Heavy Flavour Physics at HERA

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Abstract. Recent results on the production of open charm and beauty in electron proton scattering at HERA are reviewed, focussing on results obtained with the full HERA-I dataset. These results are compared with perturbative QCD calculations at NLO as well as Monte Carlo predictions at LO.

INTRODUCTION

At HERA electrons (or positrons) of energy 27.5 GeV are collided with 920 GeV protons providing a center of mass energy $\sqrt{s} \approx 318$ GeV. During the HERA-I run the HERA experiments H1 and ZEUS each collected data corresponding to an integrated luminosity of about 110 pb^{-1}, thus allowing significant tests of perturbative QCD in the area of heavy quarks.
In electron proton collisions heavy quarks are predominantly produced via the photon gluon fusion (PGF) mechanism, where a photon emitted by the incoming electron interacts with a gluon in the proton forming a quark-anti-quark pair. The major contribution is due to the exchange of almost real photons corresponding to a photon vituality $Q^2 \approx 0$ (photoproduction). In deep inelastic scattering (DIS) Q^2 is large, often defined experimentally by $Q^2 > 2\ \mathrm{GeV}^2$.
Heavy quark production can be described by a factorization ansatz consisting of four parts: proton structure, perturbatively calculable hard cross section, photon structure and fragmentation. Under the assumption that any three of the four parts are understood by theory, it is possible to study the fourth part using heavy quarks.
In the heavy quark area, the investigation of the proton structure means to determine for example the structure function F_2^c and the parton densities, especially the gluon density. Further, different evolution models for the parton densities like DGLAP or CCFM can be tested.
The hard cross section has to be calculated at a scale μ which may be choosen to be the heavy quark mass m_Q if other scales such as Q^2 are small. The transverse momentum p_T of a heavy flavour hadron, the transverse energy E_T of a heavy flavour jet or the virtuality are also possible scales leading to a multi scale problem. At large scales the heavy quarks have to be treated in the same way as the light quarks u, d, s.
At low Q^2 the photon exhibits hadronic behaviour, leading to reactions in which a parton inside the photon scatters off a parton in the proton. If the photon fluctuates into a $c\bar{c}$ pair before the hard interaction the process is called charm excitation. In these resolved processes the relative momentum fraction x_γ of the interacting parton to the photon momentum is $x_\gamma < 1$ while it is $x_\gamma = 1$ if the photon interacts directly as pointlike object.
The fourth part of the factorization ansatz - the fragmentation - describes the transition

of coloured quarks into colourless hadrons. Here the question of the universality of fragmentation is important.
The data will be compared with leading order (LO) MC predictions as well as with next to leading order (NLO) calculations. Three different schemes are distinguished for the NLO calculations. The fixed order massive scheme ([1] for photoproduction and [2] for DIS) should give the best description near to threshold and thus for example at low p_T and low Q^2. The four flavour massless scheme [3] should hold at large scales for example at large p_T. Apart from the light quarks the heavy quarks are considered in this scheme also as active flavours in the proton or photon. The third scheme involves the matched calculations [4], which are an unification of both schemes and should provide a good description in the whole kinematic region. For the LO MC generators different evolution models like DGLAP or CCFM can be used while in the NLO calculations always DGLAP evolution is applied. The MC generators AROMA [5], RAPGAP [6] and PYTHIA [7] use DGLAP evolution, while CASCADE [8] is based on CCFM evolution. AROMA and CASCADE simulate only the direct photon contribution, but CASCADE contains implicitly some contributions from charm excitation. In contrast to the DGLAP evolution model CCFM requires no ordering of the transverse gluon momentum k_T along the gluon ladder. This leads to a k_T dependent gluon density and hard scattering matrix element.

CHARM PRODUCTION

Most measurements of charm production at HERA use the reconstruction of D^* mesons, exploiting the well known mass difference method. But to determine the relative fragmentation fractions of charm hadrons, H1 and ZEUS performed measurements of all charm ground states (D^+, D^0, D_s, D^{*+}, Λ_c (ZEUS)) in DIS or photoproduction respectively [9, 10]. The fragmentation fractions obtained at HERA are in good agreement with those from e^+e^- annihilations. ZEUS has measured the fragmentation function for D^* mesons in addition using D^* events associated with a jet in photoproduction [11]. Again good agreement with the fragmentation functions determined from the e^+e^- experiments OPAL and ARGUS is found. Altogether this indicates fragmentation universality.
Differential D^* coss section in DIS are measured [12, 13]. The data of the two experiments are consistent, but small differences of the theoretical interpretation appear. As an example the pseudorapidity η_{D^*} is shown in figure 1a) and b). At H1 the NLO calculations in the figure 1a), using peterson fagmentation, CTEQ5F3 as proton parton density and $m_c = 1.4$ GeV as the central value for the charm mass, is systematically below the data especially in the forward region (large η_{D^*}). However, the CASCADE MC leads to a good description of the data. At ZEUS the NLO calculation is doing a better job especially if the ZEUS NLO QCD fit to the inclusive DIS data from ZEUS and the fixed target experiments is used as a parameterization of the parton densities. The best description is obtained if the Lund string fragmentation instead of the Peterson fragmentation is used.
In the same analysis ZEUS has determined the charm contribution F_2^c to the structure function F_2 of the proton shown in figure 1c) [12]. Nice agreement between the ZEUS

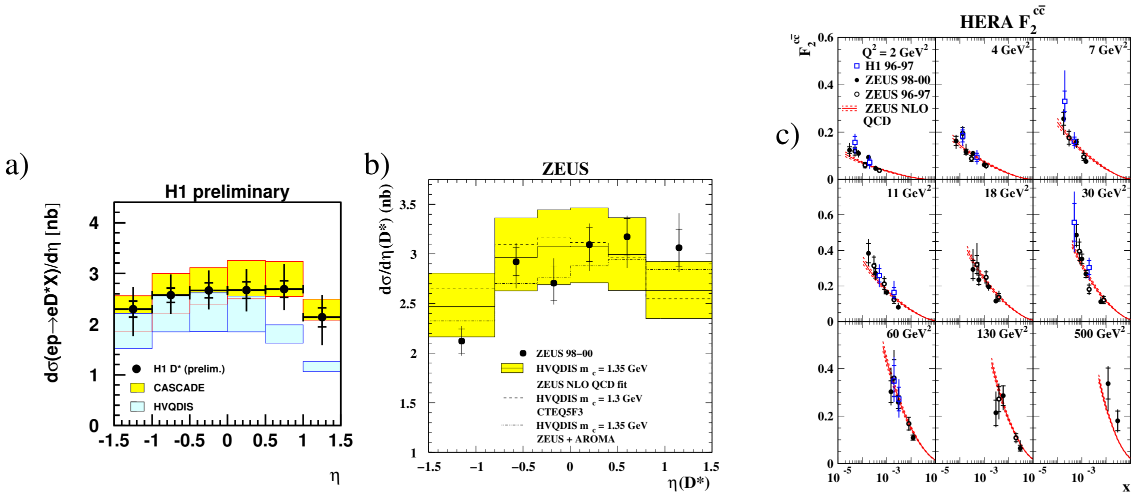

FIGURE 1. a) + b) Psedorapidity of the D^* in DIS measured by H1 (a) or by ZEUS (b) respectively. c) Charm contribution F_2^c to the structure function F_2 compared with the NLO QCD fit.

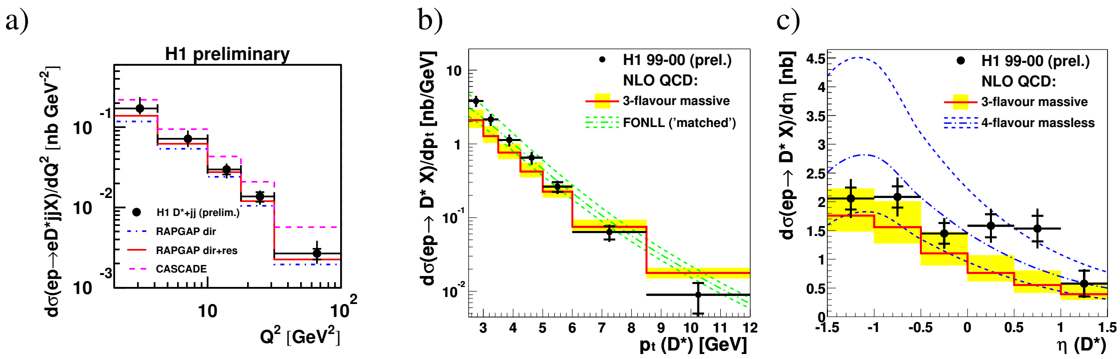

FIGURE 2. a) Q^2 distribution for D^* events associated with two jets. b) + c) Differential D^* cross sections measured in photoproduction by H1. Shown are the transverse momentum $p_T(D^*)$ and the pseudorapidity η_{D^*} of the D^*.

and H1 data and the NLO QCD fit is obtained, meaning that the prediction of the charm contribution to F_2 from scaling violations is consistent with the F_2^c measurement.

To study the production process in more detail H1 has selected events with two jets in addition to a D^* (see figure 2a) [13]. The CASCADE MC which describes the inclusive D^* data at H1 well, lies now above the data. The direct RAPGAP MC is below the data but the description of the data improves with the resolved contribution. However, the sum of direct and resolved contributions does not give a good description of the H1 inclusive D^* data.

The D^* measurements in photoproduction are compared to the three different schemes of the NLO calculations. As an example the $p_T(D^*)$ and η_{D^*} distributions obtained by H1 are presented in figures 2b) and c) [14]. The massive NLO calculations are below the data especially at low $p_T(D^*)$, while the massless and matched calculations give a reasonable agreement. ZEUS has measured in addition double differential cross sections with a larger Q^2 range [15] compared to the H1 measurement. The matched calculations

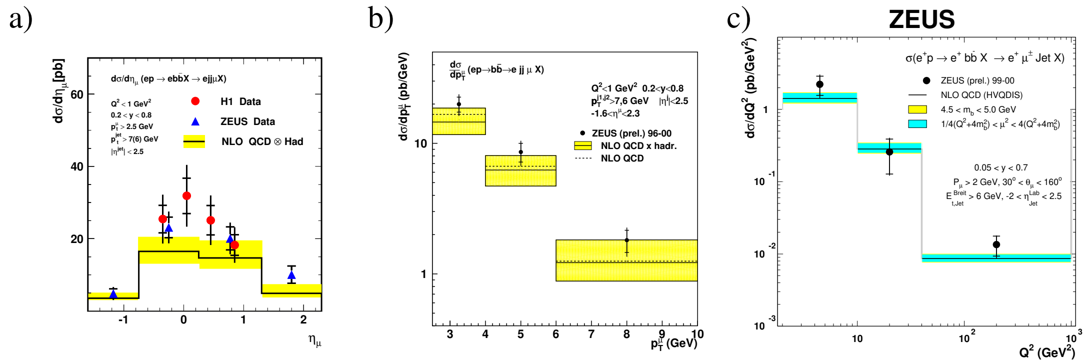

FIGURE 3. Visible cross section $\sigma(ep \to eb\bar{b}X \to e\mu\ dijet(jetDIS)\ X)$ measured in photoproduction (a+b) and in DIS (c).

are only at low $p_T(D^*)$ close to the data and in general the NLO calculations are below the data at medium $p_T(D^*)$ and large η_{D^*}.
To investigate the photon structure ZEUS has studied D^* mesons associated with two jets [16]. x_γ is reconstructed with the jets and then the direct and resolved data set are separated via a cut on x_γ at 0.75. From the $cos\theta^*$ distribution, the angle between the proton and the D^* jet in the rest frame of the two jets, a large contribution from charm out of the photon is confirmed in the LO picture.

BEAUTY PRODUCTION

At HERA the total $b\bar{b}$ cross section is about two orders of magnitude smaller than the $c\bar{c}$ cross section. Nevertheless the theoretical prediction, should be more reliable for beauty. Both experiments use semileptonic decays of beauty hadrons to tag beauty. Both the relatively long lifetime of b hadrons (H1, using their silicon vertex detector) and the high masss of the b hadrons (H1, ZEUS) are exploited. Due to the high b mass the decay particles emerge at larger angles relative to the outgoing heavy flavour meson or jet. Measurements have been performed in DIS and photoproduction [17, 18, 19]. Figures 3a) and b) show the transverse momentum of the muon $p_T(\mu)$ and the pseudorapidity of the muon η_μ in photoproduction. The data from both experiments are consistent. The massive NLO QCD prediction is somewhat below the data but the shape is reasonably well described. At H1 it seems that the discrepancies between NLO predictions and data are larger at small $p_T(\mu)$, while at ZEUS this effect is not observed. In DIS the NLO QCD calculations describe apart from the shape also the normalization. As an example the Q^2 distribution obtained by ZEUS is shown in figure 3c). The LO MC generators are all below the data though CSCADE is closest.
If in addition to the muon a D^* is reconstructed to get more information about the heavy quark final state, it is possible to separate charm and beauty via the charge and angle correlations between the two particles. In the case of charm only one correlation is possible. Here the angle $\Delta\Phi$ between the D^* and the muon is large and the two particles have opposite charges. For beauty three correlations are possible due to the fact that here the muon can come from the semileptonic decay of a beauty or charm hadron. The $\Delta\Phi$

a) b)

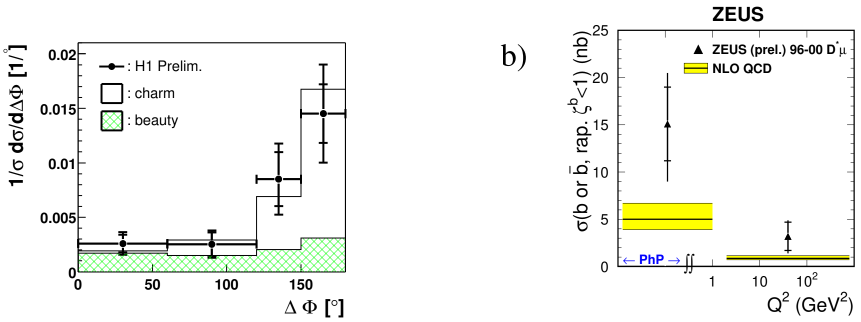

FIGURE 4. $D^*\mu$ correlations. a) $\Delta\Phi$ distribution obtained by H1, where $\Delta\Phi$ denotes the azimuthal angle difference between the D^* and the muon. b) Comparison between the ZEUS b or $\bar{b}$ cross section and the NLO QCD prediction.

distribution obtained by H1 is shown in figure 4a) [20]. The AROMA MC describes the shape of the data quite well. In figure 4b) [21] a comparison between the ZEUS b or $\bar{b}$ cross section and the NLO QCD predictions is presented. The data are all above the NLO QCD calculations but the errors are still large.

CONCLUSIONS AND OUTLOOK

Charm production at HERA has been extensively studied. The QCD calculations - LO predictions or NLO calculations - still have some problems to describe all aspects observed in the data. New precise differential beauty measurements have been shown. The data points are in photoproduction all above the NLO QCD predictions with discrepancies of about $\lesssim 1.5\ \sigma$ for each measurement.
The work is ongoing to finalize analyses on HERA-I data and first HERA-II data will come in near future. With the improved detectors (silicon vertex detectors, forward tracking, trigger,..) the investigation of new kinematic regions like the forward region is possible. Further the statistics will increase and with that new measurements like F_2^b or double tagging should become possible.

REFERENCES

1. S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, Phys. Lett., **B348** (1995), 633.
   S. Frixione, P. Nason, G. Ridolfi, Nucl.Phys., **B454** (1995), 3
2. E. Laenen, S. Riemersma, J. Smith, W.L. van Neerven, Phys.Lett., **B291** (1992), 325.
   E. Laenen, S. Riemersma, J. Smith, W.L. van Neerven, Nucl.Phys., **B392** (1993), 162 and 229.
   E. Laenen, S. Riemersma, J. Smith, W.L. van Neerven, Nucl.Phys., **B347** (1995), 143.
   B.W. Harris, J. Smith, Nucl.Phys., **B452** (1995), 109. and **B353** (1995), 535.
3. B.A. Kniehl, hep-ph/0211008, 2002.
4. M. Cacciari, S, Frixione, P. Nason, hep-ph/0102134, 2001.
5. G. Ingelman et al., hep-ph/9605285, 1996.
6. H. Jung, Comp.Phys.Comn. **86** (1995) 147.
7. T. Sjostrand, Comp.Phys.Comm. **82** (1994), 474.
8. H. Jung and G. Salam, Eur.Phys.J. **19** (2001), 351.

9. H1 Collaboration, http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-02-076.long.html.
10. ZEUS Collaboration, http://www-zeus.desy.de/physics/phch/conf/eps03/564/paper.pdf.
11. ZEUS Collaboration, http://www-zeus.desy.de/physics/phch/conf/amsterdam_paper/HFL/cfrag.ps.gz.
12. ZEUS Collaboration, DESY-03-115, submitted to Phys.Rev.D
13. H1 Collaboration, http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-03-074.long.html.
14. H1 Collaboration, http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-03-071.long.html.
15. ZEUS Collaboration, http://www-zeus.desy.de/physics/phch/conf/amsterdam_paper/HFL/dstargamma.ps.gz.
16. ZEUS Collaboration, DESY-03-015, submitted to Physics Letters B.
17. H1 Collaboration, http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-03-072.long.html.
18. ZEUS Collaboration, http://www-zeus.desy.de/physics/phch/conf/amsterdam_paper/HFL/disB.ps.gz.
19. ZEUS Collaboration, http://www-zeus.desy.de/physics/phch/conf/amsterdam_paper/HFL/b_php.ps.gz.
20. H1 Collaboration, http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-02-071.long.html.
21. ZEUS Collaboration, http://www-zeus.desy.de/physics/phch/conf/eps03/575/paper.pdf.