Including heavy quark production in ZEUS-PDF fits

A M Cooper-Sarkar

Oxford University - Dept of Physics
Denys Wilkinson Bdg, Oxford, OX1 3RH - UK

At HERA heavy quarks may contribute up to 30% of the structure function $F_2$. The potential of including heavy-quark data in the ZEUS PDF fits is explored, using $D^*$ double differential cross-sections as well as the inclusive quantities $F_2^{c\bar{c}}$, $F_2^{c\bar{c}}$. The introduction of heavy quarks requires an extension of the DGLAP formalism. The effect of using different heavy flavour number schemes, and different approaches to the running of $\alpha_s$, are compared.

Parton Density Function (PDF) determinations are usually global fits [2, 3, 4, 5], which use inclusive cross-section data and structure function measurements from deep inelastic lepton hadron scattering (DIS) data as well as some other exclusive cross-sections. The kinematics of lepton hadron scattering is described in terms of the variables $Q^2$, the invariant mass of the exchanged vector boson, Bjorken $x$, the fraction of the momentum of the incoming nucleon taken by the struck quark (in the quark-parton model), and $y$ which measures the energy transfer between the lepton and hadron systems. The differential cross-section for the neutral current (NC) process is given in terms of the structure functions by

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4x} \left[ Y_+ F_2(x, Q^2) - y^2 F_L(x, Q^2) \pm y_+ x F_3(x, Q^2) \right],$$

where $Y_\pm = 1 \pm (1 - y)^2$. In the HERA kinematic range there is a sizeable contribution to the $F_2$ structure function from heavy quarks, particularly charm. Thus heavy quarks must be properly treated in the formalism. Furthermore fitting data on charm production may help to give constraints on the gluon PDF at low-$x$.

The most frequent approaches to the inclusion of heavy quarks within the conventional framework of QCD evolution using the DGLAP equations are:

- **ZM-VFN** (zero-mass variable flavour number schemes) in which the charm parton density $c(x, Q^2)$ satisfies $c(x, Q^2) = 0$ for $Q^2 \leq \mu_c^2$ and $n_f = 3 + \theta(Q^2 - \mu_c^2)$ in the splitting functions and $\beta$ function. The threshold $\mu_c^2$, which is in the range $m_c^2 < \mu_c^2 < 4m_c^2$, is chosen so that $F_2^{c\bar{c}}(x, Q^2) = 2c^2_x xc(x, Q^2)$ gives a satisfactory description of the data. The advantage of this approach is that the simplicity of the massless DGLAP equations is retained. The disadvantage is that the physical threshold $W^2 = Q^2(\frac{1}{x} - 1) \geq 4m_c^2$ is not treated correctly ($W$ is the $\gamma^* g$ CM energy).

- **FFN** (fixed flavour number schemes) in which there is no charm parton density and all charmed quarks are generated by the BGF process. The advantage of the FFNS scheme is that the threshold region is correctly handled, but the disadvantage is that large $\ln(Q^2/m_c^2)$ terms appear and charm has to be treated ab initio in each hard process.

- **GM-VFN** (general mass variable flavour number schemes), which aim to treat the threshold correctly and absorb $\ln(Q^2/m_c^2)$ terms into a charm parton density at large $Q^2$. There are differing versions of such schemes [6, 7].

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*Charm production is described here but a similar formalism describes beauty production.

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However we also investigated the use of the FFN for 3-flavours with the renormalisation general mass variable flavour number scheme of Roberts and Thorne (TR-VFN) [8, 7].

Figure 1: Comparison of predictions for $F_{2}^{\bar{c}}$, from fits which use the GM-VFN scheme and the FFN scheme with two different factorisation scales: on the left hand side the FFN schemes still use a VFN treatment of $\alpha_s$, whereas on the right hand side a 3-flavour $\alpha_s$ is used.

For the ZEUS PDF analyses [11, 5], the heavy quark production scheme used was the general mass variable flavour number scheme of Roberts and Thorne (TR-VFN) [8, 7]. However we also investigated the use of the FFN for 3-flavours with the renormalisation and factorisation scale for light quarks both set to $Q^2$ but the factorisation scale for heavy quarks set to $Q^2 + 4m_c^2$. The reason for these choices of scheme and scale is that these are the choices made in the programme HVQDIS [10] which was used to extract $F_{2}^{\bar{c}}$ from data on $D^*$ production. Furthermore, it has recently become evident that the use of the FFN scheme implies a treatment of the running of $\alpha_s$ which is different from that of the VFN schemes. In VFN schemes $\alpha_s$ is matched at flavour thresholds [12], but the slope of $\alpha_s$ is discontinuous. In the FFN scheme we must use a 3-flavour $\alpha_S$ which is continuous in $Q^2$. This requires an equivalent value of $\alpha_s(M_Z) = 0.105$ in order to be consistent, at low $Q^2$, with the results of using a value of $\alpha_s(M_Z) = 0.118$ in the usual VFN schemes.

In Fig 1 we compare different heavy quark factorisation scales and different treatments of the running of $\alpha_s$ for predictions of $F_{2}^{\bar{c}}$. We see that within the FFN scheme the choice of the heavy quark factorisation scale makes only a small difference at low $Q^2$. The treatment of $\alpha_S$ gives larger differences. The FFN scheme and GM-VFN scheme differ for almost all $Q^2$ if $\alpha_S$ runs as for the VFN schemes. However if a 3-flavour $\alpha_S$ is applied in the FFN schemes there is much better agreement of all schemes at higher $Q^2$.

There is now new data on $F_{2}^{\bar{c}}$ [14] and $F_{2}^{b\bar{b}}$ [15] from HERA-II running to add to older the HERA-I charm data [9]. To investigate the potential of these data to constrain the gluon PDF, we used the ZEUS-pol PDF fit [13] and added the charm data. The new data do not influence the central values of the ZEUS-pol fit significantly. However there is a small improvement in the precision of the low-$x$ gluon. Fig 2 compares the PDFs and their uncertainties, as extracted from the ZEUS-pol PDF fit, with the those extracted from a similar fit including the $F_{2}^{\bar{c}}$ and $F_{2}^{b\bar{b}}$ data. This illustrates that the charm data has the potential to constrain the gluon PDF uncertainties.

We have also compared fits using the GM-VFN formalism with those using the FFN formalism with 3-flavour $\alpha_s$. When using the FFN formalism one should not really use
parametrisation was slightly modified to free the mid-$x$ gluon parameter $p_5(y)$ and the low-$x$ gluon parameter $p_6(g)$.
Figure 4: The gluon PDF and its fractional uncertainties for various $Q^2$ bins Left: before $D^*$ cross-section data are input to the ZEUS-S-13 fit. Right: after $D^*$ cross-section data are input to the ZEUS-S-13 fit

valence parameter $p_2(u) = p_2(d)$, such that the parametrization is like that of the ZEUS-JETS and ZEUS-pol fits. This fit is called ZEUS-S-13. Figure[4] shows the difference in the gluon PDF uncertainties, before and after the $D^*$ cross-sections were input to the ZEUS-S-13 global fit. Disappointingly the uncertainty on the gluon is NOT much improved.

Should we have expected much improvement? There are two aspects of the fit which could be improved. The predictions for the $D^*$ cross-sections have more uncertainties than just the PDF parametrization. A further uncertainty is introduced in the choice of the $c \rightarrow D^*$ fragmentation. The Petersen fragmentation function was used for the fit predictions. However, looking back at Fig[3] we can see that the Lund fragmentation function seems to describe the data better. To best exploit the charm data in future we need to address such aspects of our model uncertainty. Secondly, this study on the $D^*$ cross-sections used only the HERA-I charm data. We look forward to the 5-fold increase in statistics expected from HERA-II charm and beauty data.

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ZEUS-S-13

uncorrelated error
correlated error

$Q^2 = 2.5 \text{ GeV}^2$

$Q^2 = 7 \text{ GeV}^2$

$Q^2 = 20 \text{ GeV}^2$

$Q^2 = 200 \text{ GeV}^2$

$Q^2 = 2000 \text{ GeV}^2$

$Q^2 = 20000 \text{ GeV}^2$

$\lambda_H$

$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $1$

$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $1$