
Lund: 350 GeV/c π^- on nucleon	0.472 ± 0.003	0.077 ± 0.001	2.25 ± 0.03	1.09 ± 0.01

Table 8 Results of fitting the WA92 spectra of x_F and p_T^2 for D^0 , $\bar{D}^0$, D^+ and D^- as $d^2\sigma_0/dx_F dp_T^2 \propto (1 - |x_F|)^n \exp(-b p_T^2)$. Corresponding results from previous experiments and theoretical expectations are shown for comparison. The x_F and p_T^2 intervals fitted are specified. The more recent of the E769 results [41] are for fits to spectra that also include contributions from $D_s^\pm$.

	Measurement of n		Measurement of b	
	x_F -interval fitted	n	p_T^2 -interval fitted (GeV/c) ²	b (GeV/c) ⁻²
WA92: 350 GeV/c π^- on Cu, W	0.0 - 0.7 0.0 - 0.8 0.1 - 0.7	4.27 ± 0.11 4.27 ± 0.11 4.70 ± 0.16	0 - 4 0 - 4.5 0 - 7 0 - 9 0 - 10	0.89 ± 0.02 0.87 ± 0.02 0.85 ± 0.02 0.84 ± 0.02 0.84 ± 0.02
E769: 250 GeV/c $\pi^\pm$ on Be, Al, Cu, W [41]	0.0 - 0.7	4.03 ± 0.18	0 - 4	1.08 ± 0.05
E769: 250 GeV/c π^- on Be, Al, Cu, W [37]	0.1 - 0.7	3.9 ± 0.3	0 - 4	1.03 ± 0.06
WA82: 340 GeV/c π^- on Si, Cu, W [42]	0.1 - 0.7	2.9 ± 0.3	0 - 7	0.86 ± 0.05
E653: 600 GeV/c π^- on emulsion [33]	0.0 - 0.8	4.25 ± 0.24	0 - 9	0.76 ± 0.03
WA75: 350 GeV/c π^- on emulsion [43]	-0.5 - 0.5	3.5 ± 0.5	0 - 10	0.77 ± 0.04
NA32: 230 GeV/c π^- on Cu [34]	0.0 - 0.8	3.74 ± 0.23	0 - 10	0.83 ± 0.03
NA32: 200 GeV/c π^- on Si [35]	0.0 - 0.8	$2.5^{+0.4}_{-0.3}$	0 - 4.5	$1.06^{+0.12}_{-0.11}$
NA27: 360 GeV/c π^- on H [36]	0.0 - 0.9	3.8 ± 0.63	0 - 4.5	$1.18^{+0.18}_{-0.16}$
Lund: 350 GeV/c π^- on nucleon	0.0 - 0.8	3.53	0 - 7	1.03
Perturbative QCD: 350 GeV/c π^- on nucleon	0.0 - 0.8	3.99	0 - 7	0.89

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14