PHYSICS WITH CHARM QUARKS AT HERA

J. H.LOIZIDES
University College London,
Gower street,
London WC1E 6BT England
E-mail: jhl@hep.ucl.ac.uk

Measurements of charm production in deep inelastic scattering (DIS) and photoproduction have been carried out by the ZEUS and H1 collaborations at HERA. Protons at 920 GeV are collided with positrons of 27.5 GeV. Results using integrated luminosities up to 120 pb^{-1} for HERA I and 35 pb^{-1} for HERA II are presented. Single and double differential cross sections are compared to perturbative QCD (pQCD) predictions. Charm DIS and photoproduction cross sections are in reasonable agreement with pQCD calculations. Charm and jet angular correlations show regions of phase space where NLO is not sufficient to describe these data sets, indicating the need for improved calculations such as MC@NLO or NNLO predictions. Charm fragmentation ratios and fractions generally support the hypothesis that fragmentation proceeds independently from the hard sub-process in e^+e^- and ep collisions. This test of charm universality is confirmed by the measured D meson ground states at HERA and LEP. Stringent tests of QCD have been performed; theoretical errors dominate or are equivalent to experimental errors in the comparisons.

1. Introduction

The electron/positron-proton collider HERA at the DESY laboratory is a unique facility to test Quantum Chromo Dynamics (QCD) in a variety of measurements involving charm. The transition region between soft and hard interactions allows the possibility to better understand the present limits of applicability of perturbative QCD (pQCD).

When Q^2, the negative squared four momentum exchange at the electron/positron vertex, is small the reaction can be considered as a photoproduction process. Charm quarks in photoproduction and in deep inelastic scattering (DIS) have been extensively studied at HERA [1,2,3,4,5,6]. These measurements are consistent with pQCD calculations indicating boson-gluon fusion (BGF) as the dominant mechanism of charm production. Charm is mainly tagged in the 'golden' decay channel of the D^* meson

$D^{*+} \to K^- \pi^+ \pi^+$(+c.c.). More advanced instrumentation using secondary vertex tagging has been used to measure other charm cross sections at H1 [7]. ZEUS has first results in tagging of D mesons using the newly installed microvertex chamber from the recent running phase of HERA II. For more detailed information on heavy quark production such as BGF, resolved, 'massive' & 'massless' schemes see [8,9,10,12,13].

2. Inclusive charm production

The production cross sections of the charmed mesons $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$ have been measured by H1 [7]. The differential production cross sections for all four D mesons measured in the same kinematic region show similar dependence on transverse momentum $P_T(D)$ and the pseudo-rapidity $\eta(D)$ of the charmed hadron and Q^2. This similarity implies that the fragmentation fractions are independent of kinematics and can be measured from the integrated D meson cross sections. ZEUS has measured differential $D^{*\pm}$ meson cross sections as a function of Q^2 (fig. 1) across the transition region ($Q^2 \approx 1$ GeV^2) from DIS to photoproduction and compared to NLO predictions; there is good agreement throughout the entire range.

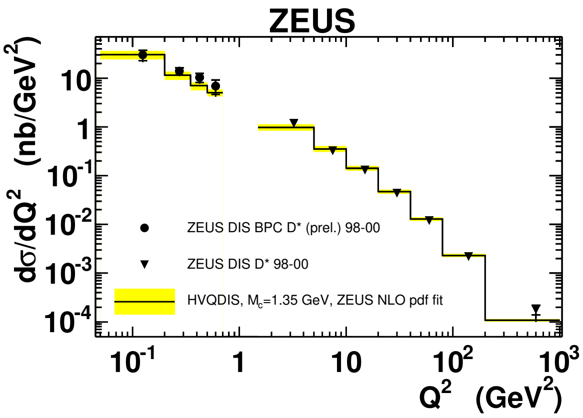

Figure 1. Differential D^* meson cross section as a function of Q^2 for low Q^2 and from previous results on D^* production at high Q^2 compared to the NLO predictions from the HVQDIS program.

Correspondingly ratios of the total production rates are used to test the isospin invariance of the fragmentation process and to extract the strangeness suppression factor γ_s (fig. 2), the fraction P_V of D-mesons produced in a vector state (fig. 3), and the ratio of neutral and charged D-meson production rates $R_{u/d}$ (fig. 4). The results are compared with values measured at e^+e^- colliders and allow tests of the assumed universality of the charm fragmentation process [7,14]. Table 1 shows the results of the branching fractions $f(c \to D^+)$, $f(c \to D^0)$, $f(c \to D_s^+)$, $f(c \to D^{*+})$ and $f(c \to \Lambda_c^+)$ (see fig. 5 for the invariant mass distribution of Λ_c candidates). The values at the different colliders are in good agreement, with competitive errors for γp; sometimes better than e^+e^- collision measurements. So the assumption that charm fragmentation fractions are universal is confirmed.

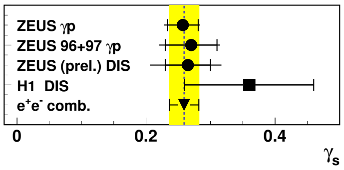

Figure 2. The strangeness-suppression factor in charm fragmentation, γ_s.

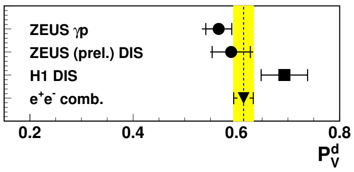

Figure 3. The fraction of charged D mesons produced in a vector state, P_{v}^d.

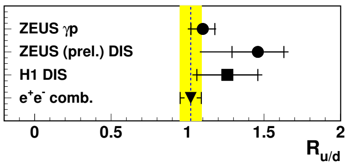

Figure 4. The ratio of neutral to charged D-meson production rates, $R_{u/d}$.

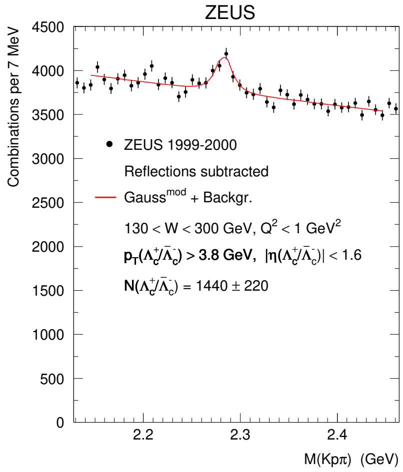

Figure 5. The $M(Kp\pi)$ distribution for the $\Lambda_c^+/\bar{\Lambda}_c^-$ candidates (dots). The solid curve represents a fit to the sum of a modified Gaussian function and a linear background function.

Table 1. The fractions of c quarks hadronising as a particular charm hadron, $f(c \to D, \Lambda_c)$. The fractions are shown for the D^+, D^0, D_s^+ and Λ_c^+ charm ground states and for the D^{*+} state.

	ZEUS (γp) $p_T(D,\Lambda_c) > 3.8\,\mathrm{GeV}$ $\lvert\eta(D,\Lambda_c)\rvert < 1.6$		Combined e^+e^- data [21]		H1 (DIS) [22]
	stat.	syst. br.	stat.$\oplus$ syst.	br.	total
$f(c \to D^+)$	0.217 ± 0.014	${}^{+0.013}_{-0.005}\,{}^{+0.014}_{-0.016}$	0.226 ± 0.010	${}^{+0.016}_{-0.014}$	0.203 ± 0.026
$f(c \to D^0)$	0.523 ± 0.021	${}^{+0.018}_{-0.017}\,{}^{+0.022}_{-0.032}$	0.557 ± 0.023	${}^{+0.014}_{-0.013}$	0.560 ± 0.046
$f(c \to D_s^+)$	0.095 ± 0.008	${}^{+0.005}_{-0.005}\,{}^{+0.026}_{-0.017}$	0.101 ± 0.009	${}^{+0.034}_{-0.020}$	0.151 ± 0.055
$f(c \to \Lambda_c^+)$	0.144 ± 0.022	${}^{+0.013}_{-0.022}\,{}^{+0.037}_{-0.025}$	0.076 ± 0.007	${}^{+0.027}_{-0.016}$	
$f(c \to D^{*+})$	0.200 ± 0.009	${}^{+0.008}_{-0.006}\,{}^{+0.008}_{-0.012}$	0.238 ± 0.007	${}^{+0.003}_{-0.003}$	0.263 ± 0.032

3. Charm jet cross sections in photoproduction

Differential inclusive D^* meson cross sections are not well described by pQCD predictions [18,19]. Therefore it is interesting to compare pQCD predictions for charm jets.

The predictions available are the 'massive' [9] scheme, where charm is produced only dynamically and there is no a priori charm in the proton or photon, and the 'massless' scheme [10], where charm is assumed to be massless and treated in the same manner as a light quark. Cross sections were measured double differentially as a function of E_T^{jet} and η^{jet} [20,11]. Both predictions describe the data well, with a slight excess seen at high values of E_T^{jet} compared to the 'massive' scheme. As the charm mass becomes small compared to the scale E_T^{jet}, this excess is not visible for the 'massless' calculation. Dijet correlation cross-sections $d\sigma/d\Delta\phi^{\rm jj}$ (fig. 6) show a large deviation from the massive NLO QCD prediction at low $\Delta\phi^{\rm jj}$ for the resolved-enriched ($x_\gamma^{\rm obs} < 0.75$) sample. These regions are expected to be particularly sensitive to higher-order effects. The HERWIG MC model which incorporates leading-order matrix elements followed by parton showers and hadronisation describes the shape of the measurements well. This indicates that for the precise description of charm dijet photoproduction higher-order calculations or the implementation of additional parton showers in current NLO calculations are needed.

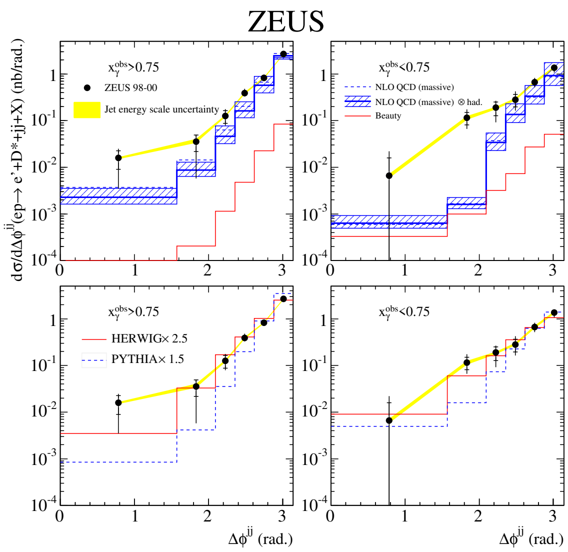

Figure 6. Cross-section $d\sigma/d\Delta\phi^{\rm jj}$ for ($ep \to e' + D^* + \text{jets} + X$), separated into direct enriched ($x_\gamma^{\rm obs} > 0.75$) and resolved enriched ($x_\gamma^{\rm obs} < 0.75$). The data (solid dots) are compared (top plots) to the massive QCD prediction with (solid line) and without (dotted line) hadronisation corrections applied. The theoretical uncertainties (hatched band) come from the change in scales simultaneously with the change in charm mass. The beauty component is also shown (upper histogram). The data are also compared (bottom plots) with HERWIG (solid line) and PYTHIA (dashed line) MC predictions are multiplied by the indicated factors.

4. Charm fragmentation functions

The hadronisation of a charm quark into a jet of particles consisting of a charmed meson and other mesons is not calculable in pQCD. The transition of a charm quark into a charmed meson is usually described by a phenomenological and non-perturbative fragmentation function, which is expected to be universal. One considerable source of uncertainty in comparing pQCD calculations in next-to-leading order (NLO) with data is due to the choice of fragmentation function and their parameters. Two widely used functions are the Peterson et al. (eq. 1) and the Kartvelishvili et al. function (eq. 2).

$$D_Q^H = \frac{N}{z[1-(1/z)-\epsilon(1-z)]^2} \ , \tag{1}$$

$$D_Q^H = N z^{\alpha}(1-z) \ . \tag{2}$$

The free parameters ϵ and α determine the 'hardness' of the respective fragmentation function. In these parameterisations, z describes the fraction of the charm quark's energy carried by the heavy meson.

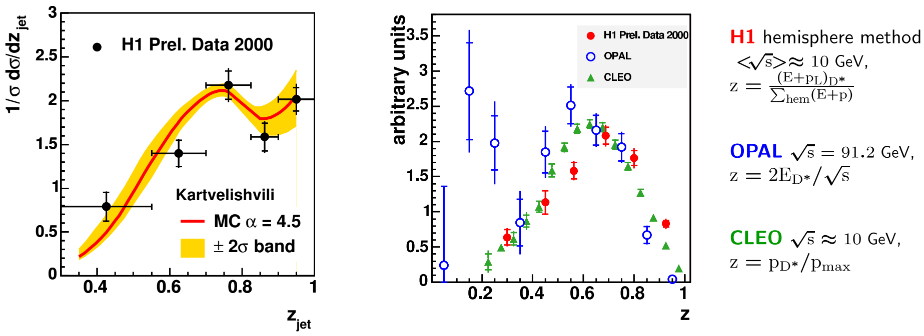

Figure 7. Measured D^* fragmentation function for jet method compared with RAPGAP model prediction using the Kartvelishvili parametrisation for non-perturbative fragmentation function (left plot). Comparison of the z-distributions from CLEO, OPAL and ALEPH with the one from the hemisphere method from H1. All distributions are normalised to unit area from $z = 0.4$ to $z = 1$ (right plot).

There are many observables sensitive to the non-perturbative fragmentation function, both in e^+e^- and ep collisions. In the case of e^+e^-, the natural choice is to measure the dependence of the D^* meson production cross section as a function of the variable z, defined as $z = E(D^*)/(\sqrt{s}/2)$.

In ep collisions this is not so obvious; H1 have considered two methods. Figure 7 shows the jet method where the energy and direction of the charm quark is approximated by reconstructing the jet which contains the D^* meson, where $z_{jet} = \frac{(E+p_L)_{D^*}}{(E+p)_{jet}}$. Another method is called the hemisphere method which allows the event to be split into two hemispheres. One hemisphere will contain the charm quark and the other the anti-charm quark, here z is defined as $z_{hem} = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)}$, where the denominator is the sum of all particles with momentum projections in the D^* hemisphere. More detailed information can be found elsewhere [23].

Table 2. The H1 extracted fragmentation parameters for Peterson and Kartvelishvili parametrisations, for RAPGAP/PYTHIA MC.

Parametrisation	Hemisphere Method	Jet Method	Range
Peterson	$0.018^{+0.004}_{-0.004}$	$0.030^{+0.006}_{-0.005}$	$0.014 < \epsilon < 0.036$
Kartvelishvili	$5.9^{+0.9}_{-0.6}$	$4.5^{+0.5}_{-0.5}$	$4 < \alpha < 6.8$

These data are compared to recent measurements in e^+e^- annihilations and are in rough agreement with the recent data from CLEO at a similar centre-of-mass energy for $c\overline{c}$ pair production. The difference at low z values in e^+e^- annihilations from OPAL is due to gluon splitting into $c\overline{c}$ pairs. The extracted values of ϵ and α span a large range (table 2); more data and a more rigorous approach is needed using NLO programs as well as theoretical developments such as MC@NLO in order to be able to attain a better understanding of fragmentation functions.

5. Charm Contribution to proton structure function F_2

The charm structure function $F_2^{c\overline{c}}$ [1,2] was extracted from:

$$F_{2,\mathrm{meas}}^{c\overline{c}}(x_i, Q^2) = \frac{\sigma_{i,\mathrm{meas}}(ep \to D^* X)}{\sigma_{i,\mathrm{theo}}(ep \to D^* X)} F_{2,\mathrm{theo}}^{c\overline{c}}(x_i, Q^2) \tag{3}$$

Latest results [17] are based on the impact parameter in the transverse plane, of tracks to the primary vertex, as measured by the H1 vertex detector. The ratio $F_2^{c\overline{c}}/F_2$ rises from 10% to 30% as Q^2 increases and x decreases. Figure 8 shows the $F_2^{c\overline{c}}$ results from ZEUS and H1 compared to the ZEUS NLO QCD fit.

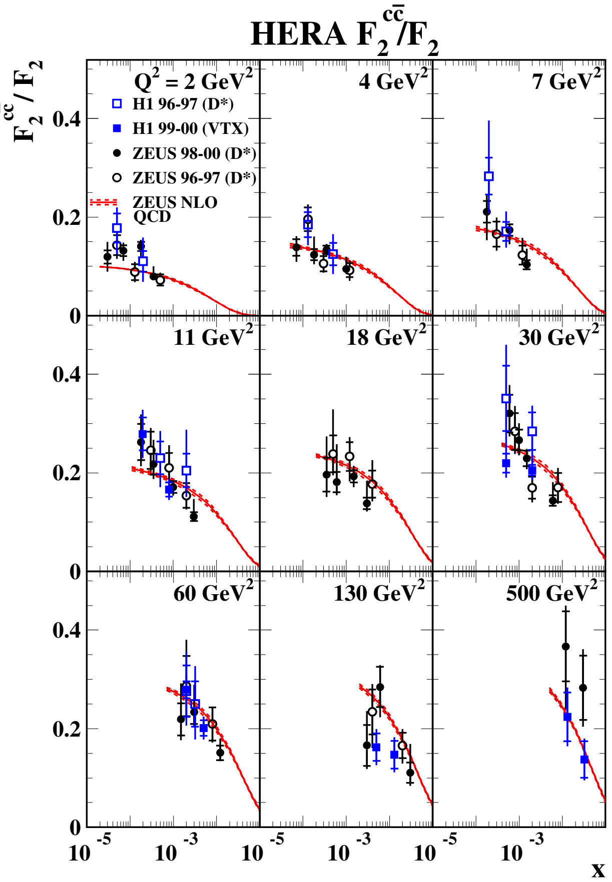

Figure 8. The $F_2^{c\bar{c}}$ results from H1, ZEUS are shown as a function of x for different bins of Q^2. The solid line represents the ZEUS NLO QCD fit with the uncertainties being the dashed lines.

Reduced experimental errors will allow these measurements to be used together with the inclusive F_2 measurements to additionally constrain the gluon density.

6. First look at HERA II data

In the most recently published ZEUS measurement [1] , made using 65 pb^{-1} e^+p data and 17 pb^{-1} e^-p data, it was observed that the D^* cross section was systematically higher in e^-p than in the e^+p data set, and rising with Q^2. Such a difference was not expected from any physics process, and so the phenomenon was treated as a statistical fluctuation. Figure 9 shows these results using the 1998-2000 data set and the newly collected 2003-2005 HERA II data where the e^-p luminosity is doubled with respect to the 1998-2000 data set. There is no evidence of any production rate anomaly in the HERA II data set.

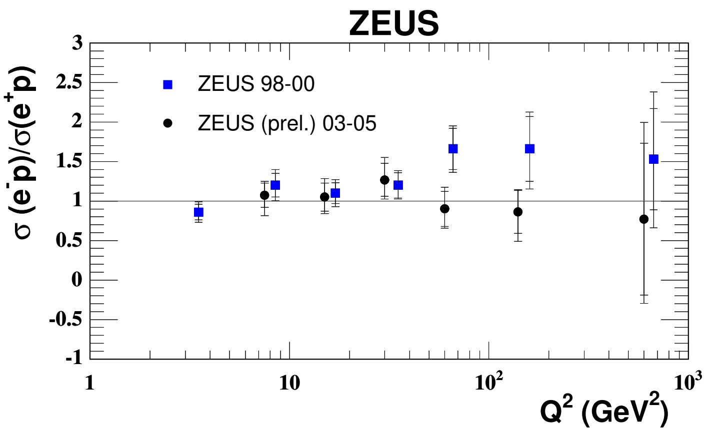

Figure 9. The ratio $\sigma(e^-p)/\sigma(e^+p)$ for the process $ep \to e' + D^* + X$, where $D^{*\pm} \to D^0, \pi_s^\pm$, and $D^0 \to K^\mp, \pi^\pm$ in the 2004-2005 running period (solid dots), compared to the ZEUS measurement for the 1998-2000 running period (solid squares).

7. Conclusions

There has been a wealth of charm physics produced at HERA from H1 and ZEUS providing stringent tests of pQCD. Charm fragmentation ratios and fractions generally support the hypothesis that fragmentation proceeds independently of the hard sub-process in ep and e^+e^- collisions. Fragmentation functions for D^* mesons have been measured and various models have been fitted to these distributions. Unfortunately, it is still unclear how one derives meaningful and applicable fragmentation functions to apply to theoretical predictions with the variation of these parameterisations being one of the largest theoretical uncertainties. Charm jet correlations show there are regions of phase space which cannot be described by NLO predictions, showing the need for improved theoretical predictions such as NNLO or MC@NLO. For these charm measurements, the theoretical errors dominate or are at best equivalent to experimental errors. The new additional instrumentation for ZEUS and higher luminosity being delivered by HERA will allow for more precise and new measurements to be made, with the aim of gaining further understanding of the production dynamics of heavy quarks in electron/positron-proton interactions.

References

1. [ZEUS Collaboration], S. Chekanov *et al.*, Phys. Rev. **D 69**, 012004 (2004).
2. [H1 Collaboration], C. Adloff et al., Phys. Lett. **B 528**, 199 (2002).
3. [ZEUS Collaboration], J. Breitweg et al., Phys. Lett. **B 481**, 213 (2000).
4. [ZEUS Collaboration], J. Breitweg et al., Eur. Phys. J. **C 12**, 35 (2000).
5. [H1 Collaboration], C. Adloff et al., Nucl. Phys. **B 545**, 21 (1999).
6. [ZEUS Collaboration], J. Breitweg et al., Eur. Phys. J. **C 6**, 67 (1999).
7. [H1 Collaboration], A. Aktas *et al.*, Eur. Phys. J. C **38**, 447 (2005), hep-ex/0408149.
8. B. W. Harris and J. Smith, Phys. Rev. **D 57**, 2806 (1998).
9. S. Frixione et al., Adv. Ser. Direct. High Energy Phys. **15**, 609 (1998).
10. G. Heinrich and B. Kniehl, Phys. Rev. **D 70**, 094035 (2004), hep-ph/0409303.
11. [H1 Collaboration],"Photoproduction of $D^{*\pm}$ Mesons Associated with a Jet at HERA," presented at DIS2005, Spring 2005.
12. M. Cacciari, S. Frixione and P. Nason, JHEP **0103**, 006 (2001), hep-ph/0102134.
13. S. Frixione and P. Nason, JHEP **0203**, 053 (2002), hep-ph/0201281.
14. [ZEUS Collaboration],"Measurement of charm fragmentation ratios and fractions in γp collisions at HERA", Lepton Photon 2005, PAPER-263.
15. [H1 Collaboration], "D^* Mesons and Associated Jet Production in Deep Inelastic Scattering," *Prepared for 32nd International Conference on High-Energy Physics (ICHEP 04), Beijing, China, 16-22 Aug 2004.*
16. [ZEUS Collaboration], S. Chekanov *et al.*, Eur. Phys. J. C **44**, 351 (2005), hep-ex/0508019.
17. [H1 Collaboration], A. Aktas *et al.*, Eur. Phys. J. C **40**, 349 (2005), hep-ex/0411046.
18. [ZEUS Collaboration], "Measurement of D^* photoproduction at HERA", submitted to ICHEP2002.
19. [H1 Collaboration], "Photoproduction of D^* Mesons at HERA", submitted to ICHEP2004.
20. [ZEUS Collaboration], S. Chekanov *et al.*, Nucl. Phys. B **729**, 492 (2005), hep-ex/0507089.
21. L. Gladilin, Preprint hep-ex/9912064 (1999).
22. [H1 Collaboration], A. Aktas et al., Eur. Phys. J. **C 38**, 447 (2005).
23. [H1 Collaboration],"The Charm Fragmentation Function in DIS," presented at DIS2005, Spring 2005.