Open charm and beauty

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ABSTRACT: Results on open charm production in ep collisions at HERA obtained with a high statistics sample are presented and compared with next-to-leading order (NLO) QCD predictions. Deep inelastic scattering (DIS) results on D^* production are used to measure the charm contribution, F_2^c, to the proton structure function F_2. The gluon density in the proton is extracted from the DIS D^* events. The differential cross sections for photoproduced D^* and D_s mesons are generally above NLO calculations, in particular in the forward (proton) direction. A study of dijet photoproduction (PHP) associated with charm yields significant contributions to the cross section of both the direct and resolved photon components. Several measurements of the $b\bar{b}$ cross section at HERA are reported in different kinematic regions.

1. INTRODUCTION

The study of heavy quark photoproduction provides an important test of perturbative QCD and sheds light on the structure of the photon. The handling of the mass of charm and beauty quarks, which imposes a hard scale on the interaction, divides the existing next-to-leading-order (NLO) calculations into two groups. In the *massive* approach [1], only light quarks (u, d, s) are assumed to be active flavours in the proton and photon and heavy quarks are produced dynamically, while in the *massless* approach [2, 3] heavy quarks are also treated as massless partons, making this approach applicable only for $p_\perp \gg m_{c(b)}$. In both cases, the formation of D mesons from the outgoing charm quarks is modelled using the Peterson fragmentation function [4]. A different model for calculating the production of charmed mesons has recently [5] been presented by Berezhnoy, Kiselev and Likhoded (BKL): in a tree-level calculation $\mathcal{O}(\alpha\alpha_s^3)$ they coherently hadronise a $(c,\bar{q})$ state, yielding both colour singlet and colour octet contributions.

The measurements that are reported here cover both the deep inelastic scattering regime, where the squared momentum transfer, Q^2, is large and the photoproduction regime, where instead $Q^2 < 1$ GeV^2.

In the DIS kinematic region, the charm contribution, F_2^c, to the proton structure function, F_2, is measured and the gluon density in the proton is extracted.

In the PHP regime information on the structure of the photon is obtained by studying the differential cross section in $x_\gamma^{\rm OBS}$, which is the fraction of the photon energy contributing to the two jets with largest transverse energy $E_T^{\rm jet1,2}$,

$$x_\gamma^{\rm OBS} = \frac{E_T^{\rm jet1} e^{-\eta^{\rm jet1}} + E_T^{\rm jet2} e^{-\eta^{\rm jet2}}}{2yE_e}, \qquad (1.1)$$

where $\eta^{\rm jet1,2}$ is the pseudorapidity of the jet, $\eta^{\rm jet} \equiv -\ln(\tan(\theta^{\rm jet}/2))$ with the polar angle defined with respect to the proton beam direction, E_e is the positron beam energy and y is the fractional energy transfer in the proton rest frame. Low values of $x_\gamma^{\rm OBS}$ suggest that only part of the initial photon was engaged in the hard interaction. In leading-order QCD this case is denoted as resolved as opposed to direct photoproduction.

The results presented here are based on HERA data using 27.5 GeV positrons with 820 GeV protons taken by the H1 and ZEUS collaborations.

2. Deep Inelastic Scattering production of D^* and Measurement of F_2^c

The D^* cross section in the DIS regime has been measured by H1 (1996 data) and ZEUS (1996+97 data). The ZEUS measurement was performed in the kinematic region $1 < Q^2 < 600$ GeV^2, $0.02 < y < 0.7$, $|\eta^{D^*}| < 1.5$ and $1.5 < p_\perp^{D^*} < 15$ GeV for the $K\pi\pi_s$ decay channel or $2.5 < p_\perp^{D^*} < 15$ GeV for the $K\pi\pi\pi\pi_s$ decay channel. The H1 measurement was performed in the kinematic region $2 < Q^2 < 600$ GeV^2, $0.05 < y < 0.7$, $|\eta^{D^*}| < 1.5$ and $p_\perp^{D^*} > 1.5$ GeV for the $K\pi\pi_s$ decay channel only. NLO calculations of the PGF process with the program HVQDIS [6] have been compared to the differential distributions and found to give a reasonable description of the ZEUS and H1 data. This allows an extrapolation of the visible D^* cross section to the full charm cross section, $\sigma_{c\bar{c}}(x, Q^2)$, from which the charm contribution, $F_2^c(x, Q^2)$, to the proton structure function can be extracted:

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

where x is the Bjorken scaling variable. Fig. 1 shows the relative charm contribution to inclusive DIS, quoted as F_2^c/F_2, that rises with Q^2 and towards low x.

3. Extraction of the gluon distribution in the proton

The fraction of the proton momentum carried by the gluon, x_g, can be reconstructed from the momenta of photon and $c$quark in a kinematic region where the PGF process dominates: $x_g = (\hat{s} + Q^2)/ys$; $\hat{s} = (p_{\perp c}^{*2} + m_c^2)/z(1-z)$; $z = (P_p \cdot P_c)/(P_p \cdot P_\gamma) = (E - P_z)_c/(2yE_e)$. Here $\hat{s}$ is the squared partonic CM energy, P_p, P_γ and P_c denote the proton, photon and $c$quark momenta respectively and $p_{\perp c}^*$ is the c transverse momentum in the γp system relative to the proton direction.

In a recent H1 analysis [8], a variable $x_g^{\rm OBS}$ is reconstructed, using the measured D^* momentum to estimate the charm momentum. The cross section as a function of $x_g^{\rm OBS}$ was measured

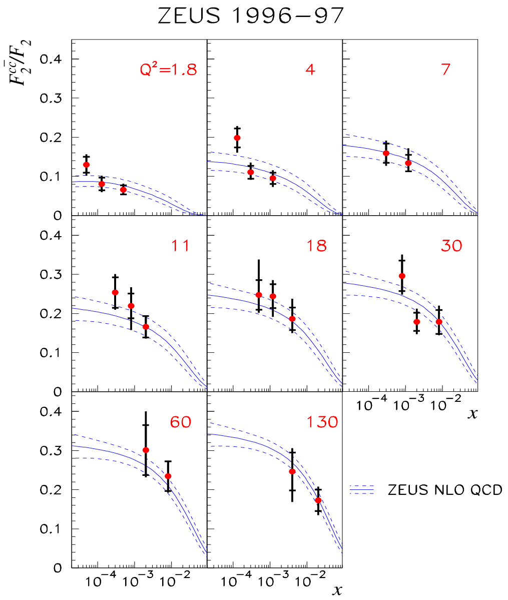

Figure 1: Relative charm contribution to inclusive DIS [7]. The curves correspond to the NLO QCD calculation using the result of the ZEUS NLO QCD fit to F_2.

in restricted $p_\perp^{D^*}$ and η^{D^*} regions, which suppress the resolved photon contribution in the forward direction, and then unfolded to the gluon density in the proton, $g(x_g)$, using the massive NLO calculation. Fig. 2 shows the $x_g g(x_g)$ distribution from DIS regime, unfolded at an average scale $\mu_F^2 = 25$ GeV^2. This direct determination of the gluon density in the proton is in agreement, within large errors, with the indirect measurement (shaded band in Fig. 2) from a QCD fit to the inclusive F_2 measurement [9].

4. D^* and D_s photoproduction

ZEUS data on inclusive D^* and D_s production for photon-proton CM energies in the range $130 < W < 280$ GeV and photon virtuality $Q^2 < 1$ GeV^2 with $|\eta^D| < 1.5$ have been collected during 1996 and 1997 [10, 11]. DIS events were removed by requiring no scattered positron found in the ZEUS calorimeter. The total number of D mesons is extracted by reconstructing the kinematic of the events for the following decay channels $K\pi\pi_s$ and $K\pi\pi\pi\pi_s$ for the D^* and $KK\pi$.

The differential cross sections in $p_\perp^D$ and in η^D are shown in Fig. 3, where the experimental

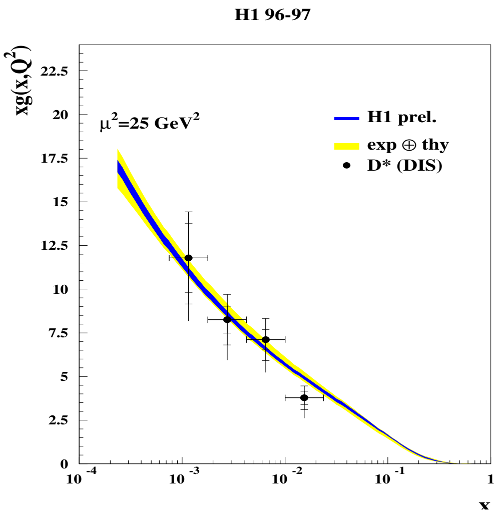

Figure 2: Gluon density obtained from the DIS D^* analysis. The results are compared to the result of the H1 QCD analysis of the inclusive F_2 measurement [9] at $\mu_F^2 = 25$ GeV^2.

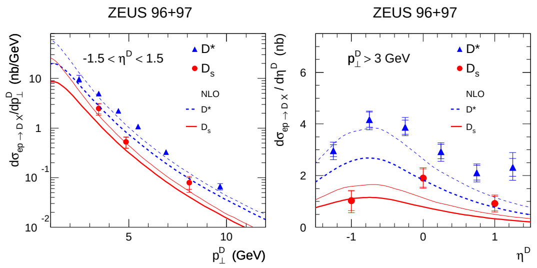

Figure 3: ZEUS differential cross sections $d\sigma/dp_\perp^D$ (left) and $d\sigma/d\eta^D$ (right) for D^* (triangles) and for D_s (dots) photoproduction, $Q^2 < 1$ GeV^2, in the kinematic region described in the text.

points are compared with a fixed-order (*massive*) NLO predictions [1] for D_s (full curves) and D^* (dashed curves) with two parameter settings. It can be seen that even for an extreme choice of the parameter values ($m_c = 1.2$ GeV, $\mu_r = 0.5 m_\perp$) the data, although closer in this case, are still too high in the high η^D region. The use of a tree-level $\mathcal{O}(\alpha\alpha_s^3)$ calculation [5], that was tuned to describe the ZEUS D^* cross sections, gives a better agreement (Fig. 5)

Two resummed (*massless*) charm calculations were performed in different ways [2, 3], using different factorisation schemes. Both extracted the ϵ Peterson's parameter [4] by fitting D^* production from e^+e^- data. The parameters μ_R and

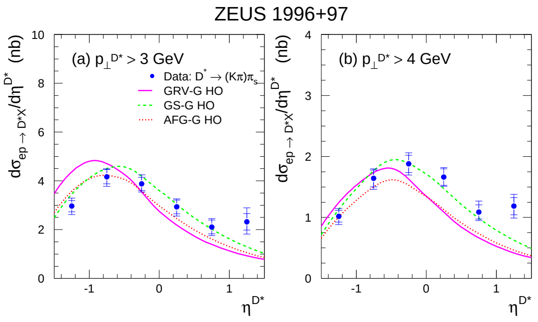

Figure 4: ZEUS differential cross sections $d\sigma/d\eta^{D^*}$ for D^* photoproduction, $Q^2 < 1$ GeV^2. The data points are compared with the NLO massless [2] predictions for different photon density parametrisations.

m_c were identical to the ones used in the massive approach. These kinds of calculations are sensitive to the photon density parametrisation, mainly to its charm content. The prediction with GS-G HO gives the best agreement (Fig. 4), even though the c and u quarks in this calculation are treated equally, without any threshold suppression of the c quark.

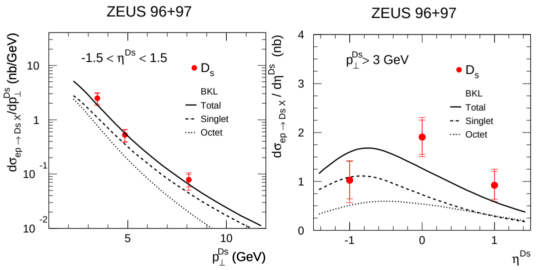

Figure 5: ZEUS differential cross sections $d\sigma/dp_\perp^{D_s}$ (left) and $d\sigma/d\eta^{D_s}$ (right) for D_s photoproduction, $Q^2 < 1$ GeV^2. The data points are compared to the BKL model [5] tuned with the ZEUS D^* data.

5. Charm dijet analysis

Charm photoproduction in a dijet sample with an associated D^* meson has been measured [10] by ZEUS. Events were required to have at least two jets reconstructed with the KTCLUS jet algorithm [12] with transverse energies $E_T^{\mathrm{jet}1,2} > 7,6$ GeV and $\eta^{\mathrm{jet}} < 2.4$. The kinematics of the hard scattering process is studied by measuring the fraction of the photon momentum contributing to the production of the two highest E_T^{jet}

x_γ^{OBS} (see Eq. (1.1)). In LO QCD at the parton level, $x_\gamma^{OBS} = 1$ for direct photon processes and $x_\gamma^{OBS} < 1$ for resolved ones. A direct (resolved) photon event is defined by selecting $x_\gamma^{OBS} \geq 0.75$ (< 0.75). The differential cross sections, $d\sigma/dx_\gamma^{OBS}$, are given in Fig. 6 and compared to the LO Monte Carlo (MC) HERWIG predictions [13] and to a parton level NLO massive charm calculation [1]. In addition to the expected large contribution of the LO direct process at high x_γ^{OBS}, there is a substantial tail towards low x_γ^{OBS} values originating from a LO resolved photon fraction, which amounts to $\approx 45\%$. The dominant contribution (93%) of the resolved component in the HERWIG MC is due to charm excitation in the photon (lightly hatched). The NLO massive charm calculation, which does not have an explicit charm excitation component, produces a tail at low x_γ^{OBS}; however, the data are still significantly above this prediction.

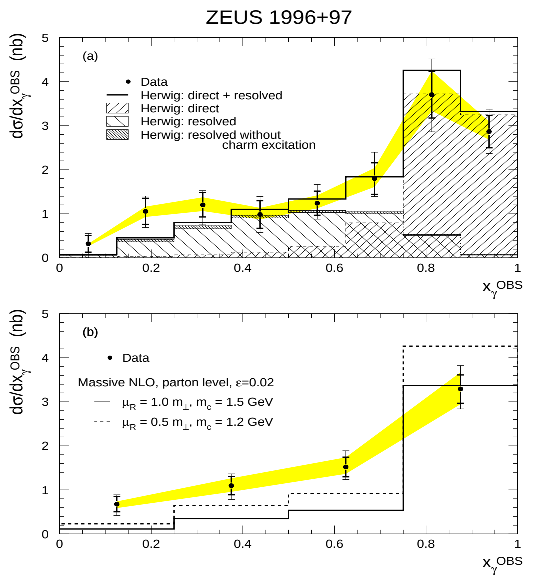

Figure 6: The differential cross section $d\sigma/dx_\gamma^{OBS}$ for dijets with an associated D^* meson with $p_\perp^{D^*} > 3$ GeV, $\left|\eta^{D^*}\right| < 1.5$ in the kinematic range $130 < W < 280$ GeV, $Q^2 < 1$ GeV^2. The experimental data (dots) are compared to the expectations of the HERWIG simulation (a) and with a parton level NLO massive charm calculation (b).

6. Beauty production

Finding beauty at HERA is not simple. Theorerical predictions of the total cross section ratios of about $\sigma_{uds} : \sigma_c : \sigma_b \sim 2000 : 200 : 1$ [1]. The measurements to date rely on the well established signature of semileptonic decays of b hadrons in jets. Due to the higher transverse b mass, the leptons in b events have a higher transverse momentum p_T^{rel} with respect to the jet direction, which approximates the flight direction of the decaying hadron. The b visible cross section can thus be obtained by unfolding the p_T^{rel} distribution; this method has been implemented by both collaboration.

H1 has published [14] the visible cross section in the muonic semileptonic channel, in the kinematic range defined by $Q^2 < 1$ GeV, $0.1 < y < 0.8$, $p_t^\mu > 2$ GeV, $35° < \theta^\mu < 130°$, measuring a value of $\sigma_{b\bar{b}}^{vis}(ep \to \mu X) = 176 \pm 16^{+26}_{-17}$ pb, this is in excess of the NLO QCD expectation of 104 ± 17 pb.

The obtained result has been extrapolated to the full phase space by means of a NLO program incorporating a Peterson type model of fragmentation, in Fig. 7 (left) the experimental value is confronted with the NLO prediction.

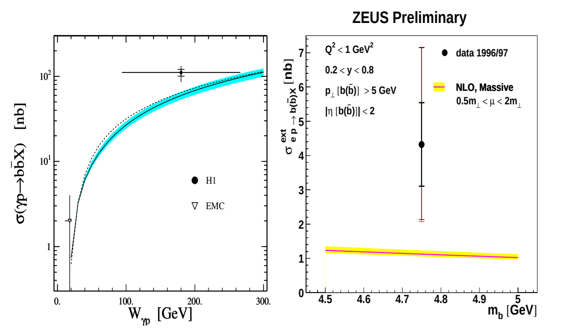

Figure 7: b production cross section, compared with NLO QCD, as measured by the H1 [14] (left) and by the ZEUS collaborations [15] (right).

ZEUS has determined the beauty cross section in three independent analyses, using both the electron channel and the muonic one (in the central-rear region and in the forward detector region) [15]. Event samples of two jets with $E_T^{jet1,2} > 7, 6$ GeV and $\eta^{jet} < 2.4$, together with electrons ($p_T^{e^-} > 1.6$ GeV, $\left|\eta^{e^-}\right| < 1.1$), barrel-rear muons ($p^\mu > 3$ GeV, $-1.75 < \eta^\mu < 1.3$) or forward muons ($p_T^\mu > 1.5$ GeV, $1.4 < \eta^\mu < 2.4$) were selected within $Q^2 < 1$ GeV and $0.2 < y <$

0.8. The $p_T^{\rm rel}$ distribution, obtained in the μ channel in the forward region, is displayed in Fig. 8. Overlayed is a Monte Carlo prediction obtained with the PYTHIA generator [16], which describes the shape of data reasonably well. It should be noted that the simulation curve is obtained with the fitted percentage of beauty. A very large

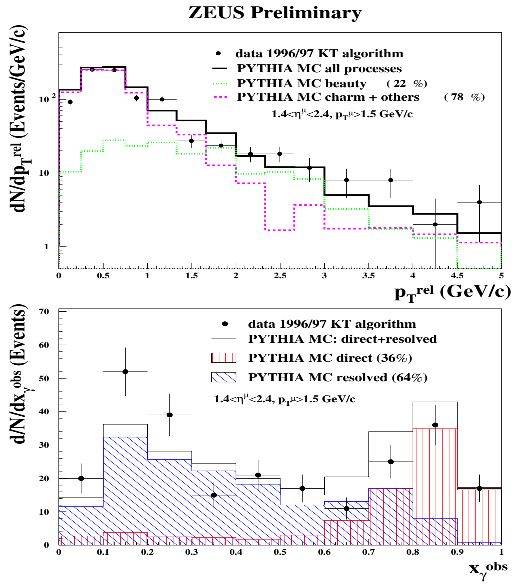

Figure 8: Observed $p_T^{\rm rel}$ (top) and $x_\gamma^{\rm OBS}$ (bottom) distributions for dijet events containing muon candidates in the forward detector region, compared with the PYTHIA generator predictions [15].

contribution of resolved processes ($x_\gamma^{\rm OBS} < 0.75$) is also seen, Fig. 8 (bottom).

The visible cross section obtained are:

$$\sigma_{b\bar{b}}^{\rm vis}(e^+p \to e^- + {\rm dijet} \ + X) = 39 \pm 11^{+23}_{-16} \ {\rm pb}$$

$$\sigma_{b\bar{b}}^{\rm vis}(e^+p \to \mu \ + {\rm dijet} \ + X) = 36.4 \pm 5.2^{+10.4}_{-9.1} \ {\rm pb}$$

$$\sigma_{b\bar{b}}^{\rm vis}(e^+p \to \mu \ + {\rm dijet} \ + X) = 20.5 \pm 6.5^{+6.3}_{-5.7} \ {\rm pb}$$

which are $\sim 1.5\,\sigma$ above the HERWIG prediction and compatible with the PYTHIA prediction.

In the case of the electron decay mode, $b\bar{b}$ cross sections are extrapolated using Monte Carlo events to the region where $p^{b(\bar{b})} > 5$ GeV and $\left|\eta^{b(\bar{b})}\right| < 2$. The obtained value can be compared with a *massive* NLO prediction [1], Fig. 7 (right). The experimental value is found to be $\sim 1.5\,\sigma$ higher than the calculation.

7. Summary

Recent results of heavy quark productions from HERA have been presented and compared with various theoretical predictions. Heavy quark production at HERA provides an interesting testing ground for QCD.

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