HEAVY FLAVOR AND QCD AT HERA

Olaf Behnke
DESY - H1 group, Notkestrasse 85, D-22607 Hamburg, Germany

(On behalf of the H1 and ZEUS collaborations)

Recent results of open charm and beauty production in ep scattering at HERA are presented. In deep inelastic scattering NLO QCD predictions describe well the measured differential charm cross-sections. In contrast both observed charm and beauty cross-sections in photoproduction are significantly exceeding NLO expectations.

1 Introduction

Open heavy flavor production at HERA is conceived as being mainly mediated by the boson gluon fusion process (see Fig. 1a), where a photon emitted from the electron "fuses" with a gluon from the proton to build a $q\bar{q}$ pair with $q = c, b$. Measuring this reaction offers some

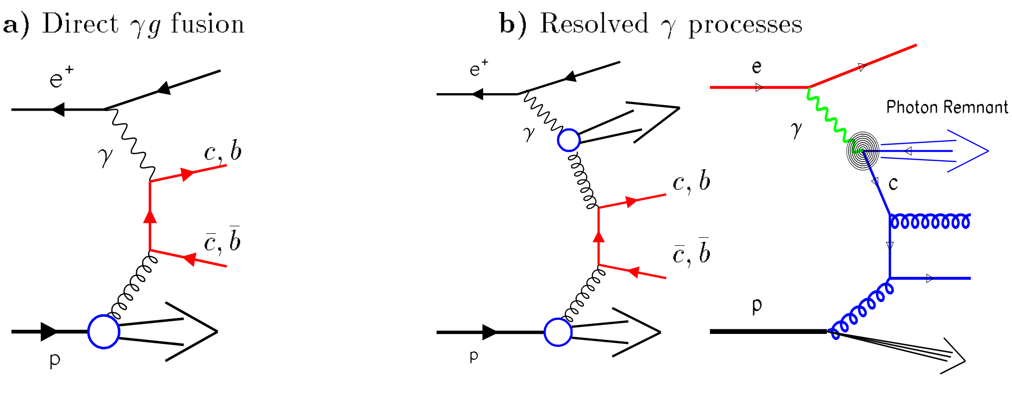

Figure 1: Leading order contributions to open heavy flavor production at HERA

unique possibilities. The process is directly sensitive to the gluon density in the proton, which can be determined. Two hard scales are available and can be chosen to enable the convergence of the perturbative QCD calculation. The first is the virtuality Q^2 of the exchanged photon, with accessible values at HERA ranging from zero (photoproduction) to larger values (DIS), reaching up to $Q^2 \approx 40000\,\mathrm{GeV}^2$. The second is the mass of the heavy quark, which allows to extend the calculations to the photoproduction regime.

Further significant contributions to heavy flavor production at HERA are expected from the so called "resolved" processes (see Fig. 1b), in which the photon initially fluctuates into hadronic objects and a part of these enter into the hard scattering. These processes are strongly suppressed at larger photon virtualities.

Two theoretical approaches are available to describe heavy flavor production at HERA. In the so called *massive* Ansatz[1] u,d and s are the only active flavors in the proton and charm and beauty are dynamically produced in the hard scattering. It is expected that this approach works well in the region $p_t \leq m_q$, where p_t (m_q) is the transverse momentum (mass) of the heavy quark. At higher transverse momenta $\alpha_s log^n(p_T^q/m_q)$ terms can lead to divergent corrections. In this domain the so called *resummed* or *massless* approach[2] is expected to be superior, where charm and beauty are regarded as active flavors in the proton and the photon (massless partons) and fragmented only after the hard process into massive quarks. In this Ansatz the above divergent terms are resummed to all orders into non-perturbative fragmentation functions.

In the following we will "take a walk" through the scales, i.e. in Q^2 from photoproduction to DIS and in m_q from charm to beauty and compare the data for each case with predictions from massive NLO theory. The results presented here are based on data sets corresponding to $6.6 - 9.7$ pb^{-1} and ~ 37 pb^{-1} of luminosity measured in H1 [3] and ZEUS [4] detectors respectively, while the HERA collider was operated with 820 GeV protons colliding on 27.5 GeV positrons.

2 Charm

2.1 Photoproduction: Comparison of D_s and D^* differential cross-sections

Open charm production at HERA has been mainly analysed via the relatively clean channels $D^{*+} \to D^0\pi_s^+$ with subsequent decays $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^-\pi^+$[a]. Recently ZEUS has achieved the first measurement[5] of D_s photoproduction at HERA using the decay channel $D_s \to \phi\pi^+ \to K^+K^-\pi^+$. The kinematic region explored is $Q^2 < 1\,\mathrm{GeV}^2$, $130 < W_{\gamma p} < 280\,\mathrm{GeV}$ ($W_{\gamma p}$ is the proton-photon centre-of-mass energy), $3 < p_t^{D_s} < 12\,\mathrm{GeV}$ and $-1.5 < \eta^{D_s} < 1.5$. Fig. 2 shows the measured differential cross-sections $d\sigma/dp_t^{D_s}$ and $d\sigma/d\eta^{D_s}$, which are significantly above the the curves from a massive NLO calculation. This confirms the excess seen in the previously obtained results for D^{*+} production in the same kinematic region (see Fig. 2). ZEUS measures the cross-section ratio $\sigma_{ep\to D_s X}/\sigma_{ep\to D^* X}$ in the above defined kinematic region to be $0.41 \pm 0.07(\mathrm{stat.})\,^{+0.03}_{-0.03}(\mathrm{syst.}) \pm 0.10$. This agrees well with the ratio $f(c \to D_s^+)/f(c \to D^{*+}) = 0.43 \pm 0.04 \pm 0.11$, extracted from e^+e^- experiments, supporting the universality of charm fragmentation.

2.2 Deep Inelastic Scattering: $F_2^{c\bar{c}}$ and $xg(x)$

In DIS observed D^* cross-sections and massive NLO predictions are generally in much better agreement [6,7] than in photoproduction. The only significant discrepancy is seen in the ZEUS data[6], where in the forward region a higher cross-section is observed than predicted from a NLO calculation[8]. A possible explanation[6,9] for this are "attractive" interactions of the produced

[a] the latter channel only analysed by ZEUS

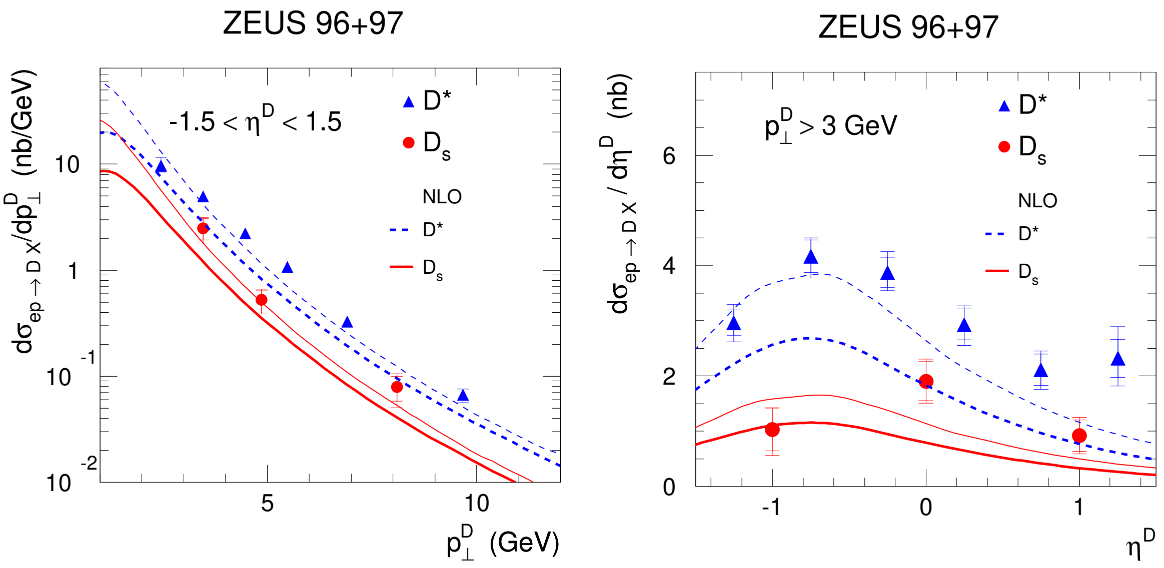

Figure 2: Differential D_s and D^* cross-sections in p_T^D (left) and η^D (right). The D_s (dots) and D^* (triangles) data are compared with NLO predictions (solid and dashed lines). The lower lines correspond to nominal parameters ($m_c = 1.5$ GeV), the upper to extreme ($m_c = 1.2$ GeV).

charm quarks or their decay products with the proton remnant, which are missing in the Peterson fragmentation[10] used in the actual calculation. By reweighting the calculation with a fragmentation from JETSET, ZEUS achieves a better description of their forward data. The good agreement between data and theory encourages ZEUS to go one step further, namely to extrapolate the D^* measurements to obtain the contribution of charm production to the total DIS cross-section. By neglecting small contributions from the structure functions F_3 and F_L, the inclusive DIS cross-section can be written as:

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

The structure function F_2^{cc} is defined as that part of F_2, where charm from the BGF process is produced, i.e. where on the left side of the above equation σ^{ep} is replaced by $\sigma^{ep\to c\bar{c}}$ and on the right side F_2 by F_2^{cc}. To measure F_2^{cc} ZEUS uses a massive NLO calculation program[8] to extrapolate the D^* results outside the accessible $p_t(D^*)$ and $\eta(D^*)$ region. The extrapolation factors are large, typically varying from 1.5 to 10, depending on Q^2 and the analysed D^0 decay channel ($K\pi$ or $K3\pi$). For the calculation ZEUS uses a gluon density determined from NLO fits to their own data. Fig. 3 shows the measured results for the ratio F_2^{cc}/F_2 in bins of Q^2 and Bjorken-x. The ratio rises to larger values of Q^2 and to lower values of x, reaching values of almost up to 0.4, which is the naive value expected, if charm and the three light flavors contribute equally to the proton quark density. As can be seen from Fig. 3 the NLO calculation matches the data well.

In the leading order direct γg fusion (Fig. 1a) the kinematical informations from the scattered lepton and one of the two charm quarks allow to calculate the proton momentum fraction x, which is carried by the gluon. This has been exploited by H1 to directly determine[7] the gluon density in the proton from the measured D^* cross-sections. In contrast to F_2^{cc} no extrapolation outside the accessible $P_t(D^*)$ and $\eta(D^*)$ region is needed. The momentum of the charm quark is approximated from the D^* momentum and a scaling factor calculated by MC.

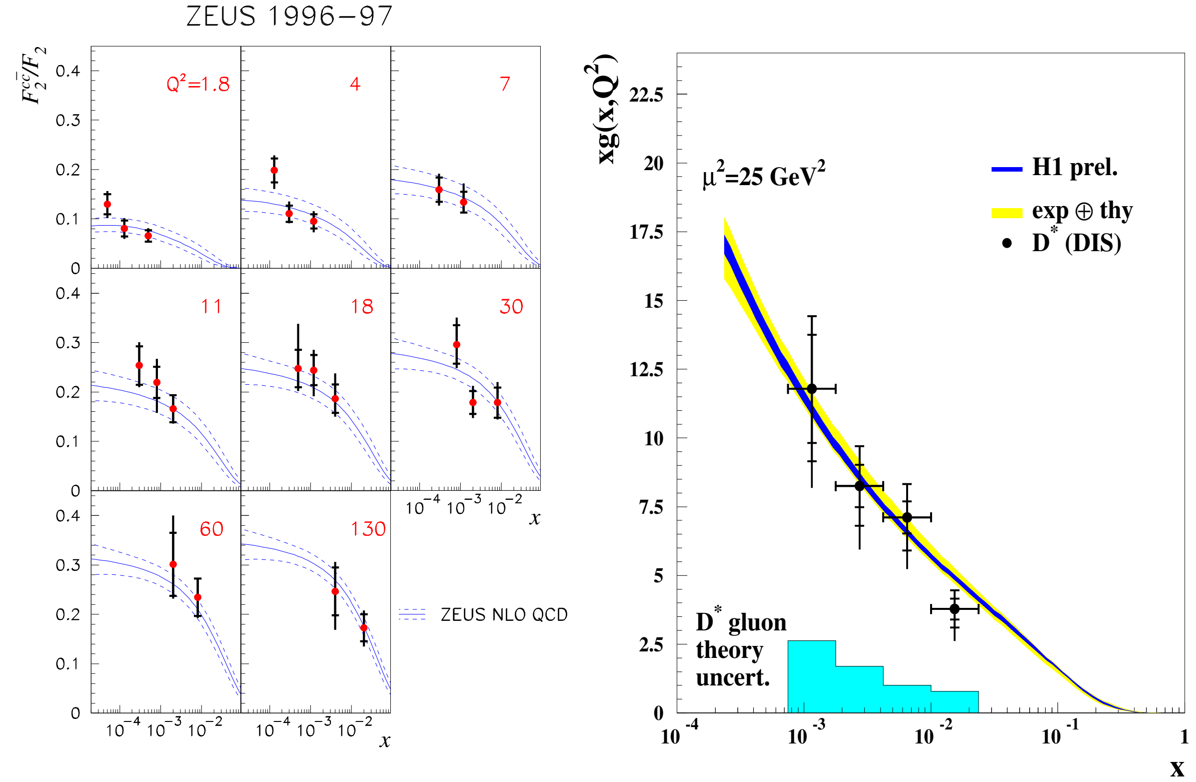

Figure 3: Left: ZEUS measurement of the ratio of F_2^{cc} to F_2 at Q^2 values between 1.8 and 130 GeV^2 as a function of x. Points with error bars are the D^* measurements, the lines are ZEUS NLO QCD calculations with different set of parameters used, i.e. varying the charm quark mass from 1.2 to 1.6 GeV. Right: H1 measurements of the gluon density xg(x) as a function of x. The points with error bars are obtained from D^* measurements in DIS. The measurements from scaling violations of F_2 are shown as bands.

Finally an iterative unfolding procedure is applied to determine the gluon density with a massive QCD calculation program[8]. The obtained density is shown in Fig. 3, where the results in all bins are evaluated at an average scale $\mu^2 = 25\,\mathrm{GeV}^2/c^2$. Also shown is the measurement of the gluon density obtained from the scaling violations of F_2. The good agreement between the two measurements supports the picture of an universal gluon density.

3 Beauty

The expected beauty cross-section at HERA is roughly two orders of magnitude smaller than for charm, due to the larger b-mass cutting down the available phase space and the smaller quark charge. In order to find these rare events a technique has been pioneered for HERA by H1[11], where high p_t leptons (muons or electrons) from semileptonic heavy flavor decays are selected in events with two jets. Within these sample beauty and charm components can be separated by the relative transverse momentum p_t^{rel} of the lepton with respect to the heavy flavor hadron direction (approximated by the direction of the associated jet), as the larger b mass leads to a harder p_t^{rel} spectrum. Four measurements[11,12] of beauty photoproduction have been made so far at HERA, using either central or forward muons or central electrons. Fig. 4 left shows the p_t^{rel} spectra for the H1 central muon data. The overlayed fit to the data yields a large ($\approx 50\%$) beauty component. In fig. 4 right the ZEUS central muon data are compared to a LO Pythia MC estimate for the charm and beauty component, with the total normalisation fixed to the

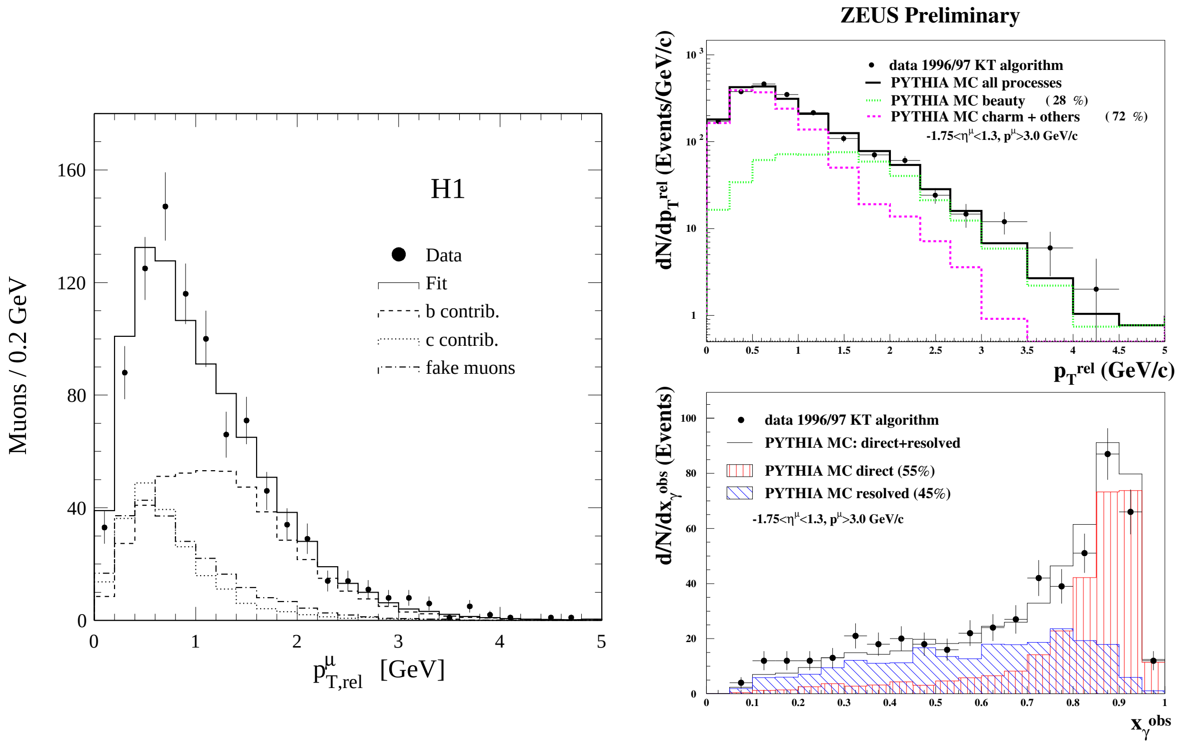

Figure 4: Left: H1 central muons p_t^{rel} spectra and a fit of different components to the data. Right top: ZEUS central muons p_t^{rel} spectra compared with a LO Pythia MC. Right bottom: x_γ^{obs} distribution in ZEUS central muons data and a fit of direct and resolved components.

data. It can be seen that a significant fraction of beauty, as it is predicted by the LO MC, is needed to describe the data at large p_t^{rel}. Nevertheless the absolute prediction of the MC normalised to the data luminosity falls a large factor of 4 below the data.

In the same selected events ZEUS uses the kinematical information of the two jets to determine x_γ^{obs}, which is in the leading order interpretation the fraction of the photon momentum, which enters into the hard scattering. The measured x_γ^{obs} spectrum in Fig. 4 clearly exhibits at lower values a large resolved photon component, which is in agreement with the Pythia MC prediction.

Details and results for all four measurements from H1 and ZEUS are summarized in table 1. All cross-section results obtained are above the respective LO-MC estimates. For the H1 muon and the ZEUS electron analyses massive NLO calculations were performed, which also fall below the data.

4 Conclusions

Results for open charm and beauty production in ep scattering at HERA have been presented and confronted with NLO QCD calculations. New results for D_s photoproduction from ZEUS confirm the previously obtained findings for D^*, that the data are lying uncomfortably high compared to the predictions. In contrast the D^* results at larger Q^2 (DIS) are in good agreement with the NLO predictions, emphasizing the role of Q^2 as a reasonable hard scale. For beauty in photoproduction a better agreement between data and theory than for charm had been naively expected due to the larger b mass. In contrast the results from all four measurements of H1 and ZEUS using muons or electrons from semileptonic decays are significantly above the theory predictions, similar as results from the Tevatron, which were also presented [13] at this conference.

Table 1: Measurements of open beauty production at HERA

Collab.	H1	ZEUS	ZEUS	ZEUS
Channel	μ	e	μ	forw. μ
Data	1995-1996	1996-1997		
Kinematic cuts	$Q^2 < 1$ $0.1 < y < 0.8$	$Q^2 < 1$ $0.2 < y < 0.8$		
Lepton cuts P_T [GeV]	$> 2.$	> 1.6	$p > 3$	> 1.5
DiJet selection	$E_T^{1,2} > 6$ GeV	$E_T^1 > 7$ GeV $E_T^2 > 6$ GeV		
σ_{vis} [pb]	176*	39	36	21
Stat. err.	± 16	± 11	± 5	± 7
Sys. err.	${}^{+26}_{-17}$	${}^{+23}_{-16}$	${}^{+10}_{-9}$	${}^{+6}_{-6}$
$\frac{\text{Data}}{\text{LO-MC}}$	4.5	4-5	1.2-3	2-5
$\frac{\text{Data}}{\text{NLO}}$	1.7 ($\sim 2\,\sigma$)	3.8 ($\sim 1.4\,\sigma$)		

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