The Heavy Flavour Content of the Proton

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Abstract
Recent measurements on heavy flavour production at HERA using the H1 and ZEUS experiments are presented. The cross sections for charm and beauty production in deep-inelastic scattering (DIS) using the HERA II data sample are shown. The results are based on various experimental methods including the reconstruction of D mesons, the measurement of semi-leptonic processes, measurements of the impact parameter, in the transverse plane, of tracks to the primary vertex and the reconstruction of the secondary vertex in the vertex detectors. The measurements are compared with the predictions of next-to-leading order (NLO) quantum chromodynamics (QCD).

1 Introduction

In perturbative QCD calculations, the production of heavy quarks at HERA proceeds dominantly via the direct photon-gluon fusion (PGF) process $\gamma g \to c\bar{c}$ ($\gamma g \to b\bar{b}$), where the photon interacts with a gluon from the proton to produce a pair of heavy quarks in the final state. Therefore, the measurement of processes involving heavy flavour production provides a test of the understanding of the QCD production mechanism and information on the gluon content of the proton. The presence of the heavy quark mass M provides an additional 'hard' scale to the momentum transfer of the exchanged boson Q and the transverse momentum of the heavy quark p_T meaning the perturbative series has to be treated in different ways depending on the relative magnitude of M, Q and p_T. At small scales ($Q, p_T \sim M$) the mass of the heavy quark is taken into account via the 'massive' PGF matrix element. At high scales ($Q, p_T \gg M$) the quark's mass may be neglected and it is treated as a 'massless' parton. The latest sets of global parton density functions (PDFs) from the MRST and CTEQ fitting groups (MRST08, CTEQ6.6) are based on heavy flavour schemes which aim to interpolate between the 'massive' behaviour at low Q^2 and 'massless' behaviour at high Q^2. The measurement of the inclusive contribution of processes involving charm and beauty to the proton structure function $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ allow to test these so-called "General Mass" schemes. The understanding of the gluon and heavy quark distributions in the region of low Bjorken x has important implications for the measurement of standard model and new physics processes at hadron colliders such as the Tevatron and LHC.

Recent measurements on charm and beauty production at HERA using the H1 and ZEUS experiments are presented here with the focus being on the DIS kinematic region. Many of the results presented in this paper utilise the full HERA II data sample and thus offer a significant improvement in precision compared with the previous HERA I results.

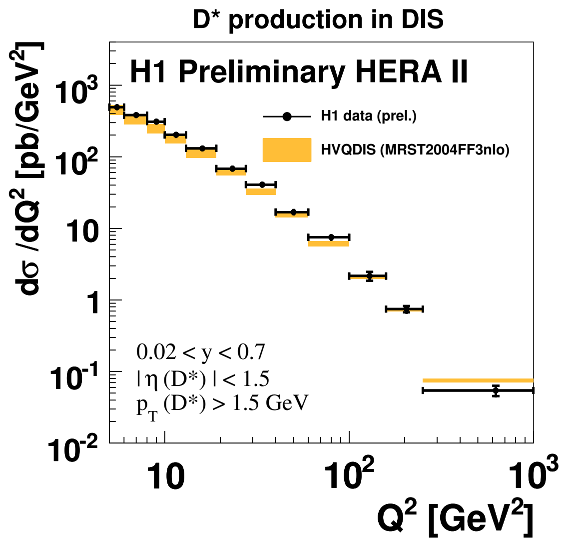

Fig. 1: The differential D^* cross section in DIS for $d\sigma/dQ^2$ as measured by the H1 collaboration

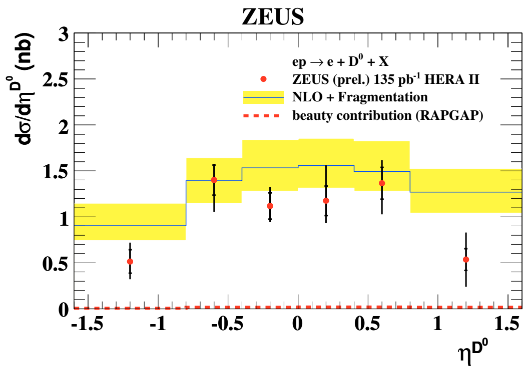

Fig. 2: The differential D^0 cross section in DIS for $d\sigma/d\eta$ as measured by the ZEUS collaboration.

2 Analysis Techniques

Charm quarks contribute around $20-30\%$ of the inclusive DIS cross section. Charmed hadrons are predominantly detected by reconstructing the decay products of $D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ or D^0 mesons in the central tracking detectors of H1 and ZEUS. For $D^{*\pm}$ measurements the "Golden Decay" chain $D^* \to K\pi\pi_{\text{slow}}$ is most often used. The signal to background ratio of the measurements can be improved by using information on the decay length significance of the secondary vertex as reconstructed by the silicon vertex detectors of the experiments.

In contrast to the rather large contribution of charm quarks to the total DIS cross section, beauty quarks contribute only a few $\%$, and an order of magnitude less at low values of Q^2. Therefore, the detection of beauty hadrons is very challenging. To extract signals use is made of the properties of beauty hadrons; their semi-leptonic decays, their relatively large mass and long lifetime. In semi-leptonic decays the large transverse momentum of the lepton w.r.t. the jet axis (p_T^{rel} method) may be used to tag events containing beauty quarks. This information can also be combined with information from the silicon vertex detectors, for example by measuring the large displacements from the primary vertex (impact parameter) of the lepton track. In analyses without the lepton requirement the impact parameter significance of all tracks with hits in the silicon vertex detectors can be combined with information from the position of the secondary vertex through use of a neural network. The c, b and light quark fractions in the data are extracted using a simultaneous fit of simulated reference distributions, obtained from Monte Carlo simulation, to the measured distributions.

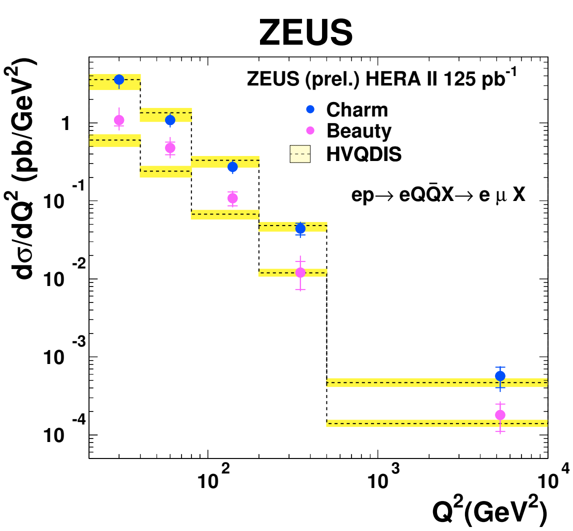

Fig. 3: The inclusive charm and beauty differential cross section in DIS for $d\sigma/dQ^2$ as measured by the ZEUS collaborationusing events with semi-muonic decays.

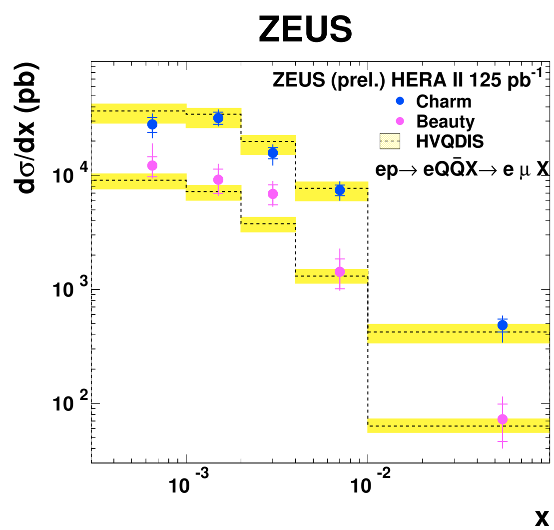

Fig. 4: The inclusive charm and beauty differential cross section in DIS for $d\sigma/dx$ as measured by the ZEUS collaborationusing events with semi-muonic decays.

3 Results

3.1 D Meson Cross Sections

The cross sections for the production of various D mesons have been made in DIS by H1 and ZEUS. The H1 collaboration have measured the $D^{*\pm}$ cross section in the range $5 < Q^2 < 1000$ GeV^2, $0.02 < y < 0.7$, $p_T(D^{*\pm}) > 1.5$ GeV and $-1.5 < \eta(D^{*\pm}) < 1.5$ [1]. The cross section is shown as a function of Q^2 in figure 1. The 'massive' NLO QCD prediction of HVQDIS [2] is shown to give an adequate description of the data over the full Q^2 range, including the high Q^2 region where the massive scheme may not be expected to be applicable.

The ZEUS collaboration have measured $D^{*\pm}$,$D^{\pm}$ and D^0 production cross sections in DIS using HERA II data samples [3–5]. The measurements of $D^{\pm}$ [4] and D^0 [5] mesons were improved by using lifetime information from the ZEUS Micro Vertex Detector. The D^0 meson cross section as a function of $\eta(D^0)$ is shown in figure 2. The cross section is reasonably well described by the prediction of massive NLO QCD.

3.2 Charm Fragmentation

The D meson cross sections described above can be measured in double differential $x - Q^2$ bins and the results used to extrapolate in p_T and η, using HVQDIS, to the full phase space in order to measure the charm structure function $F_2^{c\bar{c}}(x, Q^2)$. As well as the extrapolation it is also important to understand the fragmentation of charmed quarks into D mesons. The process is usually modelled using the convolution of the hard scattering cross section with a non-perturbative fragmentation function $D_c^{D^*}(z)$ where $z = E_{D^*}/E_c$. There exist a number of single parameter fragmentation functions which have been tuned to e^+e^- data. A recent publication on HERA I data by the H1 collaboration [6] found that these fragmentation functions were able to describe D^* data for events where there was a jet with $p_T > 3$ GeV in the centre-of-mass frame. For events without a jet the hadron level approximations to the fragmentation function were much less well described by the standard fragmentation parameters.

3.3 Inclusive Heavy Flavour Cross Sections in DIS

The inclusive cross section of charm and beauty quarks at HERA has been measured by the ZEUS collaboration [7]. The measurement was made using the semi-leptonic decay of heavy hadrons into muons in the range $Q^2 > 20$ GeV^2, $0.01 < y < 0.7$, $p_T(\mu) > 1.5$ GeV and $-1.6 < \eta(\mu) < 2.3$. The heavy flavour contributions were extracted by simultaneous fits to the missing transverse momentum, $p_T^{\mathrm{rel}}(\mu)$ and the muon impact parameter distributions. The relatively low cut on the transverse momentum of the lepton allows the inclusive charm and beauty cross sections to be extracted. These are shown as a function of x and Q^2 in figure 3. The data are reasonably well described by the predictions of massive NLO QCD, with the beauty data tending to be somewhat higher than the QCD prediction at low values of Q^2. The measurements can be extrapolated to the full phase space in order to evaluate the charm and beauty structure functions.

The H1 collaboration have analysed the inclusive production of charm and beauty quarks in DIS [8] using the impact parameter of tracks and the output of a neural network. The analysis makes use of the full available HERA II data sample. The inclusive 'reduced' beauty cross section in DIS $\tilde{\sigma}^{b\bar{b}}$ ($\tilde{\sigma}^{b\bar{b}} \simeq F_2^{b\bar{b}}$) is shown as a function of x for different values of Q^2 in figure 5. The data from the ZEUS collaboration using semi-muonic samples are also shown. The data between the different methods are in reasonable agreement, although the ZEUS results tend to be higher than H1 at low Q^2. The fully inclusive measurements are compared in the figure with the latest GM scheme predictions of MSTW and CTEQ, and are found to be generally well described. The massive FFNS prediction is also seen to be able to describe the data. The measurements were also found to be described by the NNLO predictions of MSTW.

The charm structure function $F_2^{c\bar{c}}$ is shown as a function of Q^2 for different values of x in figure 6. The data span a large range in the Q^2 and x plane. The $F_2^{c\bar{c}}$ measurements from the different experimental methods discussed above (i.e. from inclusive silicon vertex information and extrapolated from D meson and semi-muonic cross sections) are found to be in good agreement. The HERA II heavy flavour data have significantly improved in precision compared with HERA I. The precision of the HERA charm data would further improve if the data from the different methods and experiments is combined. The theoretical predictions based on the massive scheme give a reasonable description of the data across the x and Q^2 plane with the largest difference between CTEQ5F3 and MRST2004FF being in the region $Q^2 < 2m_c^2$ which is due to the different PDF inputs in this region.

4 Conclusion

Measurements of the heavy flavour content of the proton in DIS at HERA have been presented. The extraction of the inclusive cross sections $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$ allow the comparison of different

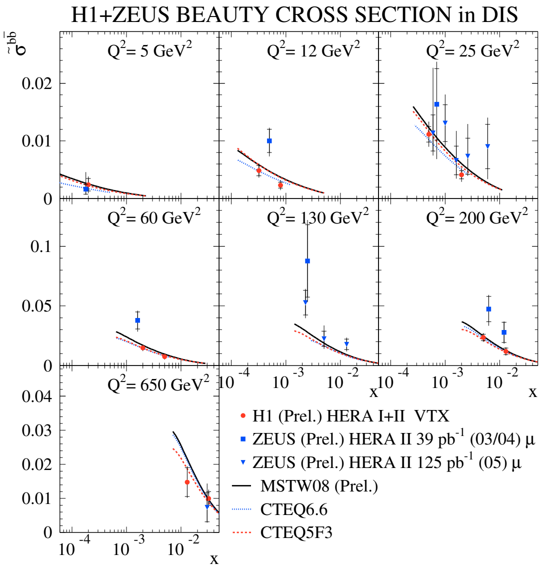

Fig. 5: The measured reduced cross section $\tilde{\sigma}^{b\bar{b}}$ shown as a function of x for 5 different Q^2 values.

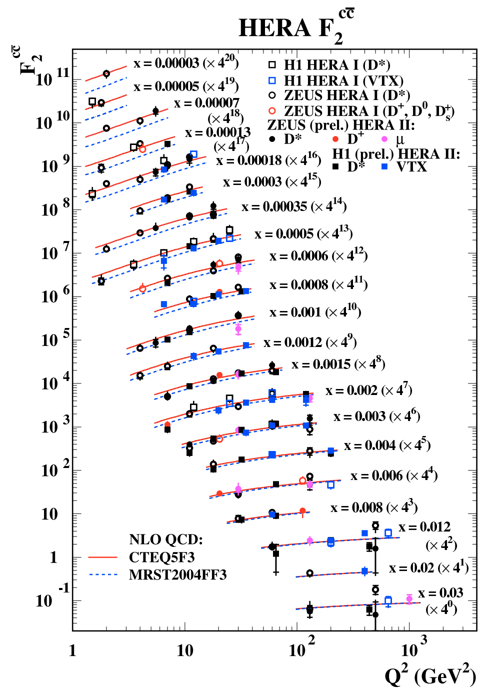

Fig. 6: The measured $F_2^{b\bar{b}}$ shown as a function of Q^2 for various x values.

experimental techniques. The cross sections are found to be well described by the predictions of perturbative QCD at NLO and NNLO.

References

[1] H1 Collaboration, "Dstar production at low Q2 with the H1 detector", contribution to the 16$^{\text{th}}$ International Conference on Deep-inelastic Scattering (DIS08), London UK, April 2008 (H1 prelim-08-072) ; H1 Collaboration, "Dstar production at high Q2 with the H1 detector", contribution to the 34$^{\text{th}}$ International Conference on High Energy Physics, Philadelphia USA, July 2008 (H1 prelim-08-074)

[2] B. W. Harris and J. Smith, Phys. Rev. D **57** (1998) 2806 [hep-ph/9706334].

[3] ZEUS Collaboration, "$F_2^{c\bar{c}}$ from $D^{\pm}$ mesons in DIS", contribution to the 15$^{\text{th}}$ International Conference on Deep-inelastic Scattering (DIS07), Munich Germany, April 2007 (ZEUS-prel-07-008)

[4] ZEUS Collaboration, "$F_2^{c\bar{c}}$ from $D^{\pm}$ mesons in DIS using 2005 $e-p$ data", contribution to the 15$^{\text{th}}$ International Conference on Deep-inelastic Scattering (DIS07), Munich Germany, April 2007 (ZEUS-prel-07-009)

[5] ZEUS Collaboration, "D^0 meson cross sections in DIS using HERA II data" (ZEUS-prel-07-034).

[6] *et al.* [H1 Collaboration], arXiv:0808.1003 [hep-ex].

[7] ZEUS Collaboration, "Charm and Beauty in DIS from muons", contribution to the 34$^{\text{th}}$ International Conference on High Energy Physics, Philadelphia USA, July 2008 (ZEUS-prel-08-007).

[8] H1 Collaboration, "Dstar production at high Q2 with the H1 detector", contribution to the 34$^{\text{th}}$ International Conference on High Energy Physics, Philadelphia USA, July 2008 (H1 prelim-08-074).