Recent experimental results in heavy flavour production at HERA

J E Cole†
Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2BZ, UK

Abstract.
A review of recent results involving heavy flavour production at the electron-proton collider HERA is presented. The role which heavy flavour production plays in the understanding of photon and proton structure is emphasised, indicating the areas in which further experimental data and the further development of theoretical calculations will be of particular benefit.

1. Introduction
At the time of the last Durham workshop, HERA was about to embark upon its most successful data-taking period to date. With a data sample of 30 – 50 pb⁻¹ available per experiment, it is now possible to perform high precision tests of QCD in heavy flavour physics as well as to observe processes never seen before at HERA.

The importance of heavy flavour production lies in the large quark masses ($m_c = 1.1 – 1.4$ GeV, $m_b = 4.1 – 4.4$ GeV [1]) which provide the hard scale required for the use of perturbative Quantum Chromodynamics (pQCD) and also in the fact that heavy flavour production in deep inelastic scattering (DIS) and direct photoproduction provides a good handle on the proton gluon density, while resolved photoproduction of heavy flavours provides a valuable probe of the photon flavour decomposition.

Heavy flavour production can be identified via several different tagging methods, such as $D_{s}^{\pm}$ reconstruction in the channels $D_{s}^{\pm} \rightarrow D^{0}\pi^{\pm}$, $D^{0} \rightarrow K^{\mp}\pi^{\pm}$ or $D^{0} \rightarrow K^{+}\pi^{-}\pi^{+}\pi^{-}$ or via $J/\psi \rightarrow \mu^{+}\mu^{-}$ decays. Beauty production, only recently observed at HERA, has been tagged via semileptonic decays involving muons and via elastic $\Upsilon$ production in the muon decay channel.

In the following, I will summarise the current status of both charm and beauty results from HERA, the interpretation of these results and the questions which remain to be answered.

† On behalf of the ZEUS and H1 Collaborations

Presented at the 3rd UK Phenomenology Workshop on HERA Physics, 20-25 September 1998, St John’s College, Durham, UK.
2. Charm Production in DIS

Early HERA charm measurements [2, 3] clearly showed that open charm in DIS is produced predominantly via boson gluon fusion (BGF) as illustrated in figure 1. More recent measurements [4, 5] have widened the accessible $Q^2$ region indicating that some additional flavour excitation contribution might be present.

![Diagram](image)

**Figure 1.** The leading order diagrams for boson gluon fusion (left) and flavour excitation (right).

Figure 2 shows the differential $D^{*\pm}$ cross sections measured by ZEUS compared to the Next-to-Leading-Order (NLO) BGF calculations of Harris and Smith [6]. Overall good agreement is observed, although an excess in the forward region and a softer than expected $x(D^*)$ distribution (the fractional momentum of the $D^{*\pm}$ in the $\gamma^*p$ frame) can be seen. These discrepancies are also observed in the H1 results [5].

![Graphs](image)

**Figure 2.** The differential $D^{*\pm}$ cross sections measured by ZEUS with respect to $Q^2$, Bjorken $x$, $W$, the $\gamma^*p$ centre of mass energy, the transverse momentum and pseudorapidity of the $D^{*\pm}$ and $x(D^*)$. The shaded band indicates the predictions of Harris and Smith and its width shows the effect of varying $m_c$ between 1.2 and 1.6 GeV.

A contribution from charm excitation implies a harder $x(D^*)$ distribution and is therefore ruled out as the explanation for these discrepancies. Hadronisation effects or
Recent experimental results in heavy flavour production at HERA

3

the presence of an additional resolved contribution could be the explanation. $F_{2c\bar{c}}$, the
charm contribution to the structure function $F_2$, has also been measured from these $D^{*\pm}$
samples and is found to agree well with the NLO BGF calculations of Laenen et al.[7].

The H1 collaboration has used DIS and direct photoproduction $D^{*\pm}$ data to
estimate the proton gluon density [8]. This density is compared to that extracted
from QCD scaling violations in $F_2$ [9]; good agreement is observed, potentially providing
evidence for the universality of the parton distributions, bearing in mind the assumptions
made during the extraction.

An extraction of the gluon density has also been made by Botje [10] through a QCD
analysis of ZEUS $F_{2c\bar{c}}$ and shows that if universality is assumed, strong constraints can
be placed on both the charm mass and $\alpha_s$.

3. Charmonium Production

Inelastic $J/\psi \rightarrow \mu^+\mu^−$ production can also be used to measure the proton gluon density
and proceeds via three different mechanisms: diffractive proton dissociation, BGF and
resolved processes. Only the BGF contribution is sensitive to the gluon density and can
be selected using the inelasticity, $z$, defined by

$$z = \frac{(E - p_z)_{J/\psi}}{(E - p_z)_{Event}}$$

(1)

BGF occurs predominantly at intermediate $z$ and both ZEUS [11] and H1 [12] have
measured the differential photoproduction cross sections with respect to $z$ in this region.
The results have been compared to predictions from the Colour Singlet (CS) [13] and
Colour Octet (CO) [14] models and are found to favour the CS model without any CO
contribution. However, the uncertainty on the CO model is sufficiently large that it
cannot currently be ruled out. This is in apparent contradiction to $J/\psi$ results from the
TEVATRON [15], where contributions from both models are required to describe the
data.

H1 have also studied inelastic $J/\psi$ production in DIS [16], where the results are
compared to the leading order (LO) CS+CO calculations of Fleming and Mehen [17].
It is observed that the shapes of the distributions are best described by the CS model,
but that adding a CO contribution substantially improves the normalisation. Further
developments are required in order to fully describe the data.

4. Open Charm Production in Photoproduction

ZEUS have also measured differential $D^{*\pm}$ cross sections in photoproduction [18] and
compared them to massive [19] and massless [20, 21] calculations as shown in figure 3. In
the massive scheme, charm is not treated as an active parton in the proton or photon and
hence can only be produced dynamically in the hard process. In the massless scheme,
charm is treated as an active parton, implying that both BGF and charm excitation may
Recent experimental results in heavy flavour production at HERA take place, leading to a larger resolved component than that predicted by the massive scheme.

<table>
<thead>
<tr>
<th>ZEUS 1996+97</th>
<th>ZEUS 1996+97</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Figure 3.** The photoproduction $D^{\pm}$ cross sections measured by ZEUS as a function of $p_T(D^{\pm})$ (left) and $\eta(D^{\pm})$ (right). It should be noted that the Kniehl et al. calculations are not reliable for $p_T(D^{\pm}) < 3$ GeV.

The variable $\varepsilon$ indicated in figure 3 is the fragmentation parameter in the Peterson model [22] used to describe $c \rightarrow D^{\pm}$ fragmentation and represents one of the major uncertainties in the theoretical models. Some discrepancy is observed between the data and the theoretical predictions, particularly in the forward region, but it appears that the best agreement is achieved with the massless model of Kniehl et al. [20], especially when the sensitivity of the massless calculations to the input photon structure function, which are not well constrained, is taken into account.

A study of charm in dijet photoproduction has also been performed using $D^{\pm}$ production. In order to study the kinematics of the underlying hard scatter, the variable $x_{\gamma}^{obs}$ is used, which is defined as

$$x_{\gamma}^{obs} = \frac{\sum_{jets}(E_{T}^{jet} \cdot e^{-\eta_{jet}})}{2E_{e}y}$$

where $\eta_{jet}$ and $E_{T}^{jet}$ are the pseudorapidity and transverse energy of the jet and the sum runs over the two jets. At LO $x_{\gamma}^{obs}$ may be used to distinguish between direct and resolved processes, but at NLO the distinction is more ambiguous.

Comparisons have been made between the data, LO Monte Carlo [23] and the NLO calculations of Frixione et al. [19]. At LO, a large resolved contribution is observed at low $x_{\gamma}^{obs}$, which is dominated by charm excitation. At NLO, the massive calculation is found to underestimate the low $x_{\gamma}^{obs}$ region. A massless NLO calculation may describe this region better.
5. Beauty Production

The observation of an elastic $\Upsilon \to \mu^+\mu^-$ signal by both the ZEUS and H1 collaborations [24, 25] was the first evidence for beauty production at HERA. It is not possible to resolve the $\Upsilon(1s)$, $\Upsilon(2s)$ and $\Upsilon(3s)$ contributions, hence only the quantity $\sigma(\gamma p \to \Upsilon p) \cdot BR$ is measured, where $BR$ is the $\Upsilon$ branching ratio to muons, and found to be $13.3^{+2.7}_{-2.3}$ pb by ZEUS and $16.0^{+7.5}_{-4.0}$ pb by H1. Comparisons made between the ZEUS results and the predictions of Frankfurt et al.[26] indicate that theory significantly underestimates this cross section. An explanation for this discrepancy has recently been proposed [27].

H1 have made the first measurement of open beauty in photoproduction using muons from semileptonic decays in dijet events [28]. By measuring the transverse momentum of the muon with respect to the thrust axis of the nearest jet, it is possible to extract the visible cross section $\sigma(ep \to b\bar{b}X)$, which is found to be $0.93^{+0.21}_{-0.12}$ nb. This can then be compared to the prediction from the AROMA Monte Carlo [29] which is 0.19 nb. Although this lies substantially below the data, it should be noted that AROMA is a LO Monte Carlo which contains only direct processes. Clearly a full NLO calculation is required.

6. Conclusions

Since the last workshop, heavy flavour physics has become one of the most exciting new areas accessible at HERA. Whilst our understanding of heavy flavour production has substantially improved, there are clearly several key issues which remain unresolved, such as the discrepancies observed in the photoproduction and DIS $D^{*\pm}$ results when compared to the theoretical predictions. There is also a need for further developments in the understanding of both inelastic $J/\psi$ and elastic $\Upsilon$ production.

Some interesting prospects are also available for the future, such as the possibility of tightening the constraints on both the charm mass and $\alpha_s$ through more precise measurements of the proton gluon density. There is also the opportunity to gain a more exact understanding of photon structure through the study of resolved charm in photoproduction. Equally, we are clearly only at the start of the study of beauty production — an area in which substantially increased statistics are required.

There is clearly a bright future in heavy flavour production with the approach of the luminosity upgrade, which will provide important information in a variety of different areas in the years to come.

Acknowledgments

I would like to thank the organisers of the Durham workshop for a very interesting and enjoyable week and also PPARC for their financial support during the last three years. Many thanks also to all those people who provided results and enlightening discussions during the preparations for the workshop and this contribution to the proceedings. The
opinions expressed in this paper are my own.

References

[27] L L Frankfurt, M F McDermott & M Strikman, Diffractive Photoproduction of Υ at HERA, to be published shortly.