EPJ Web of Conferences **80**, 00007 (2014)
DOI: 10.1051/epjconf/20148000007

Heavy flavour production at HERA

Riccardo Brugnera[1,2,a,b]

[1] *Dipartimento di Fisica e Astronomia dell'Universitá di Padova, Padova, Italy*
[2] *INFN Padova, Padova, Italy*

Abstract.
In this brief review, recent experimental results from the H1 and ZEUS collaborations on heavy flavour production in deep inelastic scattering and photoproduction regimes are summarized. The results cover charm fragmentation fractions, charm and beauty cross sections, $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ proton structure functions and the running charm- and beauty-quark masses.

1 Introduction

HERA (located at DESY, Germany) has been the only electron-proton collider ever built in the world. It collided electrons (or positrons) of energy 27.5 GeV with protons of energy 820 GeV. In 1998 the proton energy was raised to 920 GeV. During a first period (HERA-1), from 1993 to 2000, the two main experiments H1 and ZEUS collected about 120 pb^{-1} of data each. In the second period (HERA-2) from 2003 to 2007, after a main upgrade of the collider beams and of the two detectors, the collected luminosity was about 380 pb^{-1} per each experiment, three-fold the HERA-1 statistics. With such a large sample of data the two experiments have produced a large harvest of results spanning many arguments of high energy physics. In this brief contribution the following new results regarding perturbative Quantum Chromodynamics (pQCD) are described: charm fragmentation fractions, charm differential cross sections, charm and bottom structure functions and the running charm- and beauty-quark masses.

2 Charm fragmentation fractions

The fragmentation fractions of charm quarks into specific charm hadrons cannot be predicted by QCD and have to measured. It is usually assumed that they are universal, i.e. the same for charm quarks produced in e^+e^- annihilation, in ep collisions and also in pp or other hadronic collisions, even if the charm production mechanisms are not the same. The fragmentation universality can be tested by measuring the fragmentation fractions at HERA and comparing the results with those obtained with e^+e^- collisions. Additionally, the values of the fragmentation fractions are crucial parameters used in comparisons of pQCD calculations with measurements of charm production at HERA and elsewhere. The photoproduction of D^0, D^{*+}, D^+, D_s^+ and Λ_c^+ charm hadrons and their corresponding

[a] e-mail: brugnera@pd.infn.it
[b] on behalf of the H1 and ZEUS collaborations

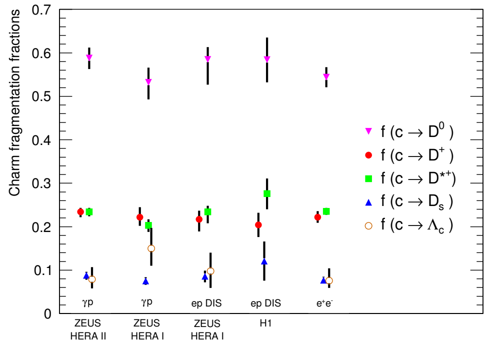

Figure 1. Fractions of charm quarks hadronising as a particular charm hadron. The latest photoproduction measurements are shown (first column) and compared to previous HERA results in photoproduction (second column), DIS (third and fourth column) and to e^+e^- data (last column), with statistical and systematic and branching-ratio uncertainties added in quadrature.

antiparticles has been studied with the ZEUS detector [1] in the kinematic range $p_T(D, D^*, \Lambda_c) >$ 3.8 GeV, $|\eta(D, D^*, \Lambda_c)| < 1.6$, $130 < W < 300$ GeV and $Q^2 < 1$ GeV^2, where p_T is the transverse momentum and η the pseudorapidity of the charm hadrons, while W is the photon-proton centre-of-mass energy and Q^2 is the virtuality of the exchanged photon. Using a total integrated luminosity of 372 pb^{-1}, the fractions of charm quarks hadronising as D^0, D^{*+}, D^+, D_s^+ and Λ_c^+ have been determined. A summary of the measurements is shown in Fig. 1. The precision of the fragmentation fractions obtained is competitive with measurements in e^+e^- collisions. All data from ep and e^+e^- collisions are in agreement with each other. This demonstrates that the fragmentation fractions of charm quarks are independent of the production process and supports the hypothesis of the universality of heavy-quark fragmentation.

3 Heavy quark production in DIS

Measurements of open charm and beauty production in deep-inelastic electron-proton scattering at HERA provide important input for stringent tests of the theory of QCD. In particular it is possible to shed light on the different theoretical schemes for the correct treatment of the mass of the charm and beauty quarks: fixed-flavour-number-scheme (FFNS) and general-mass variable-flavour-number-scheme (GM-VFNS). H1 [2, 3] and ZEUS [4] have recently published measurements of differential cross sections for D^* production from the final HERA II sets, in a similar limited phase space. These cross sections measured at visible level have been combined [5] such that one consistent data set is obtained, which can be compared directly to differential NLO cross section predictions without the need of extrapolation. The combination is based on the procedure described in [6–8], including a full treatment of the correlated uncertainties. This yields a significant reduction of the overall uncertainty of the measurements. In Fig. 2 the double differential cross sections in Q^2 and y are shown and compared to NLO predictions. The scaling variable $y = p \cdot q / p \cdot l$ is the inelasticity with p, q and l denoting the 4-momenta of the proton, photon and electron, respectively. These QCD predictions from charm production were obtained at NLO ($O(\alpha_s)^2$) using HVQDIS [9] in the 3-flavour FFNS scheme. The predictions describe the data very well.

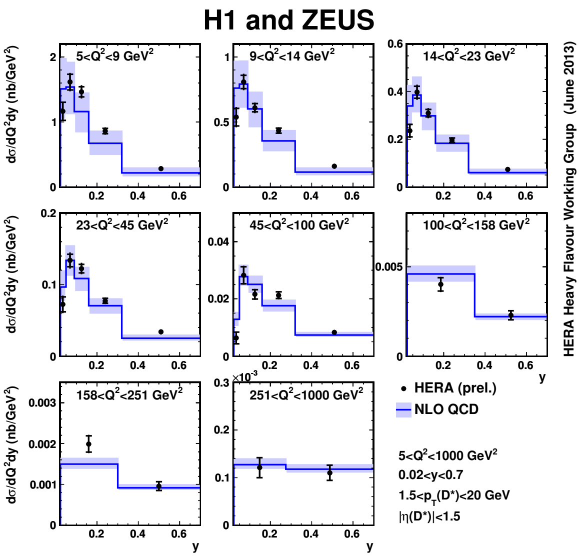

Figure 2. Double differential D^* production cross section as a function of Q^2 and y. The data points are the combined cross sections. The inner error bars indicate the uncorrelated part of the uncertainties. The outer error bars represent the total uncertainties. Also shown are the NLO predictions from HVQDIS and their uncertainties band.

4 Charm and beauty structure functions

Previous measurements have demonstrated that heavy quarks (charm and beauty for the kinematical range of HERA) are predominantly produced by the boson-gluon-fusion process, $\gamma g \to Q\bar{Q}$, which is sensitive to the gluon distribution in the proton. The mass of the heavy quark, m_Q, provides a sufficiently high scale necessary to apply pQCD. However, additional scales are involved in heavy quark production, e.g. the virtuality, Q^2, of the exchanged photon in case of DIS and the transverse momenta, p_T, of the outgoing quarks. The presence of several hard scales complicates the QCD calculations for heavy quarks production. Depending on the details of the treatment of m_Q, Q^2 and p_T, different approaches in pQCD have been formulated. The HERA data have been successfully compared with the FFNS and different implementation of the GM-VFNS. At HERA different techniques have been used to measure open charm production cross sections in DIS. The full reconstruction of D or D^* mesons, the long lifetime of heavy flavoured hadrons or their semi-leptonic decays are exploited. The published data of H1 [10–14] and ZEUS [15–18] have been combined into the paper [19]. In the kinematic domain addressed by these analyses the virtuality Q^2 of the exchanged boson is small, $Q^2 \ll M_Z^2$, charm production is dominated by virtual photon exchange. The cross section may then be written in terms of the structure functions $F_2^{c\bar{c}}(x, Q^2)$ and $F_L^{c\bar{c}}(x, Q^2)$ as

$$\frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2(Q^2)}{xQ^4}([1 + (1-y)^2)]F_2^{c\bar{c}}(x, Q^2) - y^2 F_L^{c\bar{c}}(x, Q^2)) \tag{1}$$

Here $x = Q^2/2p \cdot q$ is the Bjorken scaling variable. The suffix $c\bar{c}$ indicates the presence of a $c\bar{c}$ pair in the final state. The cross section $d^2\sigma^{c\bar{c}}/dxdQ^2$ is given at the Born level without QED and electroweak radiative corrections, except for the running electromagnetic coupling, $\alpha(Q^2)$. The results are presented in terms of reduced cross sections, defined as follows:

$$\sigma_{red}^{c\bar{c}} = \frac{d^2\sigma^{c\bar{c}}}{dxdQ^2}\frac{xQ^4}{2\pi\alpha^2(Q^2)(1+(1-y)^2)} = F_2^{c\bar{c}} - \frac{y^2}{1+(1+(1-y)^2)}F_L^{c\bar{c}} \tag{2}$$

The contribution $F_L^{c\bar{c}}$, originating from the exchange of longitudinally polarised photons, is small in the kinematic range of the present analysis and reaches up to few per cent only at high y. The combined reduced cross sections are presented in Fig. 3. The combined data using H1 and ZEUS input data are significantly more precise than any of the individual input data sets: the uncertainty of the combined results is 10% on average and reaches 6% in the region of small x and medium Q^2. This is an improvement of about a factor 2 with respects to each of the most precise data sets in the combination. These high precision data have been compared to various QCD predictions produced by different theory groups. For example, in Fig. 3 the data are compared to the predictions in the GM-VFNS by the NNPDF collaboration. Both the NNPDF-FONLL-A [20] and NNPDF-FONLL-B [21, 22] predictions describe the data fairly well at higher Q^2, while they fail to describe the data at lower Q^2. The description of the data at lower Q^2 is improved in the FONLL-C [21, 22] scheme.

A combined NLO QCD analysis has been performed using the reduced charm cross section together with the inclusive DIS cross sections [23]. The inclusion of $\sigma_{red}^{c\bar{c}}$ in the fit does not alter the central PDF significantly, and the uncertainties of the valence quark distribution functions are almost unaffected. Instead the uncertainties of the gluon, $x\bar{c}$, $x\bar{u}$ and $x\bar{d}$ distribution functions are reduced. An NLO QCD analysis has been performed in the FFNS of the ABM group [24, 25] to determine the $\overline{\text{MS}}$ running charm quark mass based on the inclusive neutral and charged current HERA-I DIS data and the charm cross section. The result for the running charm in NLO is:

$$m_c(m_c) = 1.26 \pm 0.05(\text{exp}) \ \pm 0.03(\text{mod}) \ \pm 0.02(\text{param}) \ \pm 0.02(\alpha_s) \text{ GeV}. \tag{3}$$

The errors correspond to the experimental, the model, parameterisation and α_s dependent uncertainties.

Also beauty production in DIS has been measured using several methods both by H1 and ZEUS collaborations. Here a ZEUS measurement [26] based on the measurement of inclusive jet cross sections in beauty and charm events is presented. Such a measurement has permitted the extraction of the heavy-quark contribution to F_2 with high precision. For this purpose, the long lifetimes of the weakly decaying b and c hadrons, which make the reconstruction of their decay vertices possible, as well as their large masses are exploited. Two discriminating variables, the significance of the reconstructed decay length and the invariant mass of the charged tracks associated with the decay vertex (secondary vertex), were used. This inclusive tagging method leads to a substantial increase in statistics with respect to previous ZEUS measurements. The $F_2^{b\bar{b}}$ is shown in Fig. 4 as a function of Q^2 for fixed x and is compared to previous ZEUS and H1 measurements. In a wide range of Q^2, this measurement represents the most precise determination of $F_2^{b\bar{b}}$ at HERA. It is in good agreement with the previous ZEUS analyses and H1 measurements. Several NLO and NNLO QCD predictions based on fixed- or variable-flavour-number schemes are also compared to the measurements. All predictions provide a reasonable description of the data. In a manner similar to the method used for the extraction of the running charm-quark mass, the beauty-quark mass was extracted in a simultaneous fit of the mass and parton densities. The best fit yields:

$$m_b(m_b) = 4.07 \pm 0.14(\text{exp}) \ ^{+0.01}_{-0.07}(\text{mod}) \ ^{+0.05}_{-0.00}(\text{param}) \ ^{+0.08}_{-0.05}(\text{theo}) \text{ GeV} \tag{4}$$

for the $\overline{\text{MS}}$ running beauty-quark mass at NLO. The errors correspond to the experimental, the model, parameterisation and pQCD parameters dependent uncertainties.

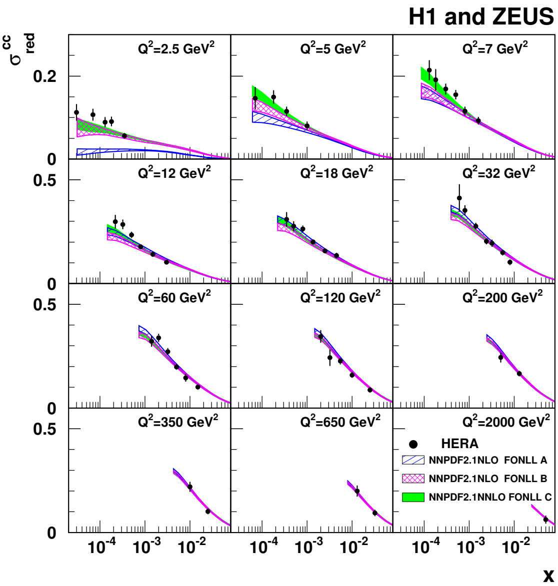

Figure 3. Combined reduced cross sections $\sigma_{red}^{c\bar{c}}$ (black points) as a function of x for fixed values of Q^2. The error bars represent the total uncertainties including uncorrelated, correlated and procedural uncertainties, added in quadrature. The data are compared to predictions by the NNPDF group. The predictions from NNPDF2.1 in FONLL-A, -B and -C are shown with their uncertainties (bands with different hatch styles).

5 Conclusions

H1 and ZEUS collaborations are still providing after many years from the end of the data taking important results on the heavy flavours field. This is obtained exploiting the full HERA statistics and the advanced knowledge of the detectors. In this brief review the presented results on fragmentation fractions, charm and bottom production in DIS put tight constraints on the QCD theory.

References

[1] ZEUS collaboration, H. Abramowicz et al., JHEP **09**, 058 (2013).

[2] H1 collaboration, F. H. Aaron et al., Phys. Lett. B **686**, 91 (2010).

[3] H1 collaboration, F. H. Aaron et al., Eur. Phys. J. C **71**, 1769 (2011).

[4] ZEUS collaboration, H. Abramowicz et al., JHEP **05**, 097 (2013).

[5] H1 collaboration, H1-prelim-13-171,
ZEUS collaboration, ZEUS-prelim-13-002.

[6] A. Glazov, AIP Conf. Proc. **792** 237 (2005).

[7] H1 collaboration, A. Atkas et al., Eur. Phys. J. C **63** 625 (2009).

[8] H1 and ZEUS collaborations, F. D. Aaron et al., JHEP **1001** 109 (2010).

[9] B. W. Harris and J. Smith, Phys. Rev. D **57** 2806 (1998).

[10] H1 collaboration, A. Atkas et al., Eur. Phys. J. C **45** 23 (2006).

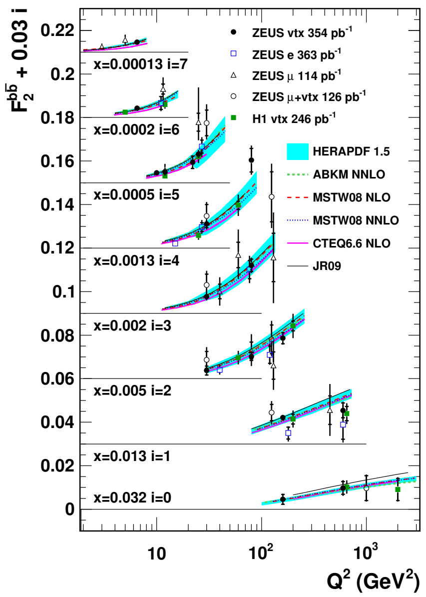

Figure 4. The structure function $F_2^{b\bar{b}}$ (filled circles) as a function of Q^2 for fixed values of x compared to previous results. The inner error bars are the statistical uncertainty while the outer error bars represent the statistical, systematic and extrapolation uncertainties added in quadrature. The measurements are compared to several NLO and NNLO QCD predictions.

[11] H1 collaboration, A. Atkas et al., Eur. Phys. J. C **51** 271 (2007).
[12] H1 collaboration, F. D. Aaron et al., Eur. Phys. J. C **65** 89 (2010).
[13] H1 collaboration, F. D. Aaron et al., Phys. Lett. B **686** 91 (2010).
[14] H1 collaboration, F. D. Aaron et al., Eur. Phys. J. C **71** 1769 (2011).
[15] ZEUS collaboration, J. Breitweg et al., Eur. Phys. J. C **12** 35 (2000).
[16] ZEUS collaboration, S. Chekanov et al., Phys. Rev. D **69** 012004 (2004).
[17] ZEUS collaboration, S. Chekanov et al., Eur. Phys. J. C **63** 171 (2009).
[18] ZEUS collaboration, S. Chekanov et al., Eur. Phys. J. C **65** 65 (2010).
[19] H1 and ZEUS collaboration, H. Abramowicz et al., Eur. Phys. J. C **73** 2311 (2013).
[20] S. Forte et al., Nucl. Phys. B **834** 116 (2010).
[21] NNPDF collaboration, R. D. Ball et al., Nucl. Phys. B **849** 296 (2011).
[22] NNPDF collaboration, R. D. Ball et al., Nucl. Phys. B **855** 153 (2012).
[23] H1 and ZEUS collaborations, F. D. Aron et al. J. High Energy Phys. **1001** 109 (2010).
[24] S. Alekhin, S. Moch, Phys. Lett. B **699** 345 (2011).
[25] S. Alekhin, S. Moch, arXiv:1107.0469.
[26] ZEUS collaboration, H. Abramowicz et al., DESY-14-083, to be published in JHEP.