$D^{*\pm}$ production in 350 GeV/c $\pi^- - N$ interactions

The BEATRICE Collaboration

M. Adinolfi¹⁾, Y. Alexandrov²⁾, C. Angelini¹⁾, D. Barberis³⁾, A. Cardini¹⁾, F. Ceradini⁴⁾,
M. Dameri³⁾, G. Darbo³⁾, A. Duane⁵⁾, V. Flaminio¹⁾, B.R. French⁶⁾, A. Frenkel⁷⁾,
C. Gemme³⁾, K. Harrison¹⁾, R. Hurst³⁾, C. Lazzeroni¹⁾, L. Malferrari⁸⁾, G. Martellotti⁷⁾,
P. Mazzanti⁸⁾, P. Netchaeva²⁾, B. Osculati³⁾, G. Penso⁷⁾, L. Rossi³⁾, M. Verzocchi⁷⁾,
D.M. Websdale⁵⁾, M. Zavertyaev²⁾.

(Submitted to *Nuclear Physics B*)

Abstract

We report measurements of $D^{*\pm}$ production in interactions between 350 GeV/c π^- particles and nuclei. Reconstruction of the decay $D^{*+} \rightarrow D^0 \pi^+$ and charge conjugate, with D^0 identified via its decays to $K^- \pi^+$ and $K^- \pi^- \pi^+ \pi^+$, has allowed isolation of a sample of 611 ± 28 $D^{*\pm}$ mesons, produced at positive x_F . Assuming a linear A-dependence, the cross-section per nucleon in the region $x_F > 0$ is measured to be $1.41 \pm 0.10 \pm 0.11 \mu\text{b}$ for D^{*+} and $1.84 \pm 0.12 \pm 0.15 \mu\text{b}$ for D^{*-} . We present measurements of differential cross-sections with respect to x_F and P_t^2 , and compare data for $D^{*\pm}$ (vector-meson) production with data for production of charmed pseudoscalar mesons.

¹⁾ Università di Pisa and INFN, Via Livornese 1291, I-56010 San Piero a Grado (PI), Italy

²⁾ Lebedev Physical Institute, Leninsky Prospect 53, RU-117924 Moscow, Russian Federation

³⁾ Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genoa, Italy

⁴⁾ Università di Roma “Roma Tre” and INFN, Via della Vasca Navale 84, I-00146 Rome, Italy

⁵⁾ Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, UK

⁶⁾ CERN, CH-1211 Geneva 23, Switzerland.

⁷⁾ Università di Roma “La Sapienza” and INFN, Piazzale Aldo Moro 2, I-00185 Rome, Italy

⁸⁾ Università di Bologna and INFN, Via Irnerio 46, I-40126 Bologna, Italy

1 Introduction

Charmed-particle hadroproduction can be described using perturbative QCD supplemented by models of hadronization and other non-perturbative processes. Existing data are consistent with theoretical predictions from this approach [1], but most of the data relate to pseudoscalar charmed mesons. As the hadronization into pseudoscalar charmed mesons is not necessarily identical to the hadronization into non-pseudoscalar charmed mesons, more data on the latter are required for the models to be fully tested.

In a previous paper [2], we presented the results of the WA92 experiment on the production of the charmed pseudoscalar mesons $\bar{D}^0$, $D^\pm$ and $D_S^\pm$. Here we give results on total and differential cross-sections for $D^{*\pm}$, identified through reconstruction of the decay chain $D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+$ or $(K^- \pi^- \pi^+ \pi^+) \pi^+$ and its charge conjugate. Results are compared with theoretical predictions and with data from other experiments, the WA92 experiment providing an improvement by a factor 4 in statistics over the previous best measurement.

2 Experiment

The WA92 experiment was performed at the CERN Ω' spectrometer, with data collection in 1992 and 1993. Using a $350 \text{ GeV}/c$ π^- beam incident on a thin metal target, a total of 1.37×10^8 events was recorded. A detailed description of the experimental setup is given elsewhere [3]. The distinctive features were a high-resolution tracking system, and a trigger giving enrichment for heavy-flavoured particles.

Coordinates on the paths of beam particles were measured using a hodoscope formed of 10 silicon microstrip planes (9 planes of $20 \mu\text{m}$ pitch, 1 plane of $50 \mu\text{m}$ pitch). Interactions occurred in a 2-mm-thick target of copper or tungsten, positioned in the fringe of the spectrometer's magnetic field. The target material was copper for 80% of the data taking and tungsten for the rest. Tracking of charged particles emerging from the interaction was performed using silicon-microstrip planes arranged as a decay detector (17 planes of $10 \mu\text{m}$ pitch, with analogue readout) and a vertex detector (12 planes of $25 \mu\text{m}$ pitch and 5 planes of $50 \mu\text{m}$ pitch). The decay detector covered the first 3 cm downstream of the target, the region where most of the charmed particles decayed. The vertex detector, which had an angular acceptance of approximately $\pm 70 \text{ mrad}$ in dip and azimuth, extended from 6 cm to 63 cm downstream of the target.

The tracking system of the spectrometer consisted of multiwire proportional chambers, placed in a 1.8 T dipolar magnetic field, and lever-arm drift chambers. Two butterfly-shaped scintillator hodoscopes, used to flag charged particles emitted with large transverse momentum (P_t) relative to the beam direction, an electromagnetic calorimeter and a muon detector were placed downstream of the spectrometer.

A silicon-strip detector, with a thickness of $300 \mu\text{m}$ and a pitch of $200 \mu\text{m}$, was placed immediately downstream of the target. This detector, termed the In-Target counter, was used in coincidence with six scintillator counters to provide a trigger for interactions. Enrichment for heavy-flavour particles was obtained using a multicomponent trigger [3], combining requests for:

- i. a secondary vertex in the region of the decay detector (vertex identification based on pattern recognition by a fast processor);
- ii. charged particle(s) with $P_t > 0.6 \text{ GeV}/c$ (≥ 1 particle for copper target, ≥ 2 particles for tungsten target);
- iii. detection of at least one muon coming from the interaction region;

- iv. transverse energy > 0.65 GeV in at least two of the 18×19 lead-glass blocks forming the electromagnetic calorimeter.

The accepted combinations were varied with target material and year of data taking. The average trigger acceptance was about 24% for $b\bar{b}$ events generated in the target, and 8% for $c\bar{c}$ events. The enrichment of $c\bar{c}$ events relative to minimum-bias events was about 4.5 [2].

Effective integrated luminosities have been evaluated for interactions in the tungsten target ($1.42 \pm 0.11 \text{ nb}^{-1}$), for interactions in the copper target ($7.76 \pm 0.39 \text{ nb}^{-1}$), for interactions in the In-Target counter when used with the tungsten target ($0.17 \pm 0.01 \text{ nb}^{-1}$), and for interactions in the In-Target counter when used with the copper target ($0.68 \pm 0.05 \text{ nb}^{-1}$). Uncertainties in the luminosity values are dominated by uncertainties in the π^- -nucleus cross-section and in the interaction-trigger acceptance for inelastic interactions [3].

3 Analysis procedure

We have identified $D^{*\pm}(2010)$ mesons by reconstructing the decay chain:

$$D^{*+} \rightarrow D^0 \pi^+ \\ \quad \quad \quad \downarrow \rightarrow K^- \pi^+ \quad \text{or} \quad K^- \pi^- \pi^+ \pi^+ .$$

Here, and in most of the following, the inclusion of charge-conjugate states is implied.

A secondary vertex formed by two or four tracks was identified as a candidate D^0 decay vertex if it satisfied the following conditions [2]:

- i. it was outside of the target;
- ii. it was well separated from the primary vertex;
- iii. it was not recognised as due to a secondary interaction or a strange-particle decay;
- iv. the parent's momentum pointed to within $20 \mu\text{m}$ of the primary vertex;
- v. the invariant mass for the decay hypothesis $K^- \pi^+$ or $K^- \pi^- \pi^+ \pi^+$ was in the range 1.847 to $1.886 \text{ GeV}/c^2$.

About 4300 D^0 decays were selected, together with a background of 2600 events from wrong track combinations. The only change with respect to our previous analysis [2] was to use a less stringent cut on the position of the primary interaction, now allowed to occur in the material of the target or in the silicon of the In-Target counter. This modification gave us a 10% increase in acceptance. No kaon identification was available, and to avoid ambiguities in flavour assignment we discarded decays compatible with both a D^0 and a $\bar{D}^0$. This led to a signal reduction of 13%.

An event's D^0 candidate was paired in turn with each track not originating from the D^0 decay vertex and having a charge opposite to that of the decay's kaon (right-sign sample). The added track was assumed to be a pion and the mass difference $\Delta M = M(D^0 \pi^+) - M(D^0)$ was determined. We rejected the few events (about 2% of the total) where the Feynman x_F variable for the $D^0 \pi^+$ combination had a negative value.

We performed a binned maximum-likelihood fit of the ΔM distribution (Fig. 1), using a gaussian to describe the signal and representing the background by a second-order polynomial multiplied by $(\Delta M - m_\pi)^k$, where m_π is the pion mass and k is a fit parameter. From the integral of the fitted gaussian, which had mean $\Delta M_0 = 145.54 \pm 0.08 \text{ MeV}/c^2$ and standard deviation $\sigma_{\Delta M_0} = 1.41 \pm 0.07 \text{ MeV}/c^2$, our signal corresponds to 611 ± 28 $D^{*\pm}$ decays, with 265 ± 18 D^{*+} decays and 346 ± 21 D^{*-} decays. The number of background events in the signal region, defined by $|\Delta M_0 - \Delta M| \leq 3\sigma_{\Delta M_0}$ or $141.31 \text{ MeV}/c^2 \leq \Delta M \leq$

$149.77 \text{ MeV}/c^2$, was found to be 130 ± 8 . We model the x_F and P_t^2 distributions relative to the background using events in the interval $180 \text{ MeV}/c^2 \leq \Delta M \leq 300 \text{ MeV}/c^2$ (sideband region).

Figure 1: Distribution of $M(D^0\pi^+)-M(D^0)$ and charge conjugate (points with error bars; right-sign data) and of $M(D^0\pi^-)-M(D^0)$ and charge conjugate (shaded circles; wrong-sign data). The dotted curve represents a fit to the right-sign data using a function that is the sum of a gaussian and a second-order polynomial multiplied by $(\Delta M - m_\pi)^k$, with m_π the pion mass and k a fit parameter.

As a check of our fitting procedure, we have used a second method to estimate the number of signal events. In this method, a wrong-sign sample was obtained by combining the D^0 candidates with tracks having the same charge as that of the kaon from the D^0 decay. The associated ΔM distribution was normalized such that the number of counts in the sideband region was the same as for the right-sign sample (overall normalization factor of 0.97 ± 0.03). The wrong-sign sample provides a good representation of the background because the branching fractions for $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^+\pi^+\pi^-\pi^-$ are about a factor of 100 lower than the branching fractions for the decays $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$. The number of reconstructed $D^{*\pm}$ particles was taken to be the difference between the number of right-sign events in the signal region and the number of normalized wrong-sign events in the same interval. The resulting estimate of 614 ± 30 is fully compatible with the value from the maximum-likelihood fit, and the systematic uncertainty in the signal estimate is consequently assumed negligible. The x_F and P_t^2 distributions of wrong-sign events in the signal region (total of 196 events) are in good agreement with those of the higher-statistics sample of right-sign events in the sideband region (total of 2240 events), validating the use of the latter sample in modelling the background kinematics.

Acceptances for $D^{*\pm}$ particles generated in the target or In-Target counter were evaluated as functions of x_F and P_t^2 (Fig. 2) using a detailed simulation [3]. This included generation of heavy-quark events by the Lund packages Pythia 5.4 [4] and Jetset 7.3 [5], and a detector description based on Geant 3.21 [6]. In total, about 10^6 events were simulated, each containing a $D^{*\pm}$ of positive x_F , decaying as $D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$ or $(K^-\pi^-\pi^+\pi^+)\pi^+$. Simulated events were subject to the same trigger conditions, reconstruction and selection as the experimental data. Events were weighted as a function of the x_F and P_t^2 of the generated $D^{*\pm}$, such that the kinematic distributions after reconstruction matched those of the background-subtracted data.

The overall positive- x_F acceptance was calculated as the ratio of the number of simulated $D^{*\pm}$ mesons identified to the number of events generated. The values obtained were $(1.29 \pm 0.07) \times 10^{-3}$ for interactions in the tungsten target, $(4.02 \pm 0.08) \times 10^{-3}$ for interactions in the copper target, $(1.76 \pm 0.29) \times 10^{-3}$ for interactions in the In-Target counter with the tungsten target, and $(5.48 \pm 0.41) \times 10^{-3}$ for interactions in the In-Target counter with the copper target. The lower acceptances for data relating to the tungsten target are due to the trigger requesting a larger number of particles with $P_t > 0.6 \text{ GeV}/c$. The $D^{*+} \rightarrow D^0 \pi^+$ acceptance once the D^0 decay was found was about 70%, varying slightly with target material. The unidentified D^{*+} were lost partly because of the spectrometer's acceptance (20% of cases), but mainly because of inefficiencies in reconstructing low-momentum tracks.

Figure 2: $D^{*\pm}$ acceptances as a function of x_F (top) and P_t^2 (bottom), averaged over all materials.

4 Results

4.1 Inclusive cross-sections

We take the cross-section, σ , per nucleus of atomic mass A to be related to the cross-section, σ_0 , per nucleon as $\sigma = \sigma_0 A^\alpha$. Since most (about 85%) of the $D^{*\pm}$ we identify are produced in copper, and we have only low statistics for tungsten and silicon, we do not measure α . We assume the value $\alpha = 1$, which is expected from perturbative QCD and is

consistent with our previous measurement of $\alpha = 0.95 \pm 0.06 \pm 0.03$ [2] for $\bar{D}^0$, $D^\pm$ and $D_S^\pm$. The positive- x_F cross-section per nucleon is then computed as:

$$\sigma_0 = \frac{N^*}{B^* [A_{\text{Cu}} \mathcal{L}_{\text{Cu}} \epsilon_{\text{Cu}} + A_{\text{W}} \mathcal{L}_{\text{W}} \epsilon_{\text{W}} + A_{\text{Si}} (\mathcal{L}_{\text{Si}}(\text{Cu}) \epsilon_{\text{Si}}(\text{Cu}) + \mathcal{L}_{\text{Si}}(\text{W}) \epsilon_{\text{Si}}(\text{W}))]} ,$$

where N^* is the total number of D^{*+} and/or D^{*-} for which the decay chain is reconstructed (all materials); B^* is the product of the branching fractions [7]

$B(D^{*+} \rightarrow D^0 \pi^+) = (68.3 \pm 1.4)\%$ and $B(D^0 \rightarrow K^- \pi^+ \text{ or } K^- \pi^- \pi^+ \pi^+) = (11.45 \pm 0.41)\%$; $A_{\text{Si}} = 28.1$, $A_{\text{Cu}} = 63.5$ and $A_{\text{W}} = 183.8$ are the atomic masses of silicon, copper and tungsten respectively. For target material X (Cu or W), $\mathcal{L}_X$ and ϵ_X are the integrated luminosity and $D^{*\pm}$ acceptance relative to events in the target; $\mathcal{L}_{\text{Si}}(X)$ and $\epsilon_{\text{Si}}(X)$ are the corresponding quantities for events in the In-Target counter.

The inclusive positive- x_F cross-sections obtained are:

$$\begin{aligned} \sigma_0(D^{*+}) &= 1.41 \pm 0.10 \pm 0.11 \mu\text{b}, \\ \sigma_0(D^{*-}) &= 1.84 \pm 0.12 \pm 0.15 \mu\text{b}, \\ \sigma_0(D^{*+}, D^{*-}) &= 3.25 \pm 0.16 \pm 0.26 \mu\text{b}, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. The statistical uncertainties include a contribution resulting from the finite statistics in the acceptance evaluation, but are dominated by uncertainties in the numbers of reconstructed decays. The systematic uncertainties take into account the uncertainties in the luminosities (6%), in decay branching fractions (4%), and in simulation acceptances (4%).

Figure 3: $D^{*\pm}$ inclusive cross-section as a function of the incident π^- momentum. The QCD curve is based on next-to-leading-order ($O(\alpha_s^3)$) calculations for $c\bar{c}$ pairs, and is normalized to the weighted mean of the data. Cross-sections from previous experiments have been recalculated using updated branching fractions [7]. The uncertainties shown are the quadratic sum of statistical and systematic contributions.

Taking into account the energy dependence of charmed-particle cross-sections predicted by perturbative QCD, our measurement of $\sigma_0(D^{*\pm})$ is consistent with results from other experiments [8, 9, 10], performed at different π^- momenta (Fig. 3). (We do not consider the low-precision NA27 measurement [11] for production on a hydrogen target, since in

this case the parameterisation $\sigma = \sigma_0 A^\alpha$ may not be applicable [12].) Our result represents an improvement by a factor of 4 in statistics over the previous best measurement for a π^- beam (Table 1).

Table 1: Numbers of $D^{*\pm}$ identified and inclusive cross-section measurements assuming a linear A-dependence. Cross-sections from previous experiments have been recalculated using updated branching fractions [7].

experiment	number of $D^{*\pm}$	$\sigma(D^{*\pm})$ (μb)
WA92 350 GeV/ c π^- on Si,Cu,W	611 ± 28	$3.25 \pm 0.16 \pm 0.26$
E769 [8] 250 GeV/ c π^- on Be,Al,Cu,W	103 ± 9	$2.80 \pm 0.31 \pm 0.21$
NA32 [9] 230 GeV/ c π^- on Cu	147 ± 12	$2.49 \pm 0.22 \pm 0.36$
NA32 [10] 200 GeV/ c π^- on Si	46 ± 7	$2.08 \pm 0.52 \pm 0.17$

4.2 Ratios of cross-sections

Using our previous measurement of $\sigma_0(\bar{D}^0) = 7.86 \pm 0.14 \pm 0.52 \mu\text{b}$ [2], the value we find for the ratio $\sigma_0(\bar{D}^0)/\sigma_0(D^{*\pm})$ is 2.42 ± 0.13 (statistical uncertainty only quoted), in agreement with results from other experiments [8, 9, 10] (Table 2). The ratio is useful for checking consistency between experiments because the dominant systematic uncertainty usually comes from the uncertainty in the branching fraction $B(D^{*+} \rightarrow D^0\pi^+)$, and this is common to all measurements. There is no evidence for a dependence of the relative production frequency on beam momentum. This is as expected, given that all of the measurements are for centre-of-mass energies well above the threshold for $D^{*\pm}$ production.

Table 2: Measurements of $\sigma_0(D^0, \bar{D}^0)/\sigma_0(D^{*+}, D^{*-})$. The uncertainties shown are statistical only. These dominate over the systematic uncertainty, which is essentially due to the uncertainty on the branching fraction $B(D^{*+} \rightarrow D^0\pi^+) = (68.3 \pm 1.4)\%$ [7].

experiment	$\sigma_0(D^0, \bar{D}^0)/\sigma_0(D^{*+}, D^{*-})$
WA92 350 GeV/ c π^- on Si,Cu,W	2.42 ± 0.13
E769 [8] 250 GeV/ c π^- on Be,Al,Cu,W	3.05 ± 0.42
NA32 [9] 230 GeV/ c π^- on Cu	2.58 ± 0.26
NA32 [10] 200 GeV/ c π^- on Si	2.12 ± 0.63

The value we obtain for the ratio of the D^{*-} cross-section to the D^{*+} cross-section is $\sigma_0(D^{*-})/\sigma_0(D^{*+}) = 1.30 \pm 0.12$, showing a relative enhancement of D^{*-} production at positive x_F . Our value is in good agreement with measurements from WA82 [13] and E769 [14], and is very similar to values found for $\sigma(D^-)/\sigma(D^+)$ [2, 8, 13] (Table 3). The

Lund event generator predicts enhanced production of D^{*-} and D^- at positive x_F , but overestimates the effect by about a factor of 1.7.

Table 3: Ratios of cross-sections.

experiment	$\sigma(D^{*-})/\sigma(D^{*+})$	$\sigma(D^-)/\sigma(D^+)$
WA92 350 GeV/c π^- on Si,Cu,W	1.30 ± 0.12	1.34 ± 0.06
WA82 [13] 340 GeV/c π^- on Si,Cu,W	1.8 ± 0.3	1.34 ± 0.13
E769 [8, 14] 250 GeV/c π^- on Be,Al,Cu,W	1.2 ± 0.14	1.44 ± 0.18

A $D^\pm$ may be produced directly, or it may be produced in the decay of either a $D^{*\pm}$ or a higher-mass resonance. The fraction, β , of observed $D^\pm$ coming from decays of excited charmed states with quarks having non-zero orbital angular momentum ($D_{L \neq 0}$ states) is:

$$\beta = \frac{\sigma_0(D_{L \neq 0}) B(D_{L \neq 0} \rightarrow D^\pm X)}{\sigma_0(D^\pm)} ,$$

where $B(D_{L \neq 0} \rightarrow D^\pm X)$ is the branching fraction to $D^\pm$ without intermediate $D^{*\pm}$. The cross-section for directly produced $D^\pm$ mesons can then be written:

$$\sigma_0(D^\pm)_{\text{direct}} = \sigma_0(D^\pm) - \sigma_0(D^{*\pm}) B(D^{*\pm} \rightarrow D^\pm X) - \beta \sigma_0(D^\pm) .$$

Similarly, the fraction, γ , of observed $D^{*\pm}$ coming from $D_{L \neq 0}$ decays is:

$$\gamma = \frac{\sigma_0(D_{L \neq 0}) B(D_{L \neq 0} \rightarrow D^{*\pm} X)}{\sigma_0(D^{*\pm})} ,$$

and the cross-section for directly produced $D^{*\pm}$ mesons is given by:

$$\sigma_0(D^{*\pm})_{\text{direct}} = \sigma_0(D^{*\pm}) - \gamma \sigma_0(D^{*\pm}) .$$

The ratio, V/P , between production frequencies for charmed vector mesons and charmed pseudoscalar mesons is then:

$$\frac{V}{P} = \frac{\sigma_0(D^{*\pm})_{\text{direct}}}{\sigma_0(D^\pm)_{\text{direct}}} = \frac{\sigma_0(D^{*\pm})}{\sigma_0(D^\pm)} \cdot \frac{[1 - \gamma]}{\left[1 - \frac{\sigma_0(D^{*\pm})}{\sigma_0(D^\pm)} B(D^{*\pm} \rightarrow D^\pm X) - \beta\right]} .$$

If all quark spin states are equally probable, this ratio is 3. Our present measurement of $\sigma_0(D^{*\pm})$ and our previous measurement of $\sigma_0(D^\pm) = 3.24 \pm 0.08 \mu\text{b}$ [2] give:

$$\sigma_0(D^{*\pm})/\sigma_0(D^\pm) = 1.003 \pm 0.055 .$$

Using this and the branching-fraction measurement $B(D^{*\pm} \rightarrow D^\pm X) = 0.317 \pm 0.29$ [7], V/P has been calculated for different values of β and γ (Fig. 4). For the spin-counting expectation to be correct, the fraction of $D^\pm$ from $D_{L \neq 0}$ is constrained to be between 0.34 and 0.67. Also at LEP [15], where the $c\bar{c}$ production mechanism is different, and in other fixed-target experiments [8, 9, 10], V/P can be equal to 3 only if a significant fraction of $D^\pm$ mesons are produced in $D_{L \neq 0}$ decays with no intermediate $D^{*\pm}$. We have searched for evidence in our data for $D_{L \neq 0}$ decays to $D^\pm$ and one or two $\pi^\pm$, but the experimental sensitivity is too low for us to be able to draw any firm conclusion.

Figure 4: Ratio $V/P = \sigma_0(D^{*\pm})_{\text{direct}}/\sigma_0(D^{\pm})_{\text{direct}}$ as a function of β , the fraction of $D^{\pm}$ mesons from $D_{L\neq 0}$ decays (no intermediate $D^{*\pm}$), for different values of γ , the fraction of $D^{*\pm}$ mesons from $D_{L\neq 0}$ decays. The dashed line at $V/P = 3$ represents the spin-counting expectation.

4.3 Differential cross-sections

We obtain the D^{*+} and D^{*-} invariant differential cross-sections with respect to x_F and P_t^2 using events in the signal region, with corrections for background and acceptance (Figs. 5 and 6). The combined results for D^{*+} and D^{*-} are compatible with the corresponding measurements for pseudoscalar charmed mesons [2] (Fig. 7): χ^2 probability of 31% for x_F , and of 25% for P_t^2 . Predictions from perturbative QCD and from the Lund event generator (Fig. 7) differ slightly from one another, particularly at large values of x_F and P_t^2 , but both are in reasonable agreement with our data, within the experimental uncertainties.

Figure 5: Invariant differential cross-sections as a function of x_F . The curves (dotted for D^{*-} , solid for D^{*+}) represent fits to the data using $d\sigma_0/dx_F \propto (1 - |x_F|)^n$.

Figure 6: Invariant differential cross-section as a function of P_t^2 . The curve represents a fit to the data using $d\sigma_0/dP_t^2 \propto 1/(1 + P_t^2/\beta^2)^r$.

Parameterising the x_F distribution as $d\sigma_0/dx_F \propto (1 - |x_F|)^n$, the $D^{*\pm}$ data for $x_F < 0.6$ are fitted by $n = 4.3 \pm 0.4$. The uncertainty quoted is statistical only, but dominates over the systematic uncertainties. This value of n is equal, within errors, to the value $n = 4.27 \pm 0.11$ that we measured for pseudoscalar charmed mesons [2]. Comparison with other experiments [9, 10, 14] suggests an increase of n with π^- momentum over the range 200 GeV/c to 350 GeV/c (Table 4). However, given the large uncertainties, the measurements are also consistent with n being constant (χ^2 probability of 60% for fit to constant n).

Table 4: Comparison of values obtained fitting $D^{*\pm}$ x_F distributions as $d\sigma_0/dx_F \propto (1 - |x_F|)^n$.

experiment	x_F fit range	n	n_L	n_{NL}
WA92 350 GeV/c π^- on Si,Cu,W	0.0 to 0.6	4.3 ± 0.4	4.9 ± 0.5	3.9 ± 0.4
E769 [14] 250 GeV/c π^- on Be,Al,Cu,W	0.1 to 0.6	3.5 ± 0.3	2.9 ± 0.4	4.1 ± 0.5
NA32 [9] 230 GeV/c π^- on Cu	0.0 to 0.8	$3.14^{+0.40}_{-0.39}$	$2.62^{+0.53}_{-0.49}$	$3.83^{+0.66}_{-0.62}$
NA32 [10] 200 GeV/c π^- on Si	0.0 to 0.7	$2.8^{+1.1}_{-0.9}$	$4.7^{+1.9}_{-1.6}$	$1.7^{+1.4}_{-1.0}$

The x_F distributions have been fitted separately (Fig. 5) for leading (D^{*-}) and non-leading (D^{*+}) particles, yielding n_L and n_{NL} as fit parameters. We measure $n_L = 4.9 \pm 0.5$ and $n_{NL} = 3.9 \pm 0.4$, consistent with the two parameters being equal (χ^2 probability of 25%). In contrast, a leading-particle effect of the type described by the Lund event generator would result in n_{NL} being greater than n_L ($n_L(\text{Lund}) = 2.69 \pm 0.01$ and $n_{NL}(\text{Lund}) = 4.26 \pm 0.02$).

Charmed-particle differential cross-sections relative to P_t^2 are often fitted using $d\sigma_0/dP_t^2 \propto \exp(-bP_t^2)$. This parameterisation is inadequate for data covering a large range in P_t^2 , but b values for fits to restricted intervals can be useful for comparing with older experiments. For $P_t^2 < 4 (\text{GeV}/c)^2$, the $D^{*\pm}$ distributions are fitted by $b = 0.84 \pm$

Figure 7: Invariant differential cross-sections as a function of x_F (top) and P_t^2 (bottom) for $D^{*\pm}$ and $D^\pm$. Curves given by next-to-leading order QCD for $c\bar{c}$ pairs (solid line) and by the Lund event generator for $D^{*\pm}$ (dashed line) are normalized to the data.

$0.05 (\text{GeV}/c)^{-2}$, where the uncertainty quoted is again statistical only. This value of b is compatible with the value $b = 0.89 \pm 0.02 (\text{GeV}/c)^{-2}$ obtained in our study of pseudoscalar charmed-meson production [2], and with b values for $D^{*\pm}$ from other experiments [9, 10, 14] (Table 5). A fit to the distribution from the Lund event generator yields $b(\text{Lund}) = 0.94 \pm 0.05 (\text{GeV}/c)^{-2}$, also consistent with our measurement.

The P_t^2 distribution predicted by next-to-leading-order QCD for $c\bar{c}$ pairs has been found to be well described, over the whole P_t^2 range, by a function of the form [16] $d\sigma_0/dP_t^2 \propto 1/(1 + P_t^2/\beta^2)^r$, where β and r are free parameters. For a beam momentum of $350 \text{ GeV}/c$, β and r have a small dependence on the choice of QCD parameters, respectively varying in the ranges $1.9\text{--}2.0 \text{ GeV}/c$ and $5.1\text{--}5.4$. Our data are well fitted with $\beta = 1.9 \pm 0.2 \text{ GeV}/c$, $r = 4.7 \pm 0.7$ for $D^{*\pm}$ (Fig. 6); $\beta = 2.2 \pm 0.2 \text{ GeV}/c$, $r = 5.8 \pm 0.5$ for $D^\pm$. The parameter values for $D^{*\pm}$ and $D^\pm$ are in agreement within their uncertainties, and are consistent with the theoretical expectations.

Predictions of the charmed-particle differential cross-sections with respect to P_t^2 have also been made in the context of the intrinsic- K_t model [16, 17]. Here, in an attempt to take into account non-perturbative processes, a transverse component, K_t , normally distributed with mean square $\langle K_t^2 \rangle$, is added to the incoming parton momentum before

Table 5: Comparison of values obtained fitting $D^{*\pm} P_t^2$ distributions as $d\sigma_0/dP_t^2 \propto \exp(-bP_t^2)$.

experiment	P_t^2 fit range (GeV/c) ²	b (GeV/c) ⁻²
WA92 350 GeV/c π^- on Si,Cu,W	0 to 4	0.84 ± 0.05
E769 [14] 250 GeV/c π^- on Be,Al,Cu,W	0 to 4	0.70 ± 0.07
NA32 [9] 230 GeV/c π^- on Cu	0 to 10	0.79 ± 0.07
NA32 [10] 200 GeV/c π^- on Si	0 to 5	$0.9^{+0.3}_{-0.2}$

performing the perturbative QCD calculations. The Peterson fragmentation function is used, and the defining parameter is assigned a value of 0.06. The shape of the P_t^2 spectrum that we measure for $D^{*\pm}$ favours $\langle K_t^2 \rangle \approx 2-4$ (GeV/c)² (Fig. 8): χ^2 probability of 83% for $\langle K_t^2 \rangle = 2$ (GeV/c)² and 88% for $\langle K_t^2 \rangle = 4$ (GeV/c)². The value $\langle K_t^2 \rangle = 2$ (GeV/c)² approximately reproduced the forms of the D^0 and $D^\pm$ P_t^2 spectra [2] (χ^2 probability of 82%), and was consistent with our measurement of correlations between pairs of associated charmed hadrons [18].

Figure 8: Invariant differential cross-sections as a function of P_t^2 for $D^{*\pm}$ and $D^\pm$. The curves represent the predictions of the intrinsic- K_t model, for various choices of $\langle K_t^2 \rangle$ and the Peterson fragmentation function.

4.4 Production asymmetries

Differences in the production characteristics of two particles X_1 and X_2 , with production rates R_{X_1} and R_{X_2} , can be specified in terms of an asymmetry:

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

As a function of x_F , the asymmetry between D^{*-} production and D^{*+} production is found to be rather flat (Fig. 9). An increase of asymmetry with x_F is predicted by the Lund event generator and is observed in the case of D^- and D^+ [2, 13, 19, 20]. Given the relatively large experimental uncertainties, compatibility between D^{*-}/D^{*+} asymmetry and D^-/D^+ asymmetry is not quite excluded (χ^2 probability of 3% for compatibility between $Asym(D^{*-}, D^{*+})$ and $Asym(D^-, D^+)$, and of 1% for compatibility between $Asym(D^{*-}, D^{*+})$ and the Lund event generator). The asymmetry $Asym(D^{*-}, D^{*+})$ has no evident dependence on P_t^2 .

Figure 9: Production asymmetries as a function of x_F , for D^{*-} relative to D^{*+} and for D^- relative to D^+ . The curve represents the prediction of the Lund event generator for D^{*-}/D^{*+} asymmetry, after normalizing $\sigma_0(D^{*+})/\sigma_0(D^{*-})$ to the data.

As a function of x_F and P_t^2 , $Asym(D^{*\pm}, D^\pm)$ is also fairly flat, with a mean value close to zero (Fig. 10). The data are in good agreement with the predictions of the Lund event generator: χ^2 probability of 28% for x_F and 53% for P_t^2 .

Figure 10: Asymmetry of $D^{*\pm}$ with respect to $D^\pm$, as a function of x_F (top) and P_t^2 (bottom). The curves represent the prediction of the Lund event generator for $D^{*\pm}/D^\pm$ asymmetry, after normalizing $\sigma_0(D^{*\pm})/\sigma_0(D^\pm)$ to the data.

5 Conclusions

Production of $D^{*\pm}$ vector mesons has been studied in the WA92 experiment, using a 350 GeV/c π^- beam incident on copper and tungsten targets. Reconstruction of the decay chain (and charge conjugate) $D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+$ or $(K^- \pi^- \pi^+ \pi^+) \pi^+$ has allowed the selection of a sample of 611 ± 28 $D^{*\pm}$ mesons, produced at positive x_F . Measurements of inclusive and differential cross-sections have been performed, and comparisons have been made with the experiment's previous results for pseudoscalar charmed mesons. Assuming a linear A-dependence, the measured forward cross-section per nucleon in the region $x_F > 0$ is $3.25 \pm 0.16 \pm 0.26 \mu\text{b}$. The asymmetry of D^{*-} with respect to D^{*+} as a function of x_F is rather flat, although not incompatible with the increased asymmetry at higher x_F observed for D^- relative to D^+ . The WA92 measurements generally agree with data from other experiments and are the most precise so far.

References

- [1] S. Frixione et al., Heavy Flavours II (Advanced Series on Directions in High Energy Physics - Vol. 15), eds. A.J. Buras and M. Lindner (World Scientific, Singapore, 1998), p. 609, and references therein
[preprint CERN-TH/97-016 (1997)].
- [2] M. Adamovich et al. (WA92 experiment), Nucl. Phys. B495 (1997) 3.
- [3] M. Adamovich et al. (WA92 experiment), Nucl. Instrum. and Meth. A379 (1996) 252.
- [4] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 46 (1987) 43.
- [5] T. Sjöstrand and M. Bengtsson, Comput. Phys. Commun. 43 (1987) 367.
- [6] GEANT Detector Description and Simulation Tool, CERN Program Library Long Writeup W5013 (1994).
- [7] C. Caso et al. (Particle Data Group), Eur. Phys. J. C 3 (1998).
- [8] G.A. Alves et al. (E769 experiment), Phys. Rev. Lett. 77 (1996) 2388.
- [9] S. Barlag et al. (NA32 experiment), Z. Phys. C 49 (1991) 555.
- [10] S. Barlag et al. (NA32 experiment), Z. Phys. C 39 (1988) 421.
- [11] M. Aguilar-Benitez et al. (NA27 experiment), Phys. Lett. B 169 (1986) 106.
- [12] L. Kluberg et al., Phys. Rev. Lett. 38 (1977) 670;
D. S. Barton et al., Phys. Rev. D 27 (1983) 2580;
S. P. K. Tavernier, Rep. Prog. Phys. 50 (1987) 1439.
- [13] M. Adamovich et al. (WA82 experiment), Phys. Lett. B 305 (1993) 402.
- [14] G.A. Alves et al. (E769 experiment), Phys. Rev. D 49 (1994) 4317.
- [15] V. Gibson, Proc. XXVII Int. Conf. on High Energy Physics, Glasgow, United Kingdom, 1994, eds. P.J. Bussey and I.G. Knowles (Institute of Physics Publishing, Bristol, 1995) p. 507.
- [16] S. Frixione, M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B 431 (1994) 453.
- [17] M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B 405 (1993) 507.
- [18] M. Adamovich et al. (WA92 collaboration), Phys. Lett. B 385 (1996) 487.
- [19] G.A. Alves et al. (E769 collaboration), Phys. Rev. Lett. 69 (1992) 3147;
G.A. Alves et al. (E769 collaboration), Phys. Rev. Lett. 72 (1994) 812;
G.A. Alves et al. (E769 collaboration), Phys. Rev. Lett. 72 (1994) 1946
[Erratum].
- [20] E.M. Aitala et al. (E791 collaboration), Phys. Lett. B 371 (1996) 157.