# OPEN HEAVY FLAVOR PRODUCTION AT HERA

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The production of charm and, for the first time, open beauty mesons at HERA is discussed. In photoproduction, the data are compared to different next-to-leading order QCD calculations; in deep inelastic scattering, the good agreement of the theoretical and the measured distributions is exploited to determine the charm contribution $F_2^c$ to the proton structure function and the gluon momentum distribution $xg(x)$. The first determination of the open beauty production cross section is compared with the prediction of a leading-order QCD Monte Carlo event generator.

## 1 Introduction

The measurement of differential and total cross sections for open heavy flavor production at the positron-proton collider HERA provides interesting insights into *(i)* the production mechanism for heavy quarks and its theoretical description, and *(ii)* the substructure of the proton, in particular the gluon momentum distribution. The virtuality of the photon exchanged in the scattering process allows to distinguish coarsely two different kinematic régimes: photoproduction and deep inelastic scattering.

The main contribution to the cross section is due to *direct photoproduction* events with low momentum transfer $Q^2 \sim 0$. The basic process here is photon-gluon fusion, where the positron radiates a quasi-real photon undergoing a hard scattering process with a gluon in the proton to form a $q\overline{q}$-pair. The mean photon-proton center-of-mass (cms) energy $W_{\gamma p} \sim 200\,\mathrm{GeV}$ is roughly an order of magnitude larger than at previous fixed-target experiments. This brings about a contribution of *resolved* photon, where the photon fluctuates into a hadronic state before undergoing a hard collision with a parton in the proton. As not all of the photon's energy is available for the hard sub-process, the emerging heavy quarks are typically boosted into the ("forward") direction of the out-going proton and show a transverse momentum spectrum which is softer than for direct production. It is expected that the experimental cuts strongly reduce the resolved contribution in comparison with the direct component. At next-to-leading order (NLO) QCD, only the sum of direct and resolved contributions is defined unambiguously. There are currently two approaches at NLO QCD applied for the calculation of photoproduction: The *massive* calculation [1] is a fixed order calculation, where charm and beauty are produced exclusively at the perturbative level. Here the mass of the heavy quark determines the scale enabling the description of the hard subprocess with perturbative QCD. This approach is indispensable for the calculation of the total cross section, but is expected to experience some corrections in the large-$p_\perp^q$ domain, as terms of the form $\alpha_s \log^n(p_\perp^q/m_q)$, where $p_\perp^q$ and $m_q$ are the transverse

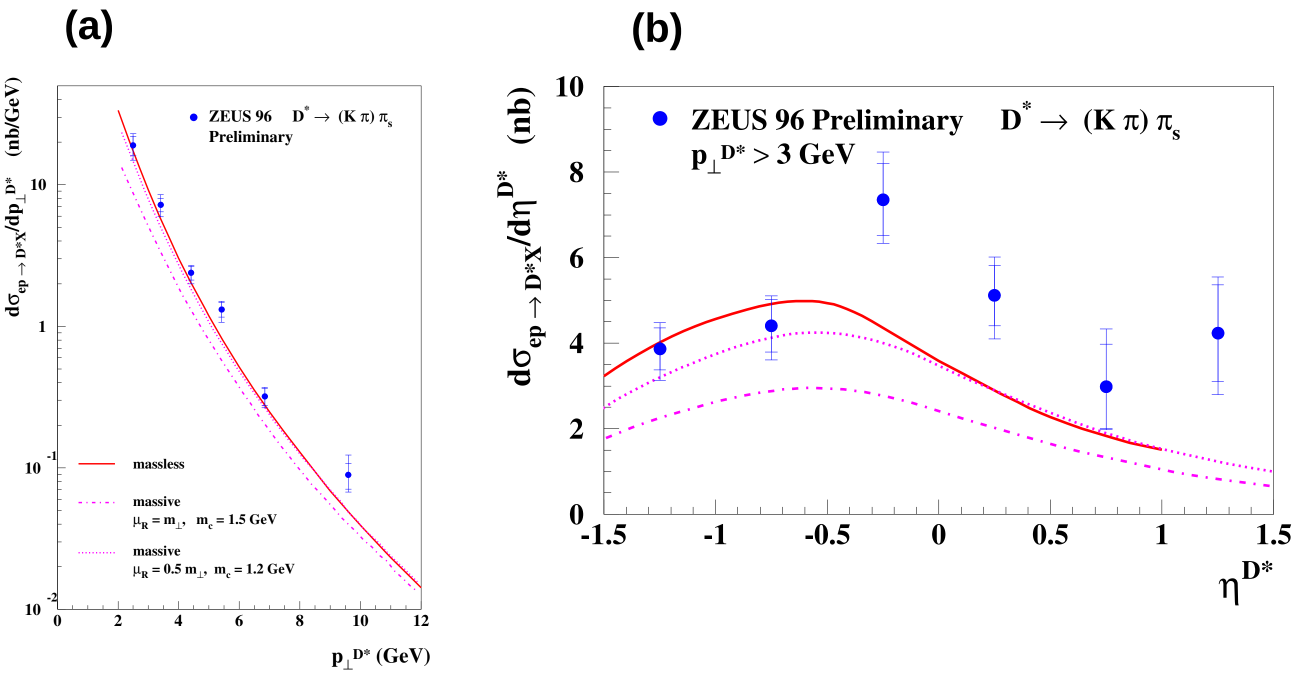


Figure 1: Differential cross sections $d\sigma/dp_\perp$ (a) and $d\sigma/d\eta$ (b) of $D^{*\pm}$-photoproduction ($Q^2 < 4\,\mathrm{GeV}^2$). The solid line corresponds to a massless calculation, the dotted and dash-dotted to the massive calculation with different choices of the renormalization scale and charm quark mass.

momentum and mass of the heavy quark $q$, are not resummed. This is done in the *massless* calculation [2], where the "heavy" quark is treated as an active flavor (massless parton) in both the proton and the photon, and fragmented only after the hard process into a massive quark. Perturbative fragmentation functions are used to resum all terms of the order $\alpha_s^n \log^n(p_\perp^q/m^q)$ and $\alpha_s^{n+1} \log^n(p_\perp^q/m^q)$. This scheme is expected to yield superior results in the high-$p_\perp^q$ region, where $p_\perp^q \gg m_q$.

In *deep inelastic scattering* (DIS), where the virtuality of the exchanged photon is typically $Q^2 > 1\,\mathrm{GeV}^2$, the production of heavy flavor is well described by the photon-gluon fusion process. The measurement can be extended to the régime where the heavy mesons have low transverse momentum, such that the massive scheme [3] provides a good description of the process.

The data presented here correspond to luminosities of $\mathcal{L} = 2.33 - 10.8\,\mathrm{pb}^{-1}$ and were recorded by the H1 and ZEUS detectors [4,5] in the years 1994 – 1996, when HERA was colliding 27.5 GeV positrons onto protons of 820 GeV.

## 2 Production of Open Charm

At HERA open charm is tagged by the reconstruction of $D^*$ mesons mainly with the decay chain $D^{*\pm} \to D^0\pi_s^\pm \to (K^\mp\pi^\pm)\pi_s^\pm$, where use is made of the small mass difference $\Delta m = m_{K^\mp\pi^\pm\pi_s^\pm} - m_{K^\mp\pi^\pm}$. The cross sections are measured in restricted kinematic ranges, where the $D^*$ candidate has to have a transverse momentum of typically $p_\perp^{D^*} > 3$ (1.5) GeV/c$^2$ and a pseudo-rapidity in the lab-frame of $-1.5 < \eta^{D^*} < 1.0$ (1.5) in the case of photoproduction (DIS).

### *2.1 Photoproduction of Open Charm: Differential Cross Sections and Resolved Contribution*

ZEUS measured [6] differential cross sections in the kinematic range $Q^2 < 4\,\mathrm{GeV}^2$ (with a median $\overline{Q^2} = 5\cdot 10^{-4}\,\mathrm{GeV}^2$) and $115 < W_{\gamma p} < 280\,\mathrm{GeV}$ and compared them to NLO massive and massless calculations (figure 1). Both calculations use the Peterson *et al.* [7] fragmentation function to describe the hadronization process $c \to D^*$, where $\epsilon_c = 0.06$ (0.0674) is used for the massive (massless) scheme. The absolute magnitude of the cross section as determined with the massless

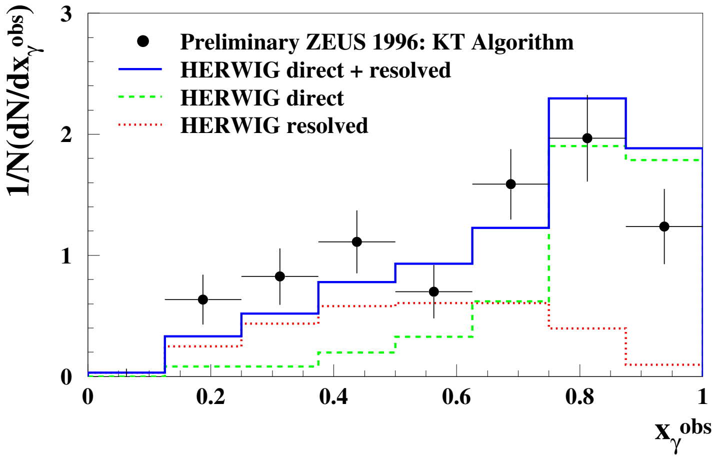


Figure 2: Distribution of $x_\gamma^{obs}$ for $D^{*\pm}$ candidates in photoproduction overlaid with the expectation of direct and resolved photoproduction (and their sum) as obtained from HERWIG.

calculation agrees better with the data than the massive calculation, which underestimates the data (for the chosen soft fragmentation) by up to 50%, depending on the choice of the charm quark mass and renormalization scale. The measured $\eta^{D^*}$ distribution shows an excess in the forward direction not reproduced by neither the massless nor the massive calculation.

Additional information on the production mechanism was obtained by the ZEUS collaboration [6] by measuring the fraction of the photon energy $x_\gamma^{obs}$ participating in the hard subprocess. The quantity $x_\gamma^{obs}$ can be reconstructed as $x_\gamma^{obs} = \sum_{\text{Jets}} E_T^{\text{Jet}} e^{-\eta^{\text{Jet}}}/2yE_e$ from the hadronic final state, where the sum runs over the two most energetic jets, $E_e$ is the initial energy of the positron and $y$ is approximately the fraction of the positron's energy carried by the photon. The jets are searched with a $k_\perp$ algorithm (a cone algorithm is used as cross-check), need to have a transverse energy of $E_T^{\text{Jet}} > 4\,\text{GeV}$ and fulfill $|\eta^{\text{Jet}}| < 2.4$. The uncorrected $x_\gamma^{obs}$ distribution is shown in figure 2 and compared to the HERWIG Monte Carlo event generator [8]. It appears that a significant contribution of resolved processes is needed to describe $D^*$ production in the measured kinematic range. In the framework of HERWIG, these processes are initiated mainly by charm quarks from the proton.

### *2.2 Open Charm Production in Deep Inelastic Scattering: $F_2^c$ and $xg(x)$*

In DIS, the massive calculation [3] provides a very good description of the differential cross sections in the kinematic ranges accessible to the two experiments, thus allowing the extraction of further information.

Neglecting contributions from $F_3$ and $F_L$ (which are estimated to be smaller than 2% in the kinematic region measured), the inclusive cross section for charm production can be written in the one-photon exchange approximation as

$$\frac{d\sigma^{c\bar{c}X}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{x \cdot Q^4}(1 + (1-y)^2)F_2^c(x, Q^2).$$

From the measured visible cross sections, H1 [9] and ZEUS [10] obtain $\sigma^{c\bar{c}X}$ by an extrapolation in $p_\perp^{D^*}$ and $\eta^{D^*}$ using AROMA [11] and the massive NLO calculations, respectively, and a gluon distribution obtained from NLO fits to their own respective data. Figure 3 (a) shows the charm contribution $F_2^c(x, Q^2)$ to the proton structure function as a function of $x$ in different bins of $Q^2$. The measured $F_2^c(x, Q^2)$ contains the sum of charm and beauty contributions, as no distinction is made between prompt $D^*$ mesons and those from $b$-decays. The contribution from $b$-decays

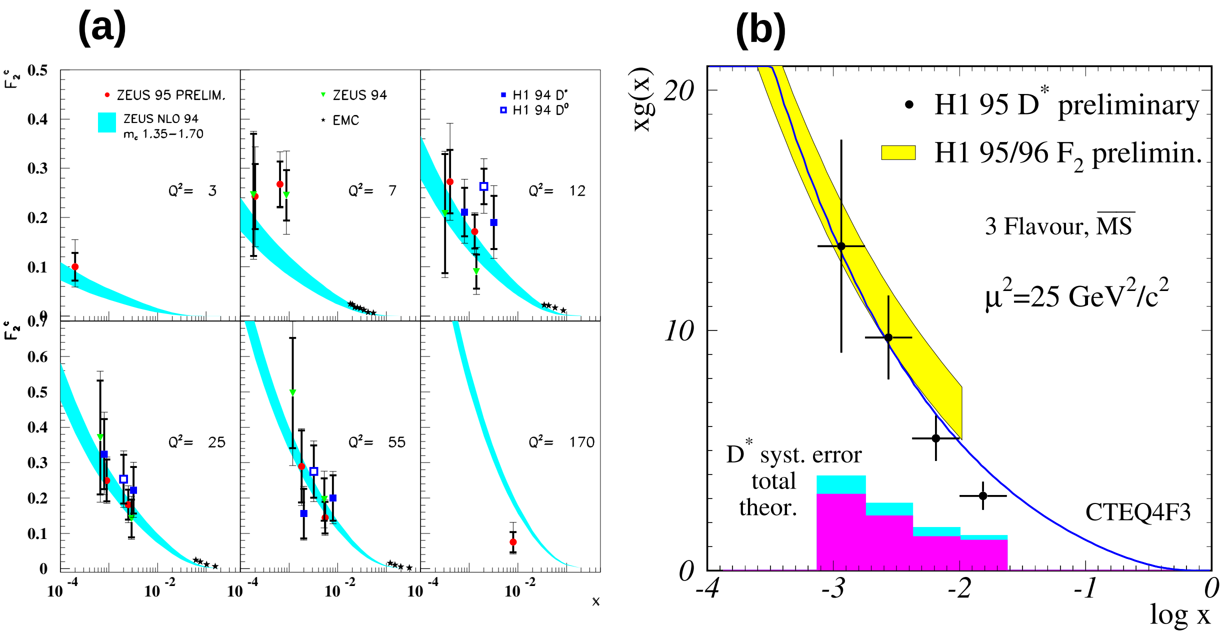


Figure 3: (a) Charm contribution $F_2^c$ to the proton structure function. (b) Gluon momentum distribution measured with $D^{*\pm}$ candidates in DIS.

is expected to be smaller than 10% in the kinematic range considered. A comparison with EMC data [12] reveals a steep rise of $F_2^c(x,Q^2)$ towards low $x$, which is reasonably well described by the massive NLO calculation, shown as a band corresponding to a variation of the mass of the charm quark from $m_c = 1.35\ldots1.70\,\mathrm{GeV/c^2}$. The contribution of charm to the total proton structure function is measured to be $< F_2^c/F_2 >= 0.237 \pm 0.045$, which is roughly an order of magnitude larger than determined by EMC at larger $x$.

The very good description of the data by the massive NLO calculation is exploited by the H1 collaboration [13] to extract the gluon momentum distribution. The observable $x_g^{obs}$ corresponds at leading order to the momentum fraction of the proton carried by the struck gluon and is reconstructed from the $D^*$-candidate. The differential cross section $d\sigma/dx_g^{obs}$ is measured in the visible range $2 < Q^2 < 100\,\mathrm{GeV}^2$, $0.01 < y < 0.7$, $p_\perp^{D^*} > 1.5\,\mathrm{GeV}/c$, $|\eta^{D^*}| < 1.5$, $(E-p_z)^{D^*}/2yE_e > 0.2$, and is unfolded iteratively to the true variable $x_g$ with the NLO program HVQDIS [14]. The unfolding takes into account NLO corrections, *e.g.* gluon radiation and fragmentation effects (Peterson *et al.* fragmentation function with $\epsilon_c = 0.060$). The unfolded cross section factorizes and the gluon distribution can be extracted bin-wise at an average scale of $\mu_0^2 = 25\,\mathrm{GeV^2/c^2}$. The result is shown in figure 3 (b) with a comparison to an indirect QCD analysis of the scaling violations of $F_2$. The results agree within the errors, which represents a non-trivial confirmation of the perturbative QCD description of the underlying process and of the universality of parton distributions.

## 3 Open Beauty Photoproduction

H1 measured the open beauty cross section in photoproduction ($Q^2 < 1\,\mathrm{GeV}^2$ and $0.1 < y < 0.8$, where $y$ is determined with the method of Jacquet-Blondel [15]) with semi-leptonic $b$-decays. Events are selected with the requirement of at least two jets with $E_T > 6\,\mathrm{GeV}$ and at least one muon in the central region of the detector with a transverse momentum $p_\perp^\mu > 2\,\mathrm{GeV}/c$. The muon has to be found within one of the jets. Beauty and charm events are separated on a statistical basis using the transverse momentum of the muon $p_{\perp,rel}^\mu$ relative to its jet axis. The measured $p_{\perp,rel}^\mu$ distribution is fitted with a beauty ($b$) and charm ($c$) component in addition to a background from fake muons, mainly from light quarks ($uds$). The shapes of the $b$- and $c$-contributions are obtained from the Aroma 2.2 Monte Carlo event generator [11]. The

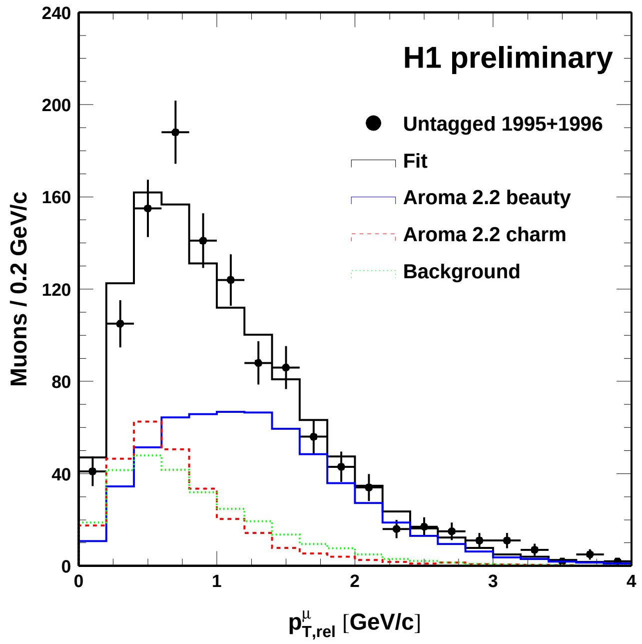


Figure 4: $p^{\mu}_{\perp,rel}$ distribution for inclusive muon candidates in 2-jet photoproduction ($Q^2 < 1\,\mathrm{GeV}^2$) events. The data are shown as filled circles, the fit and the predictions for the various components as histograms. The heavy quark components are taken from Aroma 2.2, the background is extracted directly from data.

distribution for $b$-quarks contains both direct decays ($b \to c\mu X$) and sequential decays ($b \to c \to s\mu X$, $b \to \tau \to \mu X$) with the appropriate branching ratios. The shape and normalization of the background is extracted directly from data using a detailed parameterization of the muon misidentification probability. As the charm and $uds$-background distributions are very similar in shape, a fit cannot distinguish between the two. The $uds$-background is therefore fixed to the calculated number of entries and a two-parameter fit is done to determine the size of the contributions of charm and beauty.

The relative composition of the data sample is determined with a $\chi^2$ fit to the $p^{\mu}_{\perp,rel}$ distribution and amounts to $f_b = 51.4 \pm 4.4\%$ (beauty), $f_c = 23.5 \pm 4.3\%$ (charm), and $f_{uds} = 23.5\%$ (background, fixed), with a $\chi^2/d.o.f. = 1.0$. The measured $p^{\mu}_{\perp,rel}$ distribution and the result of the fit are shown in figure 4. Other distributions, in particular the muon transverse momentum and polar angle as well as the jet transverse energy and polar angle distributions, are very well described with this data composition.

The open beauty cross section is determined from the number of muons $N^{\mu}_{b}$ attributed by the fit to $b$-decays and amounts in the visible range ($Q^2 < 1\,\mathrm{GeV}^2$, $0.1 < y < 0.8$, $p^{\mu}_{\perp} > 2.0\,\mathrm{GeV}/c$, $35° < \theta^{\mu} < 130°$) to

$$\sigma_{vis}(ep \to b\bar{b}X) = 0.93 \pm 0.08\,^{+0.21}_{-0.12}\,\mathrm{nb}, \qquad \text{(H1 preliminary)}$$

where the first uncertainty is statistical and the second systematic. The estimated visible beauty cross section of Aroma 2.2 amounts to 0.19 nb, which is roughly a factor of five below the measured value. The result has been cross-checked with the Herwig 5.9 Monte Carlo event generator [8], the difference to Aroma 2.2 is of the order of 5% and is included in the systematic error.

The visible charm cross section has been measured with the same method and shows a good agreement with the expectation. Using Aroma 2.2 for the extrapolation to the full kinematic range, the total charm cross section is consistent with the value measured with the reconstruction of $D^{*\pm}$-mesons [16].

## Conclusion

Open heavy flavor production has been studied with $D^*$ mesons and semileptonic $b$-decays. In the photoproduction régime of $Q^2 < 4\,\mathrm{GeV}^2$ and with a rather soft fragmentation of charm quarks, the massless-charm calculation provides a better description than the massive approach; both schemes fail to describe adequately the $\eta^{D^*}$ distributions in the forward direction. The data in DIS are very well described by the massive NLO QCD calculations and allow the extraction of the charm contribution $F_2^c$ to the proton structure function and the gluon density $xg(x)$. Both $F_2^c$ and $xg(x)$ are consistent with NLO QCD calculations based on the photon-gluon fusion process with gluon densities in the proton as measured by H1 and ZEUS. The open beauty cross section has been measured for the first time at HERA by the H1 collaboration and is found to be higher by a factor of five compared to the prediction of a leading-order QCD Monte Carlo event generator with parton-showers (AROMA 2.2).

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