COMBINATION AND QCD ANALYSIS OF CHARM AND BEAUTY PRODUCTION CROSS-SECTION MEASUREMENTS IN DEEP INELASTIC *ep* SCATTERING AT HERA *

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Measurements of open charm and beauty production cross sections in *ep* deep inelastic scattering (DIS) at HERA from the H1 and ZEUS collaborations are combined. Reduced cross sections are obtained in a restricted kinematic range. Perturbative QCD calculations are compared to the combined data. Next-to-leading order QCD analysis is performed using these data together with combined inclusive HERA DIS cross sections. The running charm and beauty quark masses are determined.

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1. Introduction and motivation

Deep inelastic scattering at HERA is a kinematic regime where the scattered electron is detected and the exchanged photon virtuality, Q^2, is above a few GeV^2. The dominant process for heavy quark (HQ) production (charm c or beauty b) in DIS is boson–gluon fusion (BGF), where at least 2 heavy quarks are present in the final state. The production, which is directly sensitive to the gluon density in the proton and to the masses of the heavy quarks, enables testing QCD by comparing data to next-to-leading order (NLO) predictions. Multiple scales in this process (Q^2, $m_{\rm HQ}$ and $p_{\rm T}({\rm HQ})$) allow perturbative calculations to be made.

The HERA *ep* collider operated with electrons or positrons at 27.5 GeV and protons at 820 or 920 GeV. About 130 pb^{-1} of data were taken between 1995–2000 (HERA I) and ≈ 380 pb^{-1} were taken between 2003–2007 (HERA II) by each of the two main experiments H1 and ZEUS.

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2. Heavy quark production in DIS

Several NLO schemes for HQ production in ep collisions exist:

(1) "Massive" or Fixed Flavour Number Scheme (FFNS), where $Q^2 \approx m_{\mathrm{HQ}}^2$. In this scheme, three active quark flavours (u, d, s) in the proton are considered, the heavy quarks are produced only perturbatively in the hard scattering, and mass effects are correctly included.

(2) "Massless" or Zero-Mass Variable Flavour Number Scheme (ZM-VFNS), where $Q^2 \gg m_{\mathrm{HQ}}^2$. Here, the heavy quarks are treated as massless partons, the HQ density is added as an extra flavour in the proton, and a resummation of large logarithms of Q^2/m_{HQ}^2 is performed.

At intermediate Q^2, both schemes should be merged:

(3) General-Mass Variable Flavour Number Scheme (GM-VFNS). This scheme is equivalent to FFNS for $Q^2 \approx m_{\mathrm{HQ}}^2$ and to ZM-VFNS for $Q^2 \gg m_{\mathrm{HQ}}^2$. In between, various schemes interpolate differently from each other.

3. Combination of charm and beauty data

The double differential cross section $\frac{\mathrm{d}^2\sigma^{Q\bar{Q}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2}$ can be expressed as: $\frac{2\pi\alpha^2}{x_{\mathrm{Bj}}Q^4}[(1+(1-y)^2)\sigma_{\mathrm{red}}^{Q\bar{Q}}]$, where x_{Bj} is the Bjorken-x variable, $y = Q^2/(sx_{\mathrm{Bj}})$ is the inelasticity, and s is the total energy squared of the ep system.

The heavy quark reduced cross sections, $\sigma_{\mathrm{red}}^{Q\bar{Q}}$, were measured in the kinematic range of $2.5 < Q^2 < 2000$ GeV^2; $3 \times 10^{-5} < x_{\mathrm{Bj}} < 5 \times 10^{-2}$.

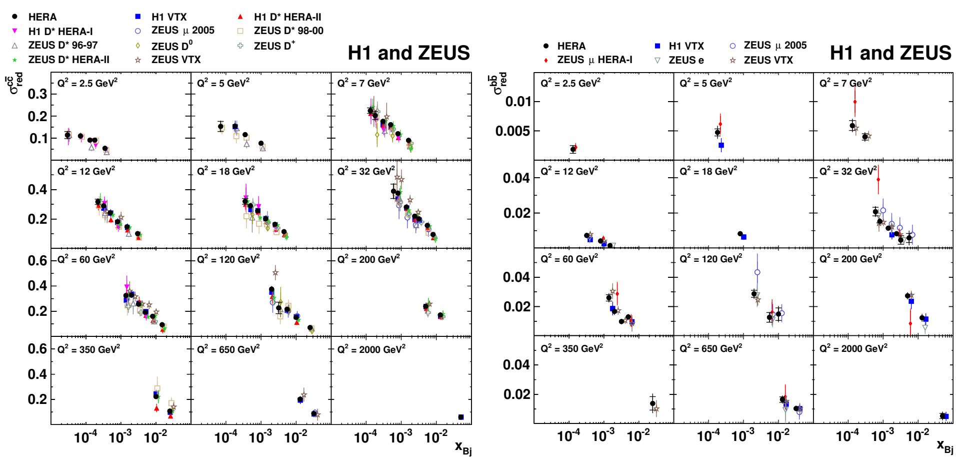

Fig. 1. Combined and separate H1 and ZEUS reduced charm (left) and beauty (right) production cross sections as a function of x_{Bj} for various Q^2 values.

Thirteen charm + beauty data sets of D^*, D^+, D^0, μ and lifetime tags from various HERA I and HERA II analyses were combined [1]. Correlations of statistical and systematic uncertainties for all data sets were taken into account. The combined data are compared to QCD predictions using various parton density functions (PDF) within the FFNS and VFNS schemes.

In Fig. 1, the charm and beauty reduced cross sections are shown as a function of x_{Bj} for various Q^2 values for the combined (full circles) and for separate H1 and ZEUS measurements. The combined results uncertainties are much smaller than each most precise separate data set.

4. Comparison with QCD predictions

In Fig. 2, the ratio of the combined reduced charm cross sections to the FFNS predictions are compared to various schemes and PDF sets at NLO and approximate NNLO. Both FFNS and VFNS describe reasonably the data. The x_{Bj} slope is steeper than the NLO predictions and it does not improve for approximate NNLO. For the reduced beauty cross sections, all predictions are in good agreement with data within large uncertainties.

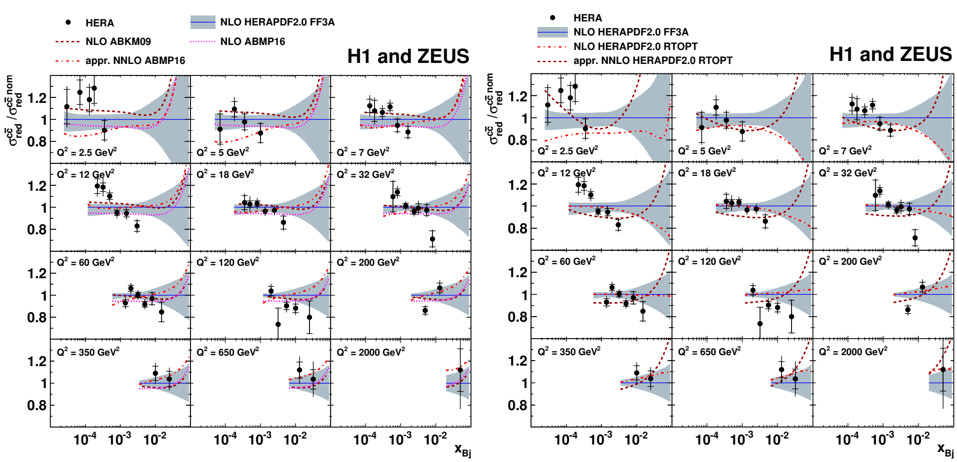

Fig. 2. Ratio of combined reduced charm cross sections as a function of x_{Bj} for various Q^2 values with respect to the FFNS NLO predictions compared to NLO and approximate NNLO FFNS (left) and VFNS (right) predictions.

5. QCD analysis

The combined HQ production together with combined inclusive DIS (with $Q^2_{\mathrm{min}} = 3.5$ GeV^2) were used to perform a simultaneous NLO fit to determine the running HQ masses $m_c(m_c)$ and $m_b(m_b)$. The fit includes PDFs in FFNS and c, b quarks running masses in the $\overline{\mathrm{MS}}$ scheme. The HQ running masses are free parameters in the fit.

The result of the fit (HERAPDF-HQMASS) yields:

$$m_c(m_c) = 1.29^{+0.05}_{-0.04}(\text{exp./fit})^{+0.06}_{-0.01}(\text{mod.})^{+0.00}_{-0.03}(\text{par.})\ \text{GeV}$$

and

$$m_b(m_b) = 4.05^{+0.10}_{-0.11}(\text{exp./fit})^{+0.09}_{-0.03}(\text{mod.})^{+0.00}_{-0.03}(\text{par.})\ \text{GeV}\ .$$

The uncertainties come from the fit, the model uncertainty and the PDF parameterisation. The results are consistent with the world average PDG2016.

Figure 3 (left) gives the ratios of combined reduced charm cross sections and HERAPDF-HQMASS fit to the nominal FFNS prediction. Both calculations describe the data almost identically. The steeper $x_{\rm Bj}$ slope persists also after the fit. For beauty, there is a good agreement between data and theory within the large uncertainties.

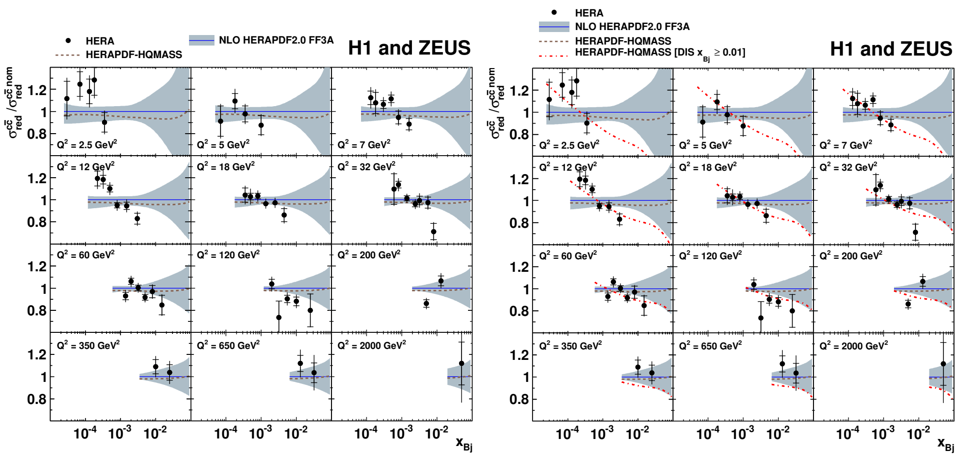

Fig. 3. Ratios of charm data and HERAPDF-HQMASS fit to the FFNS NLO predictions (left) and with $x_{\rm Bj} > 0.01$ for the inclusive DIS data (right).

The inclusive DIS cross section constrains the gluon density in the proton indirectly via scaling violation and directly via higher order corrections. Heavy flavour production via BGF probes the gluon directly in leading order (LO). The x of the incoming gluon is different from $x_{\rm Bj}$, which is measured at the photon vertex. In LO, the gluon x is given by $x = x_{\rm Bj}\,(1 + (\bar{s}/Q^2))$, where $\bar{s}$ is the invariant mass of the HQ pair. Due to the high precision of $\sigma^{c\bar{c}}_{\rm red}$, the impact of charm measurement on the gluon determination in the QCD fit can be enhanced. A cut of $x_{\rm Bj} > 0.01$ on the inclusive data in the fit reduces the impact of inclusive data in the determination of the gluon density function. The resulting function $xg(x,\mu_f^2)$, where $\mu_f^2 = 1.9\ \text{GeV}^2$ is the starting scale, is shown in Fig. 4 with no cut on $x_{\rm Bj}$ and with a cut $x_{\rm Bj} > 0.01$ on inclusive data only. The low-x gluon density function with the cut describes the charm data much better.

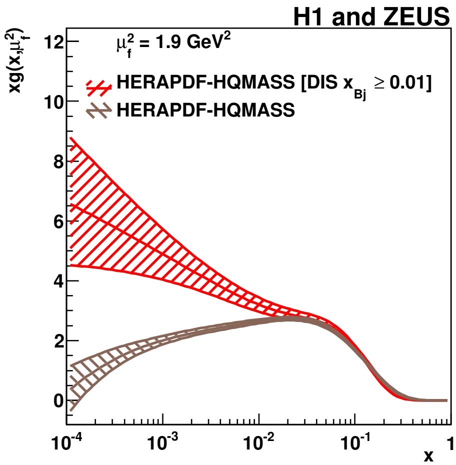

Fig. 4. The gluon density function $xg(x, \mu_f^2)$ as a function of x with and without a cut $x_{\mathrm{Bj}} > 0.01$.

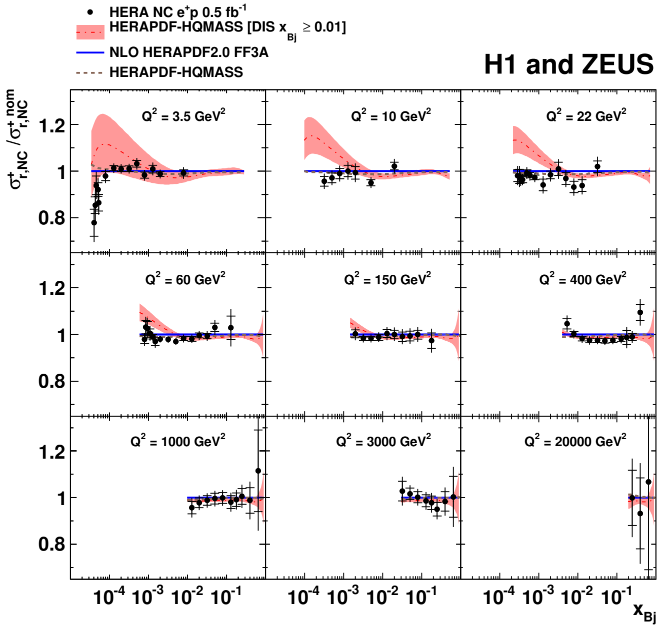

Fig. 5. Ratio of the combined reduced neutral current cross sections, $\sigma^{+}_{\mathrm{r,NC}}$, and NLO FFNS predictions based on HERAPDF-HQMASS with and without the $x_{\mathrm{Bj}} > 0.01$ cut to the reference cross sections, $\sigma^{+\ \mathrm{nom}}_{\mathrm{r,NC}}$.

In Fig. 3 (right), the ratios of combined reduced charm cross sections and HERAPDF-HQMASS fit to the nominal FFNS prediction based on HERAPDF-HQMASS are given with and without a cut $x_{\mathrm{Bj}} > 0.01$. The fit with the x_{Bj} cut on inclusive data rises more strongly towards small-x and describes the data much better. No significant improvement is obtained for the beauty data. The heavy-quark masses obtained from this fit are consistent with the previous ones.

The ratios of combined inclusive DIS reduced cross section for neutral current (NC) e^+p, $\sigma^+_{\mathrm{r,NC}}$, to NLO FFNS reference cross section, $\sigma^{+\mathrm{nom}}_{\mathrm{r,NC}}$, based on HERAPDF-HQMASS and on the fit with $x_{\mathrm{Bj}} > 0.01$ for inclusive data only are shown in Fig. 5. The predictions based on NLO FFNS and on HERAPDF-HQMASS agree with the inclusive measurements. However, the calculations with the $x_{\mathrm{Bj}} > 0.01$ cut for inclusive data fail to describe the low-x inclusive data. It is impossible to resolve the difference in describing simultaneously the inclusive and charm measurements by changing the gluon density. It is unlikely to improve this conclusion at NNLO, which gives a poorer description than NLO for the charm data.

6. Summary

— Final combined H1 + ZEUS charm and beauty results in DIS with the full HERA data, including all correlations, yield tight constraints on QCD.

— The charm results yield a better precision of $\approx 20\%$ compared to previous results. The beauty results are combined for the first time.

— The charm data are described reasonably by FFNS (best) and by VFNS. There is, however, $\approx 3\sigma$ tension in the x-slope with respect to the inclusive data.

— The beauty data are well-described by all QCD predictions within the large experimental uncertainties.

— A simultaneous fit of inclusive, charm and beauty data yields accurate results for $m_c(m_c)$ and $m_b(m_b)$ consistent with PDG and with previous measurements.

— The x-slope tension between the charm data and the inclusive data cannot be solved by varying the gluon density, adding higher orders or resumming $\log 1/x$ terms. Further investigations are needed.

REFERENCES

[1] H. Abramowicz *et al.* [H1 and ZEUS Collaborations], *Eur. Phys. J. C* **78**, 473 (2018).