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 α_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-ections. 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

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left[Y_+\,F_2(x,Q^2) - y^2\,F_L(x,Q^2) \mp Y_-\,xF_3(x,Q^2)\right],$$

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 fomalism. 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 [a]:

- 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 β function. The threshold μ_c^2, which is in the range $m_c^2 < \mu_c^2 < 4m_c^2$, is chosen so that $F_2^c(x,Q^2) = 2e_c^2 xc(x,Q^2)$ 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 $\hat{W}^2 = Q^2(\frac{1}{z} - 1) \geq 4m_c^2$ is not treated correctly ($\hat{W}$ 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 disadvantge 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]

[a]Charm production is described here but a similar formalism describes beauty production

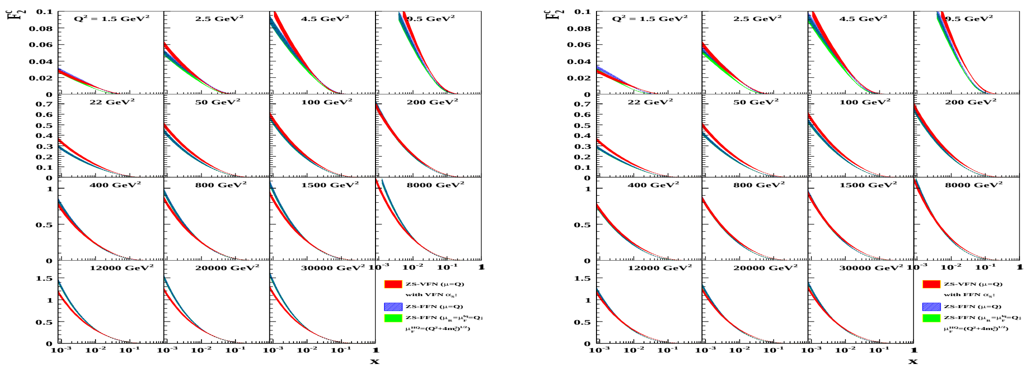


Figure 1: Comparison of predictions for $F_2^{c\bar{c}}$, from fits which use the GM-VFN scheme and the FFN scheme with two different factorisation scales: on the left hand side the FFN schemes still use a VFN treatment of α_s, whereas on the right hand side a 3-flavour α_s is used.

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 $F_2^{c\bar{c}}$ 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 α_s which is different from that of the VFN schemes. In VFN schemes α_s is matched at flavour thresholds [12], but the slope of α_s is discontinuous. In the FFN scheme we must use a 3-flavour α_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 α_s for predictions of $F_2^{c\bar{c}}$. 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 α_S gives larger differences. The FFN scheme and GM-VFN scheme differ for almost all Q^2 if α_S runs as for the VFN schemes. However if a 3-flavour α_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 $F_2^{c\bar{c}}$ [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 $F_2^{c\bar{c}}$ 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 α_s. When using the FFN formalism one should not really use

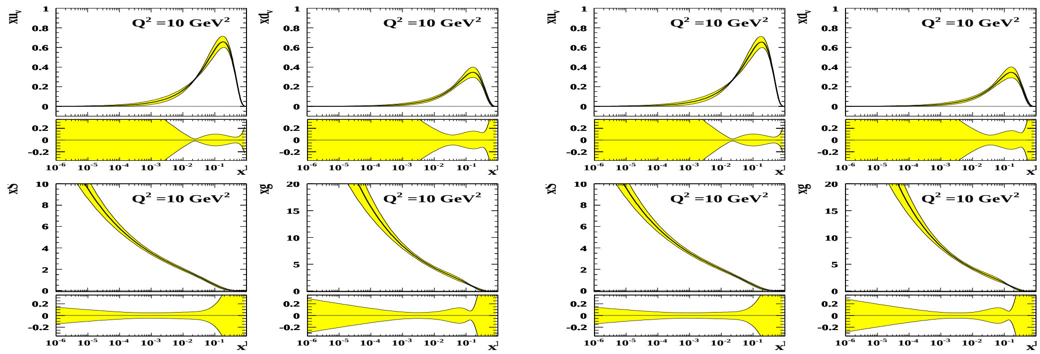


Figure 2: The u-valence, d-valence, Sea and gluon PDFs and their fractional uncertainties at $Q^2 = 10\text{GeV}^2$, from a) the ZEUS-pol PDF fit (left) and b) a smilar fit with $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ data included (right).

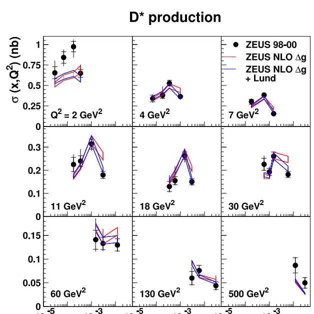


Figure 3: Double differential cross-sections for D^* production. The red lines show the predictions of the ZEUS-S-13 NLO PDF fit using the Petersen fragmentation function for the D^*, whereas the blue lines show these predictions using the Lund fragmentation function.

high-Q^2 data, because large $\ln(Q^2/m_c^2)$ terms are not resummed. Another short-coming is that the NLO FFN coefficient functions are not available for the CC processes. Since the CC reactions at HERA are at high-Q^2 we use ZM-VFN coefficient functions. In practice the χ^2 for these fits is not bad. The main difference between FFN and VFN fits is in sensitivity to the charm quark mass m_c, with the FFN fits preferring a low value $m_c = 1.35$ GeV and the GM-VFN fits favouring a higher value $m_c = 1.45$ GeV.

The small impact of the heavy flavour data on the global fit may be because we are not using the charm data optimally. $F_2^{c\bar{c}}$ is a quantity extracted from D^* cross-sections by quite a large extrapolation. It would be better to fit to those cross-sections directly. The evaluation of the theoretical predictions involves running the NLO programme HVQDIS for each iteration of the fit. However, one can shorten this process by using the same method as was used for the ZEUS-JETS fit [11]. The PDF independent subprocess cross-sections are output onto a grid, such that they can simply be multiplied by the PDFs at each iteration. The data used are the nine double differential cross-section measurements of $d^2\sigma(D^*)/dQ^2dy$ [9], see Fig. 3. When fitting D^* cross-sections, as opposed to and inclusive quantity like $F_2^{c\bar{c}}$, one must use the FFN scheme since the prediction grids are calculated using HVQDIS. This means that we cannot use ZEUS high-Q^2 data. Hence we chose to use the ZEUS-S global fit [5] as the basis for our fit, with a cut-off $Q^2 < 3000\text{GeV}^2$. The parametrisation was slightly modified to free the mid-x gluon parameter $p_5(g)$ and the low-x

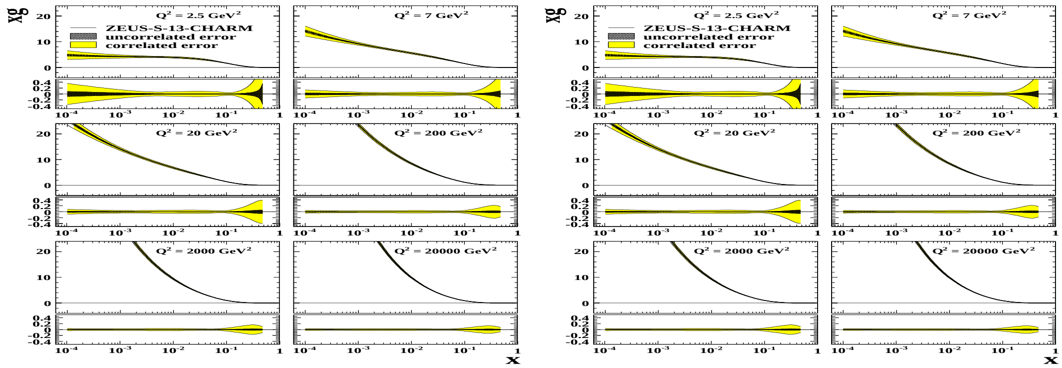


Figure 4: The gluon PDF and its fractional uncertainties for various Q^2 bins Left: before D^* cross-section data are input to the ZEUS-S-13 fit. Right: after D^* cross-section data are input to the ZEUS-S-13 fit

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 afer 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 predictiond for the D^* cross-sections have more uncertainties than just the PDF parametrization. A further uncertainty is introduced in the choice of the $c \to D^*$ 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.

References

[1] Slides:
`http://indico.cern.ch/contributionDisplay.py?contribId=246&sessionId=30&confId=24657`

[2] A.D. Martin et al., Eur. Phys.J **C23**, 73 (2002)

[3] A.D. Martin et al., arxiv **0706**, 0459 (2007)

[4] J. Pumplin et al., JHEP **0207**, 012 (2002)

[5] ZEUS Coll., S. Chekanov et al., Phys. Rev **D 67**, 012007 (2003)

[6] Wu Ki Tung et al., JHEP **0702**, 053 (2007)

[7] R.S. Thorne, Phys.Rev **D73**, 054019 (2006)

[8] R.S. Thorne and R.G. Roberts, Phys.Rev **D57**, 6871 (1998)

[9] ZEUS Coll., S. Chekanov et al., Phys. Rev **D 69**, 012004 (2004)

[10] B.W. Harris and J. Smith, Phys.Lett. **B 359**, 423 (1995)

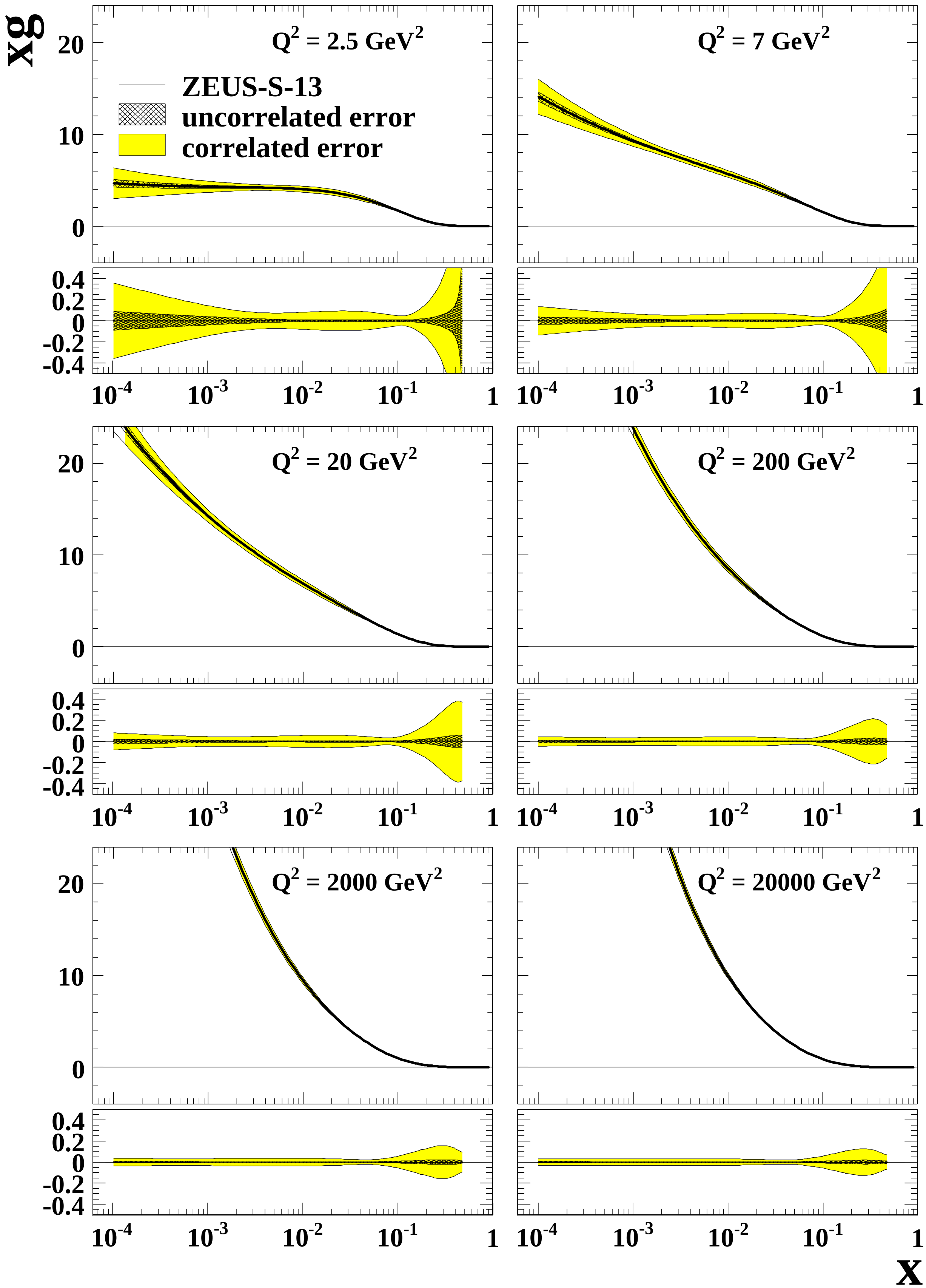
[11] ZEUS Coll., S. Chekanov et al., Eur.Phys.J **C 42**, 1 (2005)

[12] W.J. Marciano, Phys.Rev. **D 29**, 5801 (1984)

[13] K. Nagano, Proceedings of DIS2008

[14] ZEUS Collaboration, ZEUS-prel-07-007/008

[15] ZEUS Collaboration, ZEUS-Prel-07-009



xg
Q^2 = 2.5 GeV^2
ZEUS-S-13
uncorrelated error
correlated error
Q^2 = 7 GeV^2
Q^2 = 20 GeV^2
Q^2 = 200 GeV^2
Q^2 = 2000 GeV^2
Q^2 = 20000 GeV^2
x