Beauty contribution to the proton structure function and charm results

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Recent heavy quark production results in deep inelastic scattering and photoproduction from the HERA colliding-beam experiments, H1 and ZEUS, are presented. Perturbative QCD at NLO is, in general, capable of reproducing the measured differential cross sections. The exploitation of the full data sample and the combination of various data-sets has allowed very precise determinations of the $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$ structure functions. In the $\overline{MS}$ renormalisation scheme of QCD, heavy quark masses $m_{c,b}$ are expressed as functions of an enery scale parameter $m_{c,b}(\mu)$. The value of $m_b(m_b)$ has been determined for the first time at a not-purely-leptonic collider. The running of m_c with the Q^2 scale has been also established for the first time.

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1. Heavy flavour production in $e^{\pm}p$ at HERA

The HERA $e^{\pm}p$ collider, based in Hamburg, operated from 1992 to 2007 yielding collisions at a center-of-mass energy $\sqrt{s} = 319$ GeV by accelerating $e^{\pm}$ and protons up to 27.6 GeV and 920 GeV[1] respectively. A total luminosity of about 0.5 fb^{-1} was collected by each of the two general purpose experiments H1 and ZEUS. In the second phase of the program (HERA-II, 2002-2007) the physics has benefited from increased luminosity and improved detectors.

The relevant kinematic variables which we will use in the following are defined in terms of the 4-momenta of the incoming proton (P), the incoming (k) and scattered (k') electron[2]. Depending on the virtuality of the exchanged photon $Q^2 = -q^2 = -(k'-k)^2$ interactions are categorised into two "regimes": photoproduction where $Q^2 = -q^2 \simeq 0$ GeV^2 (quasi-real photon) and Deep Inelastic Scattering (DIS), where $Q^2 \gtrsim 1$ GeV^2 roughly corresponding to the possibility to have the scattered $e^{\pm}$ within the detector acceptance. Other variables widely used are the Feynman scaling variable $x = Q^2/(2P \cdot q)$ which can be thought of as the fraction of the proton momentum carried by the struck parton and the Bjorken-y or inelasticity, $y = P \cdot q/p \cdot k$, in the proton rest frame being the fraction of the electron momentum transferred to the virtual photon.

At HERA the production of heavy quarks is tightly linked to the gluon content of the proton, the dominant production mechanism being the Boson-gluon fusion process $\gamma g \to q\bar{q}$ where the heavy quark pair, $q\bar{q}$, couples to a γ emitted by the electron and to a g emitted from the proton. The relative size of beauty, charm and light flavour cross sections scales approximately as $\sigma_b : \sigma_c : \sigma_{uds} \simeq 1 : 50 : 2000$. The perturbative QCD (pQCD) approach to the production mechanism is viable thanks to the presence in the process of characterising ("hard") scales (μ) being well above Λ_{QCD}, namely the heavy quark mass m_q, the typical heavy quark p_T and, for DIS, the Q^2. The interplay of these quantities give these measurements a certain theoretical interest (multi-scale problem). Several calculation schemes exist which are supposed to give better results depending on the explored kinematic region. Fixed-flavor number schemes (FFNS) are expected to provide reliable predictions when the scales are of $\mathscr{O}(m_q)$ since they treat the produced quarks as massive objects while zero-mass variable flavour number schemes (ZM-VFNS) are applicable for $\mu \gg m_q$. ZM-VFNS allow the resummation of terms proportional to $\log(Q^2/m_q^2)$. Mixed schemes (GM-VFNS) have also been developed trying to match the previous two approaches.

The extraction of heavy flavour production signal events at HERA is based on a variety of techniques. Tagging of semi-leptonic decays by recognising μ or e-like tracks allows a sizeable statistics thanks to the relatively large semi-leptonic branching ratios. The signal from heavy quark decays is extracted on a statistical basis considering the transverse momentum of the lepton relative to an associated jet (p_T^{rel}). Full reconstruction of specific decay channels e.g. $D^{*\pm} \to (K^{\mp}\pi^{\pm})\pi_s^{\pm}$ is used for selecting samples of charm production events whith good purity while it is not viable for beauty. Life-time tagging via displaced vertices and/or large impact parameters is also used to select large signal samples in a more inclusive manner. In this case the invariant mass at the secondary vertex (m_{vtx}) is also used as a discriminating variable for beauty/charm. Finally a certain number of analyses has made use of more exclusive final states with a double tag signature: $\mu + D^*$, di-muons and di-electrons.

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[1]$E_p = 820$ GeV and $\sqrt{s} = 300$ GeV until year 1998.

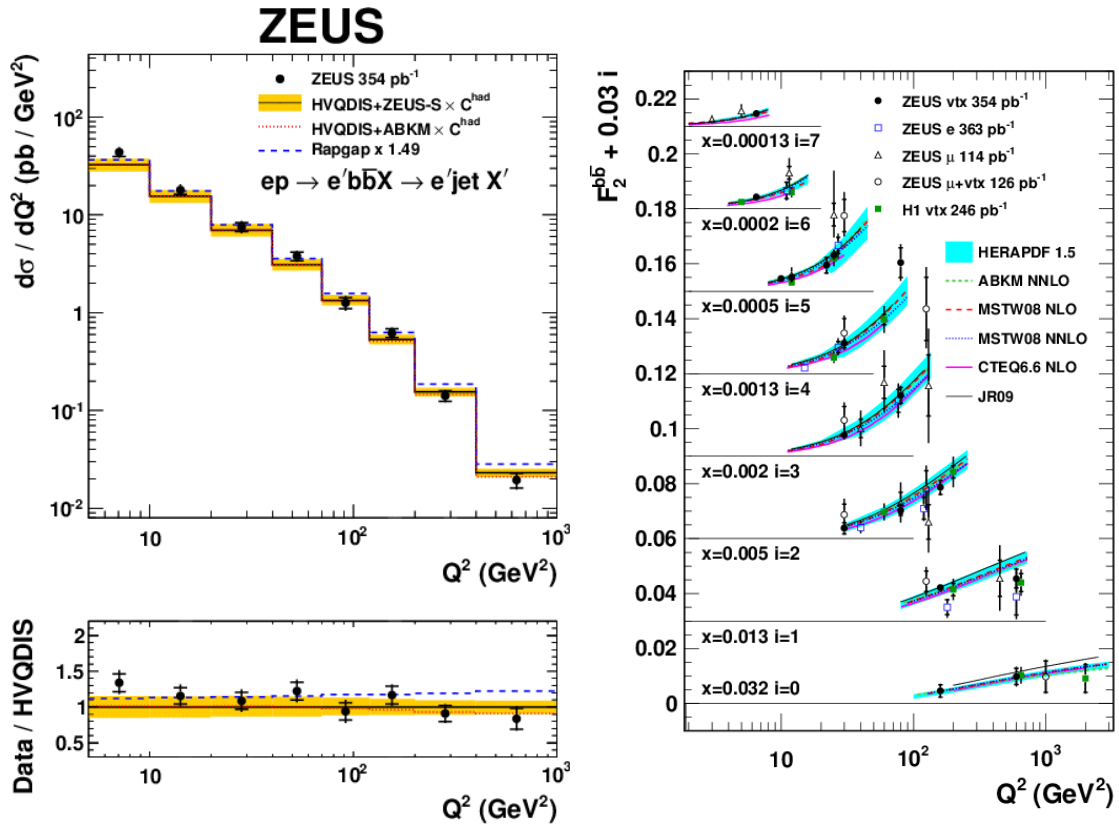[2]Here after we will denote both e^+ and e^- as "electrons".

Figure 1: Left: $d\sigma/dQ^2$ for beauty events at HERA (from [1]). Right: $F_2^{b\bar{b}}$ as a function of Q^2 in bins of x.
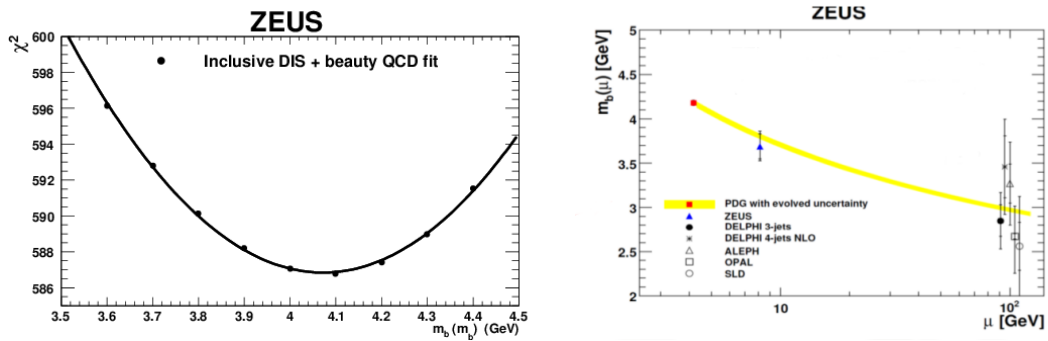

Figure 2: Left: χ^2 vs $m_b(m_b)$. The best-fit χ^2 is 587 with $n_{DOF} = 596$ and the partial contribution from the beauty data is 11.4 for 17 points. The fit for the running beauty-quark mass was performed within the HERAFitter framework choosing the ABM implementation of the FFNS at NLO and the OPENQCDRAD in the $\overline{MS}$ running-mass mode. Right: The ZEUS $m_b(m_b)$ value is shown at the point of highest sensitivity $\mu \simeq 2m_b$ and compared with LEP data ($\mu \simeq m_{Z^0}$) and the expected $m_b(\mu)$ evolution from pQCD (yellow band).

2. ZEUS: beauty and charm production in DIS

ZEUS has recently released the results of a joint analysis of beauty and charm production in DIS using a high statistics signal sample achievable using secondary-vertex tagging on the full HERA II data sample (354 pb^{-1}) [1]. This work has led to the best measurement of the beauty contribution to the F_2 proton structure function ($F_2^{b\bar{b}}$) and the first measurement of the beauty running mass at HERA.

Events were required to have a well measured scattered electron with an energy above 10 GeV, $5 < Q^2 < 1000$ GeV^2 and $0.02 < y < 0.7$. In addition, the presence of at least one (k_T clustering based) jet in the central region of pseudo-rapidity ($-1.6 < \eta_{jet} < 2.2$) with a transverse momentum $E_T^{jet} > 5(4.2)$ GeV was required for the beauty (charm) selection. Tracks with a good reconstruction in the central silicon tracker (MVD) with a $p_T > 0.5$ GeV/c were associated to the jet with a matching in the $\eta - \phi$ plane ($\Delta R < 1$) and used as inputs of a secondary vertex fitting algorithm.

Signal extraction is based on the significance of the secondary vertex decay length (L) projected along the jet axis ($S = \delta L/L$) in three m_{vtx} bins: $[1, 1.4[$, $[1.4, 2[$ and $[2, 6]$ GeV/c^2. The $S < 0$ region originates from finite resolution effects and is dominated by light flavour background events. This component is expected to be symmetric with respect to zero and it is thus subtracted to the $S > 0$ region ("mirrored significance", $|S|$) which instead contains the bulk of the signal component. A simultaneous fit of the charm and beauty contributions is performed on the $|S|$ distributions in m_{vtx} bins for $|S| > 4$. The fit has been done also in bins of several kinematic variables, namely, E_T^{jet}, η^{jet}, x and Q^2 to obtain differential cross sections in the "visible" portion of the phase space defined by the selection criteria. Perturbative QCD predictions at NLO based on the FFNS approach (HVQDIS program [2]) in general give a quite reasonable description of the data. As an example $d\sigma/dQ^2$ is shown for beauty in Fig. 1, left. Double differential cross sections in (x, Q^2) were then extracted to access $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$ according to the following equation:

$$\frac{d^2\sigma_{q\bar{q}}}{dxdQ^2} = \frac{2\pi}{xQ^4}\{[1 + (1-y^2)]F_2^{q\bar{q}}(x,Q^2) - y^2 F_L^{q\bar{q}}(x,Q^2)\} \text{ with } q = b,c \quad (2.1)$$

The extrapolation from the visible differential cross sections to the full phase space definition used here above is done using HVQDIS. Extrapolation factors for beauty lie between 1 and 1.3 (increasing at low Q^2) and up to 1.7 at high-x while for charm they are about 2-4 (the highest value being at low Q^2). The resulting $F_2^{b\bar{b}}$ is shown in Fig. 1 (right) as a function of Q^2 in bins of x (black points) together with previous H1 and ZEUS measurements. This analysis provides the best single measurement of $F_2^{b\bar{b}}$. Thanks to the much improved error the available data exhibits for the first time a certain sensitivity to different choices of the beauty mass m_b. The 17 points of Fig. 1 (right) and the inclusive HERA I F_2 data have been compared to the theoretical predictions with varying assumptions on $m_b(m_b)$ in the $\overline{MS}$ renormalisation scheme. While the inclusive data showing a small sensitivity to $m_b(m_b)$, including the beauty-analysis points a significant dependence emerges (Fig. 2, left) with a best fit at:

$$m_b(m_b) = 4.07 \pm 0.14(\text{fit})^{+0.01}_{-0.07}(\text{mod.})^{+0.05}_{-0.00}(\text{param.})^{+0.08}_{-0.05}(\text{theo.}) \text{ GeV} \quad (2.2)$$

The result is consistent with the world average, $m_b(m_b) = (4.18 \pm 0.03)$ GeV. This is the first $m_b(m_b)$ measurement at a not-purely-leptonic collider.
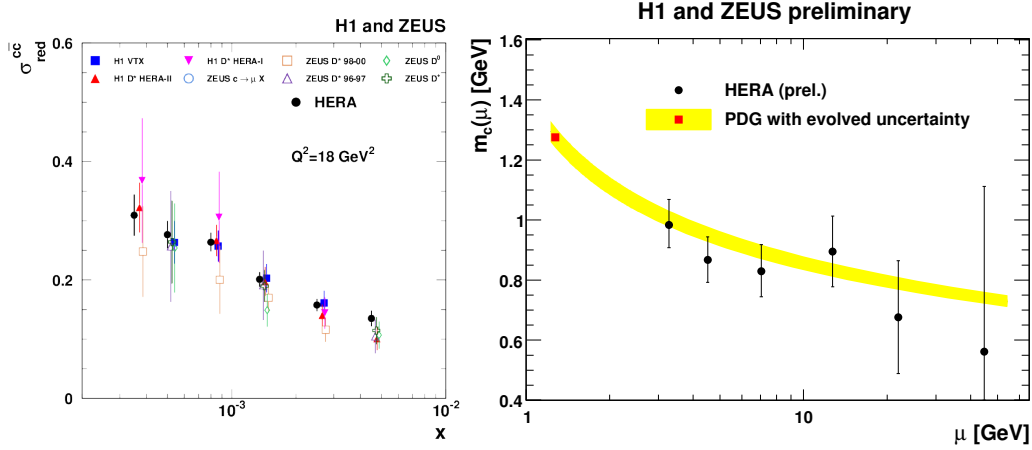
Figure 3: Left: an example illustrating the combination of HERA charm measurements for $Q^2 = 18$ GeV^2. The combined measurements are shown by the black points. Right: running charm mass $m_c(\mu)$.

3. Combination of HERA charm measurements

As outlined above (Sect. 1), HERA charm results can profit from different tagging techniques and complementary data-sets. This allows a significant gain when performing the combination of these data. In total 155 data points in 52 bins in $x - Q^2$ were combined in [3] by taking correlations properly into account. The $Q^2 = 18$ GeV^2 bin is taken as an example and shown in Fig. 3, left. A 10% uncertainty is obtained on average for the combined values going as low as 6% at small x and medium Q^2.

The determination of the running m_c mass was performed [4] by grouping the combined data into six Q^2 bins ([2.5, 7, 18, 60, 200, 650, 2000] GeV^2) and performing in each Q^2 bin an extraction procedure similar to the one which has been described above (Sect. 2). Each region is then characterised by a different hard scale μ defined as $\mu = \sqrt{\langle Q^2 \rangle + 4m_c(m_c)^2}$, $\langle Q^2 \rangle$ being the logarithmic average Q^2 in each interval. The right hand plot of Fig. 3 show the dependence of the fitted m_c as a function of the scale μ. The decrease of the running mass $m_c(\mu)$ at high scales agrees with the evolution of $m_c(m_c)$ predicted by pQCD (yellow band). As a cross check it was verified that $m_c(m_c)$ determined in each Q^2 bin is constant and consistent with the world average within the errors (not shown here). This is the first demonstration of the running of the charm quark mass.

4. Beauty photoproduction at low p_T

The H1 collaboration has published a study on beauty photoproduction near threshold using di-electrons final states [5]. Rich information becomes available by exploiting the correlations in charge and angle of the two electrons which depend on the original b-quark parent and the stage in the decay chain. "Signed" di-electron invariant mass m and $\Delta\phi$ variables are used for signal extraction. This final state gives access to the lowest values of the transverse momentum of the b quark (p_T^b) ever measured in ep (see Fig. 4). Data and NLO pQCD (FMNR program) are in agreement. An overview of beauty photoproduction results is also shown in the same figure.
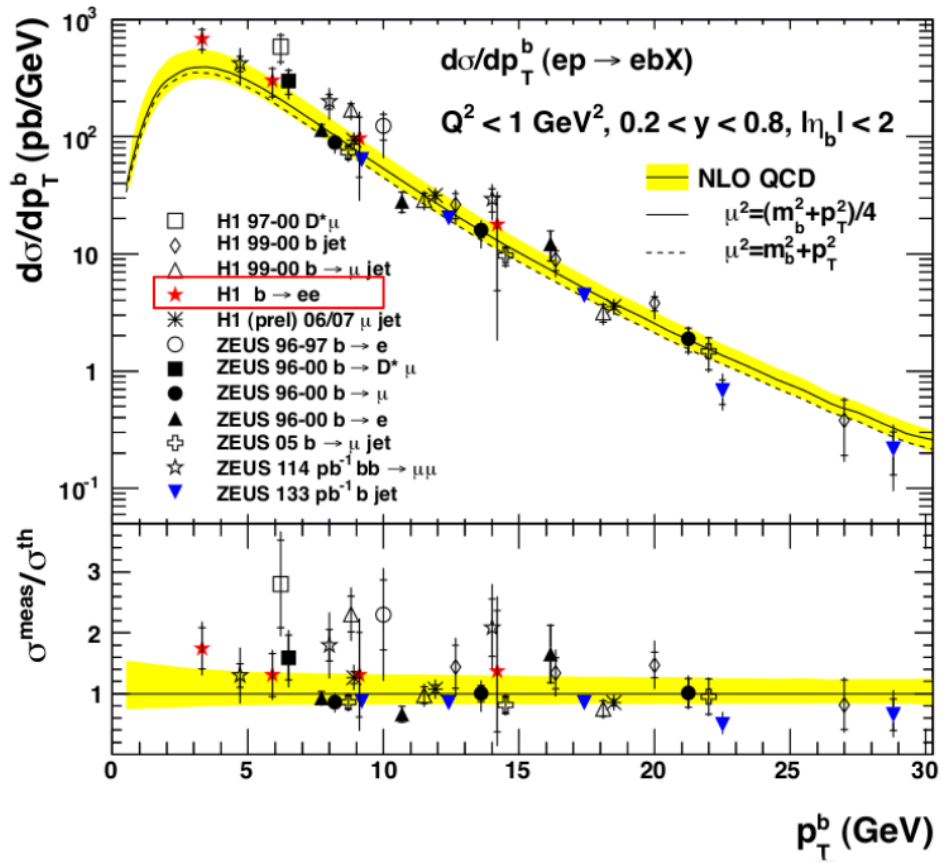
Figure 4: $d\sigma/dp_T^b$ for beauty photoproduction at HERA.

Several complementary measurements exist over a wide p_T^b range and they are, generally, well described by the theory.

5. Acknowledgements

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References

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