Heavy Flavour Production at HERA

Ringailė Plačakytė
(on behalf of the H1 and ZEUS Collaborations)

Deutsches Elektronen Synchrotron, Notkestrasse 85, 22603 Hamburg, Germany

E-mail: `ringaile@mail.desy.de`

Abstract. Measurements of open charm and beauty production at HERA provide important input for stringent tests of quantum chromodynamics and are used to constrain the parton distribution functions of the proton. The recent results on the heavy flavour production obtained by the H1 and ZEUS experiments at HERA are reviewed in this contribution.

1. Heavy Flavour Production at HERA

The production of beauty and charm quarks in ep collisions at HERA provides important tests of the theory of perturbative Quantum Chromodynamics (pQCD). At leading order, the dominant process for heavy-quark production at HERA is boson-gluon fusion (BGF) where a virtual photon emitted by the incoming electron (positron) interacts with a gluon from the proton forming a heavy quark-antiquark pair. Besides the masses of the heavy quarks, additional scales involved in the heavy flavour production are the virtuality, Q^2, of the exchanged photon in case of deep inelastic scattering (DIS) and the transverse momenta, p_T, of the outgoing quarks. Depending on the details how the scales are treated, different approaches are available in pQCD for the treatment of the heavy flavours in DIS:

- The zero-mass variable-flavour-number-scheme (ZM-VFNS): in this scheme only three light flavours are participating in the parton evolution and charm quark is treated as a massless parton above the threshold at $Q^2 \sim$ charm quark mass, m_C^2.
- Fixed Flavour Number Scheme (FFNS): heavy quarks are treated as massive at all scales but they are not considered as partons in the proton. The number of active flavours are fixed to three (four) for charm (beauty). Heavy quarks are assumed to be produced only in the hard scattering process. In the FFNS calculations [1, 2] the pole mass [40] or the running mass definition [3] is used (later adopted from the recent ABM variant of the FFN scheme).
- General Mass Variable Flavour Number Scheme (GM-VFNS): it is an interpolation scheme where a low Q^2 region with FFNS and high Q^2 region with ZM-VFN schemes are combined. The GM-VFNS profits from the advantages of those two schemes, however, at the interpolation region some level of arbitrariness of treatment heavy quarks is introduced.

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 and semi-leptonic decays of heavy hadrons. The best signal-to-background ratio is observed using the full reconstruction of D mesons albeit having the small branching ratios, the method using semi-leptonic decays profits from larger branching ratios but has worse signal-to-background

ratio. Finally, inclusive analyses using lifetime information have no limitation on branching ratios but yields the worst signal-to-background ratio. In the following, the recent HERA heavy flavour measurement are reviewed.

2. Combination of Charm Production Measurements and QCD Analysis

Nine different H1 and ZEUS charm data sets measured with different charm tagging techniques are combined into one consistent set taking into account correlated systematic uncertainties and the normalisation [4]. The effect of including the combined HERA charm data in the QCD analysis of the parton distribution functions (PDFs) of the proton was also studied in [4]. In this study, the charm and the inclusive data are used with different implementations of the GM-VFN schemes have been investigated. Different schemes can have different impacts on the charm contribution to the sea quark distribution and thus affect the flavour composition of the quark PDFs. Therefore the accuracy of the charm data influences the uncertainties on the $W^{\pm}$ and Z cross section predictions at LHC. Figure 1 (left) summarises the study by showing the charm quark mass M_C (which, due to freedom introduced by an interpolation approach in GM-VFN schemes, can be treated as a parameter in the fit) scanning results for all schemes used in the fits. It is interesting to observe that first, different schemes have different optimal charm quark mass parameter M_C^{opt}, and second, the χ^2 minimum values are comparable for all schemes despite of different optimal values of M_C. The PDFs with M_C^{opt} were then propagated to the calculation of $W^{\pm}$ and Z boson cross section predictions for the LHC. As an example, the W^+ cross section as a function of M_C for the different schemes is shown in figure 1 (right). Good agreement between these predictions is observed at M_C^{opt} which results in a reduction of the uncertainties due to the heavy flavour treatment to below 1.5%. In addition, the running mass of the charm quark $m_C(m_C)$ is determined using the FFN scheme where, unlike in GM-VFNS, the charm quark mass corresponds directly to a physical mass (figure 2, left).
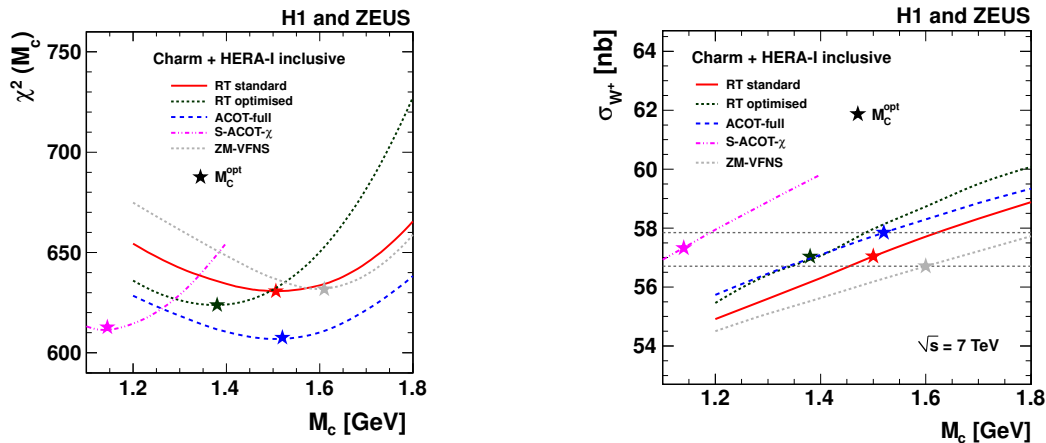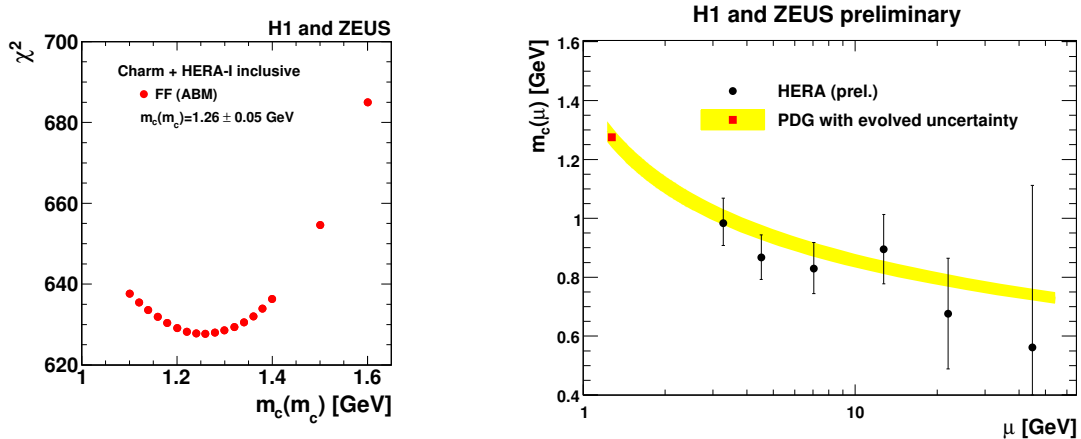

Figure 1. Left: The values of $\chi^2(M_C)$ for the PDF fit to the combined HERA inclusive DIS and charm measurements. Right: W^+ production cross section σ_{W^+} at the LHC for $\sqrt{s} = 7$ TeV obtained from the resulting PDF fits as a function of M_C. The Lines represent different heavy flavour schemes and the stars indicate the values of M_C^{opt} for each scheme.

3. Measurement of the Charm Mass Running

Similarly to running of α_s, the scale dependence of the masses of heavy quarks can be calculated perturbatively. For example, the running of the $\overline{MS}$ beauty quark mass has been established

from measurements at the LEP collider [5] but no similar measurement has been performed for charm quark so far. The combined HERA charm data [4] have been used to show the running of the charm quark mass for the first time. The basic idea is the following: the value of the charm quark mass $m_C(m_C)$ is extracted from the χ^2 distribution of data to theory comparison using PDFs obtained from inclusive DIS HERA data and the same setup in [4] but varying the charm mass. The extraction is performed from charm data subdivided into several kinematic intervals according to Q^2 and assuming the running of α_s and m_C as predicted by QCD. The measured $m_C(m_C)$ are reinterpreted in terms of a value of $m_C(\mu)$ at the typical charm measurement scale $\mu = \sqrt{Q^2 + 4m_C^2}$. This way, the effect of the initial assumption of QCD running on the interpretation of the measurement is minimised. The comparison of $m_C(\mu)$ at different scales with the expected running behavior is illustrated in figure 2 (right). More details about the extraction of the charm mass running at HERA can be found in [8].


Figure 2. Left: The values of χ^2 for the PDF fit to the combined HERA DIS and charm data as a function of the running charm quark mass $m_C(m_C)$. Right: The running of the charm mass $m_C(\mu)$ obtained in the $\overline{MS}$ mass scheme as a function of the scale μ. The PDG world average [6] and the band of its expected running [7] are also shown.

4. Latest Heavy Flavour Measurements at HERA

After the combined analysis of the charm data [4] was performed, new measurements of charm production in DIS have been reported at HERA, the most recent of which are discussed below. The charm production measured with the ZEUS detector using an integrated luminosity of 354 pb^{-1} by reconstructing $D^\pm$ mesons in the $D^\pm \to K^\pm \pi^\pm \pi^\pm$ decay channel [9]. These new precise data have the potential to constrain further the parton densities in the proton.

In the another recent ZEUS measurement, the cross sections for the photoproduction of D^* mesons have been measured at three different ep centre-of-mass energies, $\sqrt{s} = 318$, 251 and 225 GeV [10], see figure 3 (left). The dependence on $\sqrt{s}$ in this study is presented as normalised to the high-statistics measurement at $\sqrt{s} = 318$ GeV leading to the cancellation of a number of systematic effects. Predictions from the next-to leading order QCD describe the $\sqrt{s}$ dependence of the data well demonstrating consistency of the gluon distribution probed here with that extracted in PDF fits to inclusive DIS data. These results enhance the confidence in the QCD predictions of charm production rates and QCD processes for a future TeV-scale ep collider.

The new, most precise D^* data measured with integrated luminosity of 363 pb^{-1} with the ZEUS detector have been used to extract the charm contribution to the proton structure functions [11]. These data together with the measurements from H1 [12, 13] were used in
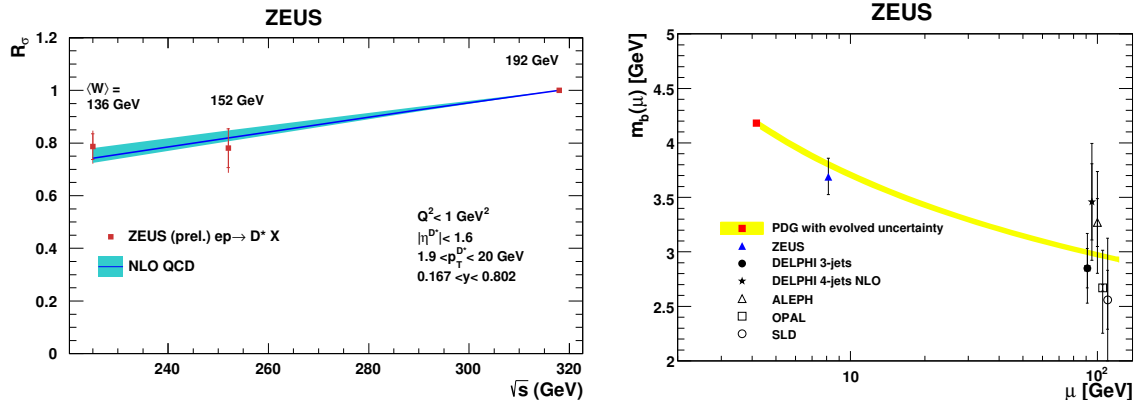
Figure 3. *Left: Normalised D^* visible photoproduction cross sections as a function of the ep centre-of-mass energy. The data points are shown with statistical uncertainties (inner error bars) and statistical and systematic uncertainties added in quadrature (outer error bars). The predictions from NLO QCD are shown as a line with the band representing its uncertainty. Right: The running of the beauty mass $m_b(\mu)$ obtained in the $\overline{MS}$ mass scheme as a function of the scale μ and compared with the PDG world average [6].*

the D* combination at the visible cross section level [14]. The cross sections were combined taking into account all relevant correlations and thus significantly reducing the uncertainties. The combined cross sections can be compared directly to differential NLO predictions without the need for extrapolation, however NNLO calculations are desired to match the data precision. Finally, the inclusive jet cross sections in beauty and charm events were used to extract the heavy-quark contribution to the proton structure function F_2 in the ZEUS collaboration [15]. In this analysis the long lifetimes of the weakly decaying b and c hadrons and their large masses were exploited. The running beauty-quark mass in the $\overline{MS}$ scheme was determined (figure 3, right) from an NLO QCD fit in the fixed-flavour-number scheme following a procedure similar to that used for a extraction of the charm-quark mass [4]. This represents the first measurement of the b-quark mass using HERA or any other hadron collider data.

References

[1] E. Laenen et al., Phys. Lett. **B291**, (1992) 325; E. Laenen et al., Nucl. Phys. **B392**, (1993) 162; E. Laenen et al., Nucl. Phys. **B392**, (1993) 229; S. Riemersma, J. Smith and W. L. van Neerven, Phys. Lett. **B347**, (1995) 143 [hep-ph/9411431].
[2] B. W. Harris and J. Smith, Phys. Rev. **D57**, (1998) 2806 [hep-ph/9706334].
[3] S. Alekhin and S. Moch, Phys. Lett. **B699**, (2011) 345 [arXiv:1011.5790].
[4] [H1 and ZEUS Collaborations], H. Abramowicz *et al.*, Eur.Phys.J. **C73** (2013) 2311 [arXiv:1211.1182].
[5] [DELPHI Collaborations], J. Abdallah *et al.*, Eur.Phys.J. **C55** (2008) 525.
[6] [Particle Data Group], J. Beringer *et al.*, Phys. Rev. **D86** (2012) 1.
[7] B. Schmidt, M. Steinhauser, CRunDec: C++ package for running and decoupling of the strong coupling and quark masses [arXiv:1201.6149]; K.G. Chetyrkin, J.H. Kuhn, M. Steinhauser, RunDec: Mathematica package for running and decoupling of the strong coupling and quark masses, Comp. Phys. Comm. **133** (2000) 43.
[8] [H1 and ZEUS Collaborations], H1-prelim-14-071, ZEUS-prel-14-006.
[9] [ZEUS Collaboration], I. Abt *et al.*, JHEP 1305, **023** 2013.
[10] [ZEUS Collaboration], H. Abramowicz *et al.*, DESY-14-082, [arXiv:1405.5068].
[11] [ZEUS Collaboration], H. Abramowicz *et al.*, JHEP 05 **097** 2013.
[12] [H1 Collaboration], F.D. Aaron *et al.*, Phys. Lett. **B686** (2010) 91.
[13] [H1 Collaboration], F.D. Aaron *et al.*, Eur. Phys. J. **C71** (2011) 1509.
[14] [H1 and ZEUS Collaborations], H1-prelim-13-171, ZEUS-prel-13-002.
[15] [ZEUS Collaboration], DESY-14-083, to be published in JHEP [arXiv:1405.6915].