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Measurement of D^+ production in Deep Inelastic ep Scattering with the ZEUS detector at HERA

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Charm production in deep inelastic ep scattering was measured with the ZEUS detector using an integrated luminosity of 354 pb^{-1}. Charm quarks were identified by reconstructing D^+ mesons in the $D^+ \to K^-\pi^+\pi^+$ decay channel. Lifetime information was used to reduce combinatorial background substantially. Differential cross sections as a function of the photon virtuality at the electron vertex, Q^2, the inelasticity, y, the transverse momentum, $p_T(D^+)$, and pseudorapidity, $\eta(D^+)$, of the D^+ meson were measured in the kinematic region $5 < Q^2 < 1000$ GeV^2, $0.02 < y < 0.7$, $1.5 < p_T(D^+) < 15$ GeV and $|\eta(D^+)| < 1.6$. Next-to-leading-order QCD predictions are compared to the data. The charm contribution, $F_2^{c\bar{c}}$, to the proton structure-function F_2 was extracted from the double-differential cross sections.

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1. Introduction

Measurements of charm production in deep inelastic *ep* scattering (DIS) at HERA provide powerful constraints on the proton structure. The dominant production mechanism, the boson-gluon fusion (BGF) process, $\gamma g \rightarrow c\bar{c}$, provides direct access to the gluon content of the proton. One crucial issue is the treatment of charm-quark mass effects.

In this report, recent measurement of charm production using D^+ mesons is presented [1]. A charm quark in the final state was identified by the presence of a D^+ meson[1], using the $D^+ \rightarrow K^-\pi^+\pi^+$ decay. The lifetime of D^+ mesons was used to suppress combinatorial background by reconstructing the corresponding secondary vertex.

Differential cross sections were measured as a function of the photon virtuality at the electron vertex, Q^2, the inelasticity, y, and the transverse momentum, $p_T(D^+)$, and pseudorapidity, $\eta(D^+)$, of the D^+ meson . The charm contribution to the proton structure-function F_2, denoted as $F_2^{c\bar{c}}$, was extracted from the double-differential cross sections in Q^2 and y. Previous measurements, as well as NLO QCD predictions, are compared to the data.

2. Theoretical predictions

Charm production in DIS has been calculated at NLO ($\mathcal{O}(\alpha_s^2)$) in the so-called fixed-flavour-number scheme (FFNS) [2], in which the proton contains only light flavours and heavy quarks are produced in the hard interaction.

The HVQDIS program [3] has been used to calculate QCD predictions for comparison to the results of this analysis, as well as to extrapolate the measured visible cross sections to obtain $F_2^{c\bar{c}}$. The renormalisation and factorisation scales were set to $\mu_R = \mu_F = \sqrt{Q^2 + 4m_c^2}$ and the charm-quark pole mass to $m_c = 1.5\,\text{GeV}$. The FFNS variant of the ZEUS-S NLO QCD PDF fit [4] to inclusive structure-function data was used as the parametrisation of the proton PDFs. The same charm mass and choice of scales was used in the fit as in the HVQDIS calculation. The coupling constant for the strong interaction $\alpha_s(M_Z)$ in the three-flavour FFNS was set to 0.105, corresponding to $\alpha_s(M_Z) = 0.116$ in the five-flavour scheme. To calculate D^+ observables, events at the parton level were interfaced with a fragmentation model based on the Kartvelishvili function [5].

A second NLO calculation was used in this analysis. It is based on the general-mass variable-flavour-number scheme (GM-VFNS) [6]. In this scheme, charm production is treated in the FFNS in the low-Q^2 region, where the mass effects are largest, and in the zero-mass variable-flavour-number scheme (ZM-VFNS) [7] at high Q^2. In the ZM-VFNS, the charm-quark mass is set to zero in the computation of the matrix elements and the kinematics. Charm is treated as an active flavour in the proton above the kinematic threshold, $Q^2 \approx m_c^2$. At intermediate scales, an interpolation is made in the GM-VFNS between the FFNS and the ZM-VFNS, avoiding double counting of common terms.

[1]Charge-conjugate modes are implied throughout the paper.

3. Selection of DIS events, reconstruction of D^+ mesons, cross-section determination

The analysis was performed with data taken from 2004 to 2007, when HERA collided electrons or positrons with energy $E_e = 27.5\,\mathrm{GeV}$ and protons with $E_p = 920\,\mathrm{GeV}$, corresponding to a centre-of-mass energy $\sqrt{s} = 318\,\mathrm{GeV}$. The corresponding integrated luminosity was $\mathscr{L} = 354 \pm 7\,\mathrm{pb}^{-1}$.

The kinematic variables Q^2 and y were reconstructed offline using the double-angle (DA) method [8], which relies on the angles of the scattered electron and the hadronic final state. The selected kinematic region was $5 < Q^2_{\mathrm{DA}} < 1000\,\mathrm{GeV}^2$ and $0.02 < y_{\mathrm{DA}} < 0.7$.

The D^+ mesons were reconstructed using the decay channel $D^+ \to K^-\pi^+\pi^+$. In each event, track pairs with equal charges were combined with a third track with the opposite charge to form D^+ candidates. The pion mass was assigned to the tracks with equal charges and the kaon mass was assigned to the remaining track. The three tracks were then fitted to a common vertex and the invariant mass, $M(K\pi\pi)$, was calculated. The kinematic region for D^+ candidates was $1.5 < p_T(D^+) < 15\,\mathrm{GeV}$ and $|\eta(D^+)| < 1.6$.

A powerful discriminating variable to suppress combinatorial background originating from light-flavour production is the decay-length significance, S_l. It is defined as $S_l = l/\sigma_l$, where l is the decay length in the transverse plane, projected on to the D^+ meson momentum, and σ_l is the uncertainty associated with this distance. The S_l distribution is asymmetric with respect to zero, with charm mesons dominating in the positive tail. Detector resolution effects cause the negative tail, which is dominated by light-flavour events. A cut $S_l > 4$ was applied; according to MC studies this optimises the statistical precision of the measurement. In addition, the χ^2 of the fitted secondary vertex, $\chi^2_{\mathrm{sec.vtx.}}$, was required to be less than 10 for three degrees of freedom, to ensure good quality of the reconstructed D^+ vertex.

Figure 1 shows the $M(K\pi\pi)$ distribution for the selected D^+ candidates. To extract the number of reconstructed D^+ mesons, the mass distribution was fitted with the sum of a modified Gaussian function for the signal and a second-order polynomial to parametrise the background. The number of D^+ mesons yielded by the fit was $N(D^+) = 8356 \pm 198$.

For a given observable, Y, the differential cross section in the i^{th} bin was determined as

$$\frac{d\sigma}{dY} = \frac{N^i - N^i_b}{\mathscr{A}^i_c \,\mathscr{L}\, \mathscr{B} \Delta Y^i} \cdot \mathscr{C}^i_{\mathrm{rad}},$$

where N^i is the number of reconstructed D^+ mesons in bin i of size ΔY^i. The reconstruction acceptance, $\mathscr{A}^i_c$, takes into account geometrical acceptances, detector efficiencies and migrations due to the finite detector resolution. The values of $\mathscr{A}^i_c$ were determined using the RAPGAP MC simulation for charm production in DIS [9]. The quantity $\mathscr{L}$ denotes the integrated luminosity and $\mathscr{B}$ the branching ratio for the $D^+ \to K^-\pi^+\pi^+$ decay channel, which is $9.13 \pm 0.19\%$ [10]. The radiative corrections, $\mathscr{C}^i_{\mathrm{rad}}$, were used to correct measured cross sections to the Born level. For the acceptance determination, the charm MC events were reweighted [11] to reproduce the Q^2, $p_T(D^+)$ and $\eta(D^+)$ distributions in the data. For all measured cross sections, the contribution of reconstructed D^+ mesons originating from beauty production, N^i_b, was subtracted using the prediction from the RAPGAP MC simulation.

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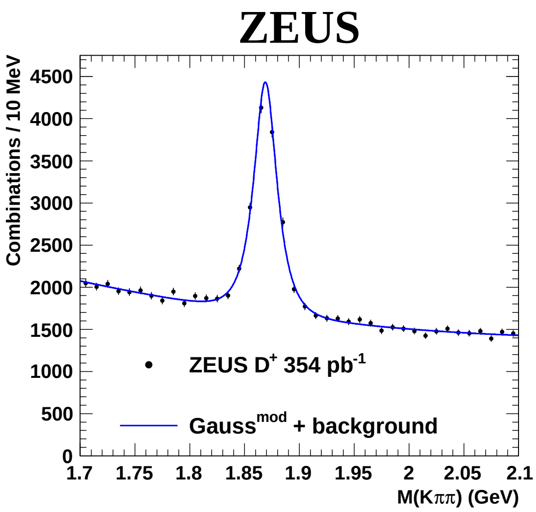

Figure 1: Mass distribution of the reconstructed D^+ candidates. The solid curve represents a fit by the sum of a modified Gaussian for the signal and a second-order polynomial for the background.

4. Results

4.1 Cross sections

The production of D^+ mesons in the process $ep \to e'c\bar{c}X \to e'D^+X'$ (i.e. not including D^+ mesons from beauty decays) was measured in the kinematic range:

$$5 < Q^2 < 1000\,\mathrm{GeV}^2,\, 0.02 < y < 0.7,\, 1.5 < p_T(D^+) < 15\,\mathrm{GeV},\, |\eta(D^+)| < 1.6.$$

The differential cross sections as a function of Q^2, y, $p_T(D^+)$ and $\eta(D^+)$ are shown in Fig. 2. The data presented here are in good agreement with the previous ZEUS D^+ measurement[2] [12]. They have significantly smaller uncertainties and supersede the previous results. The NLO QCD predictions calculated in the FFNS, using HVQDIS [4], provide a good description of the measurements. The experimental uncertainties are smaller than the theoretical uncertainties.

4.2 Extraction of $F_2^{c\bar{c}}$

The inclusive double-differential $c\bar{c}$ cross section in Q^2 and $x = Q^2/sy$ can be expressed as

$$\frac{d\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2^{c\bar{c}} - y^2F_L^{c\bar{c}}\right],$$

where $F_2^{c\bar{c}}$ and $F_L^{c\bar{c}}$ denote the charm contributions to the structure-function F_2 and the longitudinal structure function, F_L, respectively.

The differential D^+ cross sections, $\sigma_{i,\mathrm{meas}}$, measured in bins of Q^2 and y, were used to extract $F_2^{c\bar{c}}$ at reference points Q_i^2 and x_i within each bin, using the relationship

$$F_{2,\mathrm{meas}}^{c\bar{c}}(x_i, Q_i^2) = \sigma_{i,\mathrm{meas}}\frac{F_{2,\mathrm{theo}}^{c\bar{c}}(x_i, Q_i^2)}{\sigma_{i,\mathrm{theo}}},$$

[2]The contribution of D^+ mesons from beauty decays was subtracted using the scaled RAPGAP MC predictions.

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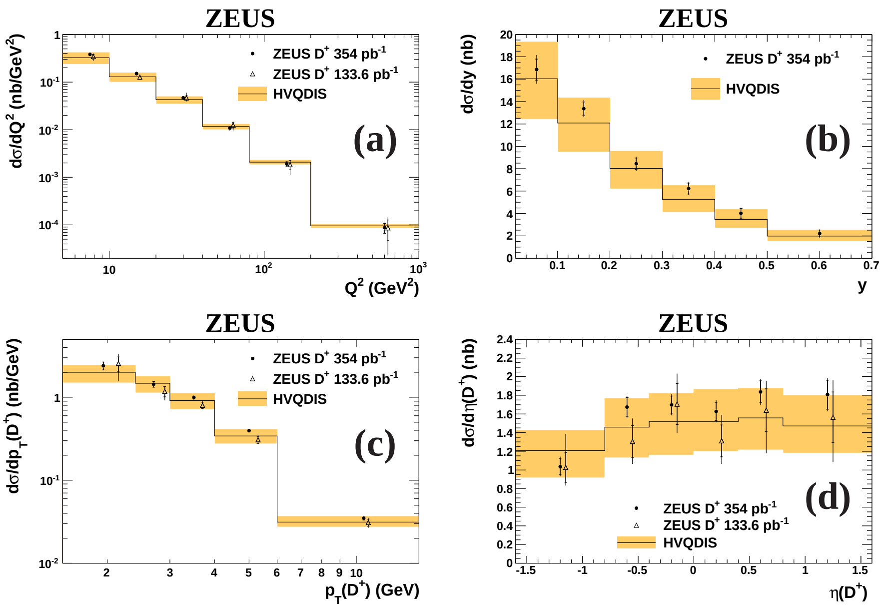

Figure 2: Bin-averaged differential cross sections for D^+ meson production in the process $ep \to e'c\bar{c}X \to e'D^+X'$ as a function of (a) Q^2, (b) y, (c) $p_T(D^+)$ and (d) $\eta(D^+)$. Results obtained in this analysis are shown as filled squares. The results of the previous ZEUS measurement are also shown (open triangles). The solid lines and the shaded bands represent the NLO QCD predictions in the FFNS with estimated uncertainties.

where $F_{2,\mathrm{theo}}^{c\bar{c}}$ and $\sigma_{i,\mathrm{theo}}$ were calculated at NLO in the FFNS using the HVQDIS program. This procedure corrects for the $f(c \to D^+)$ hadronisation fraction and for the extrapolation from the restricted kinematic region of the D^+ measurement ($1.5 < p_T(D^+) < 15\,\mathrm{GeV}$, $|\eta(D^+)| < 1.6$) to the full phase space.

The extracted values of $F_2^{c\bar{c}}$ are presented in Fig. 3. Figure 3 also shows a comparison to a previous ZEUS measurement of $F_2^{c\bar{c}}$ using D^* mesons [13]. The previous results were corrected to the Q^2 grid used in the present analysis using NLO QCD calculations. The two measurements are in good agreement and have similar precision. NLO QCD predictions in the FFNS and GM-VFNS were also compared to the data. Both predictions provide a good description of the data.

5. Conclusions

The production of D^+ mesons has been measured in DIS at HERA in the kinematic region $5 < Q^2 < 1000\,\mathrm{GeV}^2$, $0.02 < y < 0.7$, $1.5 < p_T(D^+) < 15\,\mathrm{GeV}$ and $|\eta(D^+)| < 1.6$. The present results supersede the previous ZEUS D^+ measurement based on a subset of the data used in this analysis. Predictions from NLO QCD describe the measured cross sections well. The charm contribution to the structure-function F_2 was extracted and agrees with that extracted from previous D^* measurements. NLO QCD calculations describe the data well.

The results presented here are of similar or higher precision than measurements previously published by ZEUS. The new precise data provide an improved check of pQCD and have the potential to constrain further the parton densities in the proton.

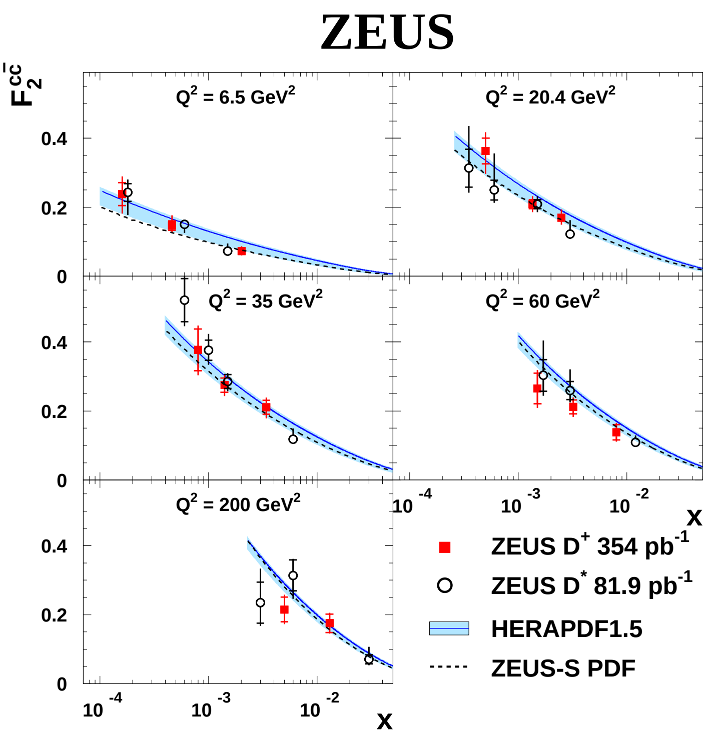

Figure 3: Structure-function $F_2^{c\bar{c}}$ as a function of x for various values of Q^2. Results obtained in this analysis are shown as filled squares. Also shown are the results of a previous $F_2^{c\bar{c}}$ measurement by ZEUS (open points) based on D^* production. Also shown are predictions in the GM-VFNS based on HERAPDF1.5.

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