Open Heavy Flavour Production at HERA

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Selected results from open heavy flavour production at HERA are presented. The production of charm and bottom quarks is discussed and compared with predictions from pertubative QCD. The fragmentation fractions of charm quarks into several charmed mesons are compared between ep and e^+e^- collisions.

1. Introduction

HERA collides 820/920 GeV protons and 27.5 GeV electrons or positrons, with a centre-of-mass energy of 300/318 GeV. Heavy quarks are predominantly produced in pairs via boson-gluon (BGF) fusion, where the production cross section for charm quarks is about two orders of magnitude larger than for bottom quarks. In deep inelastic scattering heavy quark production is sensitive to the gluon distribution in the proton. In photoproduction, the exchanged photon can also serve as a source of partons and hadrons, leading to a contribution of the cross section from parton-proton scattering which can be used to investigate the hadronic structure of the photon. The masses of the heavy quarks define a hard scale, which make perturbative QCD (pQCD) applicable to predict the production cross section. However, in photoproduction the contribution from parton-proton scattering can only be uniquely separated in lowest order and therefore all higher order calculations require assumptions about the parton distributions in the photon. In the DIS case all available calculations assume that the production of heavy quarks can be factorised and treated independently of the proton remnant. In fixed order (FO) next-to-leading order (NLO) QCD calculations the heavy quark is exclusively produced in the hard scattering [1], whereas in resummed (RS) NLO calculations the heavy quark is an active flavour inside the proton or the photon [2]. The analyses presented here make use of a large variety of Monte Carlo simulations based on LO QCD. The references to these models can be found in the quoted papers describing the measurements.

Another interesting field of heavy flavour physics are fragmentation studies. One of the obvious questions is if the fragmentation of quarks into different hadrons is universal and independent of the production mechanism of the quarks. For c-quark production at HERA this question is of particular relevance because for the absolute measurement of the $D^\star$ cross section a measurement of the fragmention fraction of $c \rightarrow D^\star$ from e^+e^- has to be used. By comparing the production cross sections of excited D-mesons from ep collision with those from e^+e^- collisions the hypothesis of the universality of fragmentation can be tested.

To describe the cross sections the usual DIS kinematic variables are used:

$$Q^2 = -(k-k')^2 = -q^2,\ x = \frac{Q^2}{2P \cdot q},\ y = \frac{q \cdot P}{k \cdot P}$$

Here k, k', P and q denote the four vectors of the incoming positron, the outgoing positron the proton and the intermediate photon, respectively.

2. Open Charm Production

In photoproduction, charm production has been compared with NLO calculations by measuring the D^* [3] and D_s cross sections [4]. The integrated D^* cross section is consistent with a NLO-RS-calculation, however the differential cross sections are not described as can be seen in fig. 1 for

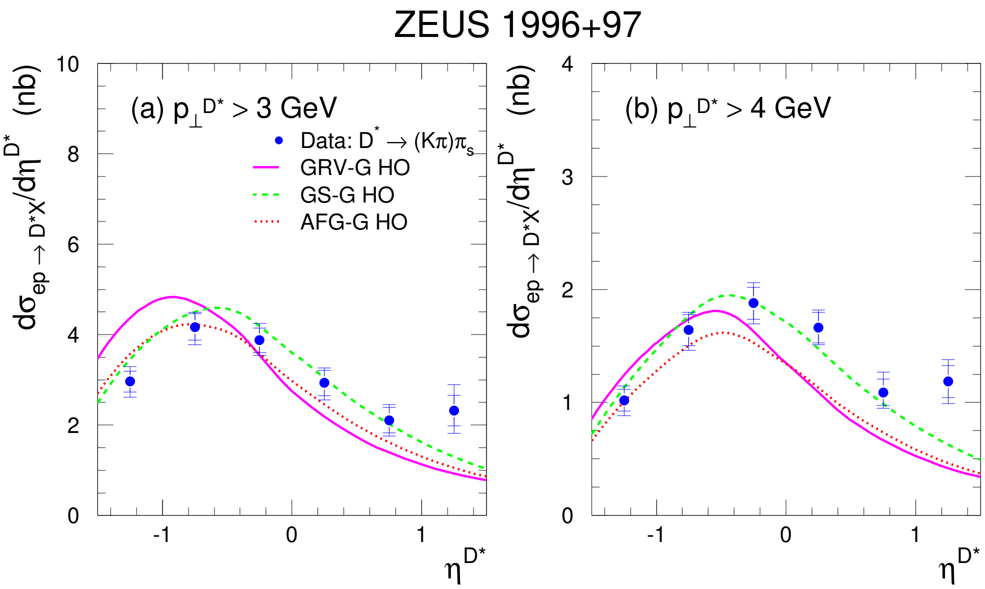

Figure 1. Differential cross section for $d\sigma/d\eta^{D^*}$ for D^* photoproduction [3]. The curves show predictions of the RS NLO calculation of Kniehl et al [2].

the pseudo-rapidity. In addition some sensitivity to the choice of the photon parton density is observed. The best description is obtained with the GS-HO parton density function, in which charm and u-quarks contribute equally. In fig. 2 the differential cross section for D^* and D_s production as function of the transverse momentum of the D-meson is shown and compared to a FO-NLO calculation. For both mesons the absolute normalization of the cross section is sensitive to the choice of parameters. For the D_s the measured cross section is above the prediction for most data points. Assuming a high c-quark mass the D^* cross section can be approximately reproduced.

Both ZEUS and H1 have measured the inclusive D^* production in DIS and have translated this into a measurement of $F_2^{c\bar{c}}$, the charm contribution to the proton structure function F_2 [5], using the relation

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

Fig. 3 shows $F_2^{c\bar{c}}$ from both experiments in the NLO DGLAP scheme. The data are described by the FO NLO QCD calculation, which is also

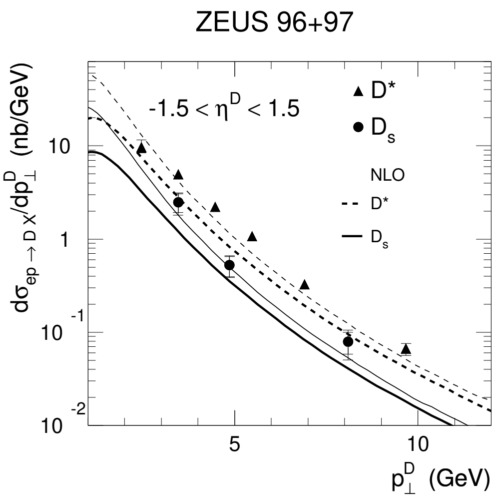

Figure 2. Differential cross sections $d\sigma/dp_\perp^D$ for D^* and D_s photoproduction [4]. The D^* (triangles) and D_s (dots) data are compared with the FO NLO predictions (FMNR) [1] for D^* (dashed curves) and D_s (full curves) with two parameter settings: m$_c$= 1.5 GeV, μ_R=m$_\perp$ (thick curves) and m$_c$= 1.2 GeV,μ_R=0.5m$_\perp$

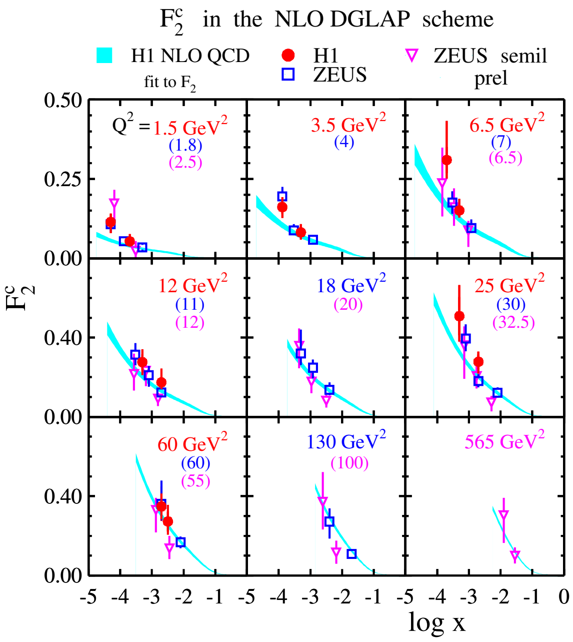

Figure 3. The structure function $F_2^{c\bar{c}}$ as function of x in bins of Q^2 as measured by H1 and ZEUS compared to a prediction from a NLO QCD fit to F_2 by H1 [5].

used to extrapolate the measured cross section to the full phase space. As for F_2, a steep rise of $F_2^{c\bar{c}}$ towards low values of x as well as strong scaling violations can be seen. The ratio of $F_2^{c\bar{c}}/F_2$ rises towards low x and amounts to more than 25% for $Q^2 > 6.5\ \mathrm{GeV}^2$. However, detailed comparisons of differential cross sections show that the FO NLO calculation underestimates the D^* production in proton direction. Therefore H1 compared their data also with a LO CCFM based simulation [6]. The CCFM prediction, in which the gluon emission is angular ordered, includes parton and gluon densities from an H1 measurement of F_2 using this model. In particular for low transverse momenta the CCFM model describes the D^* production in proton direction better than the DGLAP based FO NLO calculation.

ZEUS recently reported that for $Q^2 > 20\ \mathrm{GeV}^2$ the $D^{*\pm}$ cross sections differ slightly in e^-p and e^+p interactions [7], while the standard

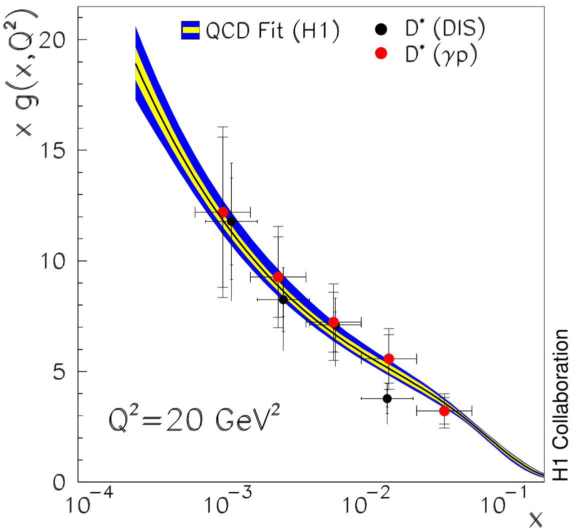

Figure 4. The gluon densities, by H1, from D^* production in photoproduction and in DIS, compared to the gluon density obtained from a QCD fit to F_2

charm production mechanisms contain no charge dependence on the lepton of the ep interaction. More e^-p data are needed to investigate whether or not this is a statistical fluctuation. On the basis that charm production is dominated by boson gluon fusion, H1 has extracted the gluon density from the inclusive D^* production [8], as shown in fig. 4. Data from photoproduction at a scale $\mu = 20\ \mathrm{GeV}^2$ are plotted together with those from DIS at $Q^2 = 20\ \mathrm{GeV}^2$ and are compared to a recent QCD fit to F_2 [9]. The gluon distribution in the proton generated by the DGLAP equations agrees remarkably well with that from the direct measurement of charm production and supports the NLO QCD description of ep scattering.

3. Charm Fragmentation

To compare results from different experiments it is usually assumed that the fragmentation of quarks is independent of their production mechanism. This assumption can be tested by measuring the cross sections of excited D and D_s

$f(c \to D_1^0 =$	$(1.46 \pm 0.18^{+0.33}_{-0.27} \pm 0.06)\%$	ZEUS
	$(1.8 \pm 0.3)\%$	CLEO
$f(c \to D_2^{*0} =$	$(2.00 \pm 0.58^{+1.40}_{-0.48} \pm 0.41)\%$	ZEUS
	$(1.8 \pm 0.3)\%$	CLEO
$f(c \to D_{s1}^+ =$	$(1.24 \pm 0.18^{+0.08}_{-0.06} \pm 0.14)\%$	ZEUS
	$(1.6 \pm 0.4 \pm 0.3)\%$	OPAL

Table 1
Measured fragmentation fractions of charm quarks into several D-mesons

mesons. Using the known $c \to D^*$ branching fraction ZEUS has measured the fragmentation fractions of c-quarks to D_1^0, D_2^{*0}, and D_{s1}^+ mesons and compared them with the most precise measurements from e^+e^-. As can be seen from Table 1 all results agree within their errors [10]. The ratio of the inclusive D_s to D^* production has also been measured by ZEUS [4]. The result of $0.41 \pm 0.07\,^{+0.03}_{-0.07}$ has been found in good agreement with that from e^+e^- of 0.43 ± 0.04 [11]. These ratios can be translated into strangeness suppression factors γ_s of the LUND model which yield 0.27 ± 0.05 for the ep measurement and 0.26 ± 0.03 for the e^+e^- measurement. The relative production of vector (V) and pseudo-scalar (PS) states is sensitive to hadronisation effects and by measuring the D^* and D^0 cross sections the ratio $P_V = \frac{V}{V+PS} = \frac{D^0}{D^0+D^*}$ can be obtained. A measurement by ZEUS [12] yields $P_V = 0.546 \pm 0.045 \pm 0.028$ in good agreement with the results from OPAL and ALEPH of 0.57 ± 0.05 and 0.595 ± 0.045, respectively [13]. In summary, no difference in charm fragmentation has been found between ep and e^+e^- scattering and all results favour an universal charm fragmentation.

4. Open Beauty Production

Due to the large mass of the b-quark, which serves as a hard scale, its production is expected be to described by perturbative QCD. On the other hand the production cross section is suppressed by a factor 100 with respect to that of c-quarks, which still limits the statistical precision of the measurements. Both experiments, H1 and ZEUS have measured inclusive b-production in photoproduction [14]. Experimentally, both experiments select events with leptons and jets. The leptons with a large transverse momentum with respect to the closest jet come predominantly from semileptonic b-decays. In this way a statistically enriched sample of semileptonic b-decays is selected. H1 performed the first measurement of this kind at HERA with muons. ZEUS has used this method with electrons identified by the dE/dx of charged tracks and more recently with muons. Fig. 5 shows the transverse momentum spectrum of electrons measured by ZEUS with the contributions from b- and c-quarks which have been estimated by a fit of the HERWIG Monte Carlo. The fitted fractions of the heavy quark contributions agree with the prediction, but the absolute cross section is underestimated by the simulation by a factor of 3.8. More recently H1 also selected b-enriched samples with an impact parameter method [15]. From

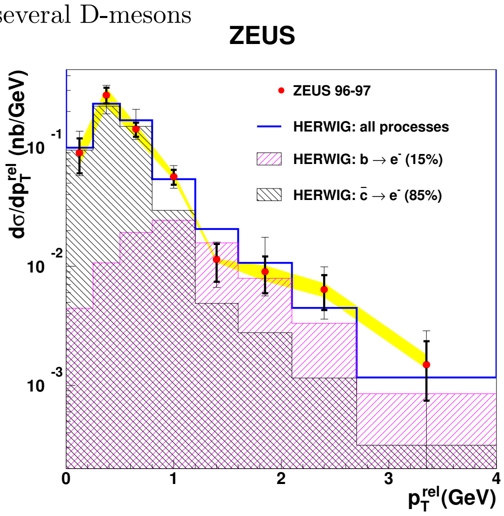

Figure 5. The differential cross section $d\sigma/dp_T^{rel}$ for heavy quark decay. The data is compared to the HERWIG MC prediction (open histogram), which has been fitted to the data and scaled up by a factor of 3.8

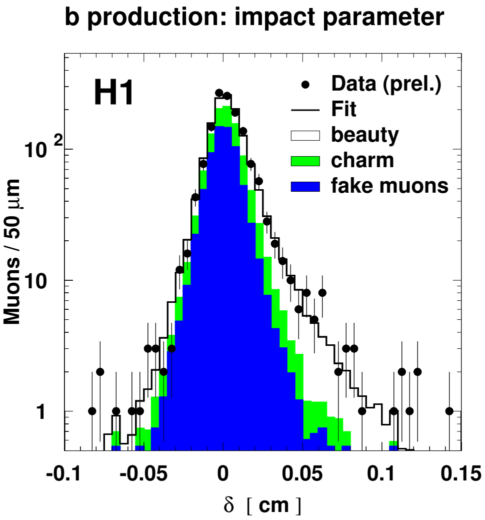

Figure 6. Distribution of muon impact parameters and its decomposition

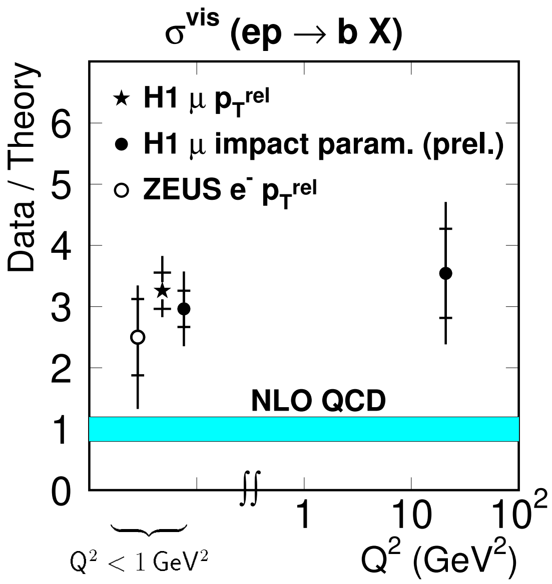

Figure 7. Open b production from H1 and ZEUS as function of Q^2, compared to NLO calculations

fig. 6 the asymmetry of the muon impact parameter distributions can be clearly seen. H1 used this method to measure b-cross sections both for photoproduction and DIS [15,16]. The results are summarized in fig. 7. The experimental cuts and acceptances differ for the different measurements therefore they are normalized to the prediction from FO NLO calculations. It can clearly be seen that all measurements lie above the prediction.

Combining the two H1 measurements from photoproduction yields a cross section of $\sigma_{vis}(ep \to b\bar{b} \to \mu X) = 170 \pm 25$ pb which has to be compared with the NLO prediction of 54 ± 9 pb. Also the LO Monte Carlos underestimate the measurement, AROMA: 38 pb, CASCADE (CCFM-splitting): 66 pb. In the case of ZEUS the difference between measurement and prediction is somewhat smaller. The measured cross section $\sigma^{b\to e^-}_{e^+p\to e^+dijet+e^-+X} = 24.9 \pm 6.4^{+4.2}_{-7.3}$ pb has been compared with the predictions of HERWIG (8 pb), Pythia (18 pb) and CASCADE (20 pb). It is interesting to notice that b-production in $\gamma\gamma$ scattering as measured by L3 and OPAL at LEP is also underestimated by NLO QCD calculations [17]. Studies of b-production in $p\bar{p}$ collisions at the Tevatron, as presented by CDF and D0, show that NLO calculations underestimate the cross section systematically for transverse momenta below 20 GeV [18].

At HERA more data are needed for precise differential measurements to investigate the currently observed disagreements between measurement and prediction. It needs to be tested if the current problems can be resolved by including higher order corrections and more detailed models of the fragmentation effects into the predictions, or if there are more severe problems in the understanding of heavy quark production.

5. Prospects

Recently HERA has been upgraded for higher luminosity and the detectors have been modified and improved in particular in their vertexing and tracking capabilities. It is expected that about 1 fb^{-1} per experiment will be collected within the next five years which provides great prospects for precision measurements of heavy flavour production. Charm production in proton direction at all values of Q^2 and possible differences in charm production from $e^- p$ and $e^+ p$ interactions can be investigated in great detail. With precise differential beauty-cross section measurements in large areas of the phase space one can hope to understand to what extent perturbative QCD is able to describe beauty production.

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