HEAVY FLAVOUR PRODUCTION AT HERA

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Abstract

Recent results from the experiments ZEUS and H1 on charm production in \( ep \) collisions are reviewed. The topics are elastic and inelastic \( J/\psi \) photoproduction, \( D^* \) photoproduction differential cross sections and a first look at the proton structure function \( F_2^{c\bar{c}} \).

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1 Introduction

The production of heavy quarks in electron proton interactions proceeds, in QCD, almost exclusively via photon gluon fusion, where a photon emitted from the incoming electron interacts with a gluon in the proton by forming a quark-antiquark pair. Therefore, heavy quarks, in particular charm, offer the classical way \[1, 2\] towards a determination of the gluon density in the proton.

Beauty production, with respect to charm, is expected \[3\] to be suppressed by about two orders of magnitude: at HERA, for \(\sqrt{s} = 300\) GeV, cross sections are \(\sigma(ep \to c\bar{c}) \approx 1\mu\text{b}\) and \(\sigma(ep \to b\bar{b}) \approx 5\text{nb}\). No indication of \(b\) or \(\Upsilon\) production has been reported by neither the H1 nor ZEUS collaboration up to now. With the total luminosity accumulated so far \(10\) pb\(^{-1}\), the era of HERA \(b\) physics has not yet started. (Truth production will never happen at HERA, obviously.)

Consequently, this talk deals with charm only, with the production of hidden charm in the first, with open charm in the second part. In section 2, elastic and inelastic \(J/\psi\) production are discussed, in section 3 new results on \(D^*\) photoproduction are presented, and a first measurement of the proton structure function \(F_2^{c\bar{c}}\) is shown.

2 Hidden Charm

HERA Kinematics: At HERA, electrons (or positrons) of energy 27 GeV collide head-on with 820 GeV protons, providing a center-of-mass energy \(\sqrt{s} = 300\) GeV. The kinematics of deep inelastic scattering (DIS) is described using the well-known Lorentz invariants \(Q^2 = -q^2\) and \(x = Q^2/(2pq)\), where \(p\) is the 4-momentum of the incoming proton and \(q\) that of the exchanged photon. The scaling variable \(y\) is related to these by \(Q^2 = xys\). In the photoproduction limit \(Q^2 \approx 0\), as in the DIS case, typical photon-proton center-of-mass energies \(W\) are 100 - 200 GeV. HERA thus extends the range of fixed-target photoproduction experiments by an order of magnitude. Consequently, given the same scale of the partonic subprocess, the parton densities in the proton are probed at much smaller momentum fractions of the parton in the proton, \(x_p \sim 10^{-3}\).

Classification: To the photoproduction of \(J/\psi\) mesons, several processes contribute which lead to well distinguished experimental signatures. In the elastic process \(\gamma p \to J/\psi p\), the proton stays intact and leaves the detector through the beam-pipe, such that nothing but the \(J/\psi\) decay products is detected. The scattering is diffractive, i.e. only 4-momentum is transferred to the proton, no color is exchanged. Diffractive processes
where the proton breaks up ("diffractive p-dissociation") constitute a background to the exclusive elastic reaction. It can however effectively be suppressed by rejecting events where apart from the $J/\psi$, proton debris is detected under very small angles.

In contrast, in the inelastic case a hard gluon from the proton interacts with the photon to form the $c\bar{c}$ pair. According to the color singlet model [4] another gluon has to be subsequently radiated, in order to restore the $J/\psi$ color quantum numbers. The inelastic process involves color flow between the proton and the charm system, and after hadronization energy depositions are spread over wider regions of the detector.

The processes may also be separated by use of the elasticity variable $z$ that can be calculated from the longitudinal momenta of the $J/\psi$ products and of all final state particles: $z = (E - p_z)_{J/\psi}/(E - p_z)_{\text{all}}$. Elastic production gives $z \approx 1$, for diffractive dissociation $z$ is smaller, but still close to 1. Inelastic production leads to values $0 < z < 1$. There is also a so-called resolved contribution, where the photon fluctuates into a hadronic state and a parton from that state interacts with the proton. These processes cluster at small $z$ and can thus be suppressed by a lower cut on this variable.

### 2.1 Elastic $J/\psi$ production

The ZEUS and H1 experiments have meanwhile – with integrated luminosities of about 3 pb$^{-1}$ collected in 94 – accumulated samples of order 1000 elastic events each, where the $J/\psi$ mesons are reconstructed in the decay channels $J/\psi \rightarrow \mu^+\mu^-, e^+e^-$. The measured cross sections are corrected for remaining contaminations from diffractive dissociation ((17$^{+8}_{-5}$ ± 10)% and (12 ± 12)% for ZEUS and H1, respectively) and for feed-down from $\psi'$ decays. The results [5, 6] are displayed as a function of the $\gamma p$ center-of-mass energy $W$ in Fig. 1a together with results from fixed-target experiments [7]. The cross section exhibits a steep rise that cannot be explained in the framework of a soft vector meson dominance model [8] where an energy dependence $\sigma_{el} \sim W^{4\epsilon}$ with $\epsilon \approx 0.08$ is expected. This conclusion can be drawn from the HERA data alone.

Ryskin and co-workers have argued [9] that due to the high scale of the process given by $Q^2_0 = M^2_{J/\psi}/4$, perturbative QCD methods should be applicable. In their model, a gluon ladder diagram gives the dominant contribution to the cross section, which is therefore found to be proportional to the square of the gluon density in the proton: $\sigma_{el} \sim [g(x)]^2$ with $x = M^2_{J/\psi}/W^2 \sim 10^{-3}$. Recent leading order (LO) calculations in the Ryskin model, including some next-to-leading (NLO) effects [10], are also displayed in Fig. 1a; using different parameterizations of the gluon density in the proton [11] [12], which are all
Figure 1: Elastic $J/\psi$ photoproduction cross section, measured at fixed target and HERA experiments, versus $\gamma p$ center-of-mass energy. The curves are the QCD predictions of the gluon ladder model [10] (a) and of the color octet model [15] (b).

consistent with inclusive structure function measurements at HERA [13]. The model can reproduce the steep rise of the cross section with $W$. The potentially high sensitivity of the elastic $J/\psi$ cross section as a probe of the gluon density is clearly illustrated. However, before this can be used as a measurement of $g(x)$, a better understanding of the model uncertainties has to be gained.

A complementary approach is provided by the non-relativistic QCD (NRQCD) scheme developed by Bodwin, Braaten and Lepage [14]. Here, the $J/\psi$ production amplitude is factorized into a hard boson-gluon fusion part – yielding a $c\bar{c}$ system in a color octet state in the first place – and a soft part that describes the subsequent transition of the octet state into a color singlet $J/\psi$ meson. The latter transition is described by color octet matrix elements, the cross section is symbolically written as $\sigma \sim g(x) \cdot \sum [n] \langle 0 | O_{\Delta[n]} | 0 \rangle$, where $[n]$ runs over the dominating angular momentum states. The matrix elements are treated as phenomenological parameters; fitting them to lower energy data gives a
Figure 2: a) Inelastic $J/\psi$ photoproduction cross section versus $W$. The curves are NLO QCD predictions for two different sets of parton density parameterizations. b) Inelastic $J/\psi$ cross section versus elasticity $z$, together with QCD calculations of color singlet and possible octet contributions (see text).

prediction [15] for the HERA regime. This is shown in Fig. 1b together with the same data as in Fig. 1a. Again, a good description of the measurements is obtained, using, for example, the parton density parameterization set MRS(A') [11]. Note, however, that in this model the cross section depends linearly on the gluon density $g(x)$. – The theoretical debate on how to best describe elastic $J/\psi$ photoproduction is open at present.

2.2 Inelastic $J/\psi$ production

Cross section measurements done by ZEUS [16] and H1 [6] for inelastic $J/\psi$ production in the range $z < 0.9$ are shown as a function of $W$ in Fig. 2a and compared to next-to-leading order QCD calculations [17].

The measurements are done at $z$ above 0.4 typically and extrapolated to $z = 0$; the correction is about 10%. The agreement with NLO QCD is best when a steeply rising gluon density distribution (like MRS(G) [11]) is used, together with a low value of the
charm quark mass and a rather large strong coupling constant. Nevertheless, the NLO calculation still falls short in describing the normalization of the data by some amount, indicating that contributions from even higher orders may be significant. The calculation is considered most reliable in the region where the NLO corrections are small, this is for $z < 0.8$ and transverse momenta of the $J/\psi$ $p_\perp > 1$ GeV/c. The H1 measurements in this restricted range are in very good agreement with NLO QCD, but the sensitivity to the gluon density in the proton is much reduced.

The $z$ dependence of the cross section is sensitive to possible color octet contributions to $J/\psi$ production. Such processes have recently been proposed [18] to explain the high quarkonium production rates observed at the Tevatron. The differential cross section $d\sigma/dz$ has been measured by H1 and is shown in Fig. 2b, together with calculations [19] drawn separately for the familiar color singlet contributions and for color octet contributions. The color octet matrix elements used in the calculation were extracted from fits to prompt $J/\psi$ production data from the Tevatron [20]. The measured distribution clearly disfavors large color octet contributions to inelastic $J/\psi$ production at HERA.

3 Open Charm

3.1 $D^*$ photoproduction

Photoproduction of open charm occurs via direct photon gluon fusion, $\gamma g \to c\bar{c}$ or via resolved processes where a parton inside the photon scatters off a parton inside the proton, e.g. $gg \to c\bar{c}$. The latter are known to dominate the production of light quarks, but are expected to contribute much less to heavy quark production. Due to the smaller available energy of the parton from the photon side, and the consequently lower center-of-mass energy of the hard subprocess, the resolved events are characterized by a stronger boost into the proton direction and smaller transverse momenta $p_\perp$. The experimental cuts limit the measurement to central rapidities and large $p_\perp$ and thus additionally suppress the resolved contribution to a level of below 10 % typically.

Both ZEUS and H1 have tagged $c\bar{c}$ events through the detection of muons from semileptonic decays and through reconstruction of $D^*$ decays, and derived cross sections from the two methods. The published results [21, 22] that take advantage of the well known clean signature of the decay chain $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$ are more precise than the so far presented (preliminary) inclusive muon data which suffer from higher background [23].

The new H1 analysis of 94 data exploits a $D^*$ signal of more than 200 events in the
kinematical region $p_\perp(D^*) > 2.5 \text{ GeV/c}$ and rapidity $-1.5 < \hat{y} < 1$. The measurement is done for the case where the scattered positron is either registered in the electron detector of the luminosity system ("tagged"), or not required to be seen at all ("untagged"). The total charm cross section is shown as a function of the $\gamma p$ center-of-mass energy $W$ in Fig. 3, together with the ZEUS result (using 93 data) \cite{21} and previous fixed target measurements \cite{24}. The cross section rises strongly with energy; at HERA it is about an order of magnitude higher than at fixed target energies.

There are however large extrapolation factors involved in the transformation from the visible $p_\perp$ and $\hat{y}$ range to total cross sections. These give rise to large systematic errors associated with uncertainties in the parton distributions in the proton and the photon. They are included in the total errors in Fig. 3a, the inner error bars of the H1 data indicate the experimental errors alone. The following example may illustrate the dependences. The H1 measurement with tagged data, at $W = 200 \text{ GeV}$, would change from $(12.2 \pm 2.0 \pm 1.8) \mu\text{b}$ to $(7.4 \pm 1.2 \pm 1.1) \mu\text{b}$, if the parton density parameterization MRS(D0') instead of the steeper MRS(A') set \cite{11} were used for the extrapolation. However, the QCD prediction changes in the same direction: from $9.8 \mu\text{b}$ to $3.9 \mu\text{b}$, respectively. A similar picture is obtained for variations of the parton densities in the photon. Hence the total cross section is not well suited for the determination of gluon densities.

**Differential cross sections:** H1 has therefore returned to the visible kinematic range that is free of extrapolation uncertainties and measured differential cross sections \cite{22}. The $p_\perp$ distribution is shown in Fig. 3b and compared to NLO QCD calculations using the program of S. Frixione et al. \cite{25}. The data are in good agreement with QCD. The figure illustrates that the value for the charm mass used in the calculation mainly affects the region of low $p_\perp < 3 \text{ GeV}$. – The rapidity distribution is displayed in Fig. 3c together with the results of NLO QCD calculations where the gluon density has been varied in the proton (dashed histogram), or in the photon (dotted). The backward region of negative rapidities is most sensitive to the parton content of the proton, whereas the effect of the photon structure is most pronounced in the forward direction, outside the visible range shown. The agreement between data and theory is only marginal here. This may give rise to speculations about possible contributions from the excitation of intrinsic charm in the photon \cite{26}; the experimental errors are however still too large to draw firm conclusions.

**Diffractive production:** H1 has found first evidence for diffractive charm photoproduction at HERA, by searching for $D^*$ mesons in (untagged) $\gamma p$ events with a rapidity gap. The selection requires the pseudo-rapidity of the most forward calorimetric energy deposition to be $\eta_{\text{max}} < 2$, as in \cite{27}. A clear signal is found in the mass difference distri-
Figure 3: a) Total $\gamma p \rightarrow c\bar{c}X$ cross section versus $\gamma p$ center-of-mass energy $W$. The curves are NLO QCD predictions for different factorization and renormalization scales $\mu$. b) Differential charm cross section versus $p_t$. The histograms are NLO QCD predictions for different values of the charm quark mass. c) Differential charm cross section versus rapidity. The histograms are NLO QCD predictions for different parameterizations of the parton densities, showing the effect of varying the proton (dashed vs. full) or photon (dotted vs. full) densities.
Figure 4: a) $D^*$ signal in the invariant mass difference $\Delta M = M(K\pi\pi) - M(K\pi)$ for photoproduction events with a rapidity gap. The hatched histogram indicates the background estimated from wrong charge combinations. b) Background subtracted $\eta_{\text{max}}$ distribution of $D^*$ events. The histograms are Monte Carlo predictions (hatched: PYTHIA [28], open: RAPGAP [29]) normalized to the data (see text).

3.2 Open charm in DIS: $F_2^{c\bar{c}}$

Charmed mesons have also been observed by H1 [30] and ZEUS in deep inelastic scattering. Here the outgoing electron is measured in the central detectors and the kinematics ($x, Q^2$) of the scattering process is determined from the measured electron energy and direction. In addition to the $D^*$ channel measured also in photoproduction, a $D^0$ signal from the decay $D^0 \rightarrow K^-\pi^+$ has been seen in the $M(K^-\pi^+)$ invariant mass distribution. For
$Q^2 > 10 \text{ GeV}^2$, H1 quotes from their 94 data inclusive cross sections\footnote{Charge conjugate states are implicitly included.} of $\sigma(ep \to eD^{\ast+}X) = (9.6 \pm 1.1 \pm 1.3)$ pb and $\sigma(ep \to eD^0X) = (22.5 \pm 3.6 \pm 2.9)$ pb the ratio of the two being about as expected.

The statistics of about 100 events in each channel permits to separate the data into a small number of bins in $x$ and $Q^2$. From the double differential cross section the charm contribution $F^{c\bar{c}}_2$ to the proton structure function is extracted, using the the parton model formula

$$
\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha}{xQ^4} \left(1 + (1 - y)^2\right) \cdot F^{c\bar{c}}_2(x, Q^2) \hspace{1cm} (1)
$$

The result is shown in Fig. 5. In the probed range, $F^{c\bar{c}}_2$ amounts to around 20% of the total $F_2$. The systematic errors include those arising from the charm signal extraction (background shape, branching ratio) as well as those associated with the electron measurement (calibration, bin center and radiative corrections). For comparison, NLO QCD calculations\cite{31} using two different structure function parameterizations are also shown, resulting from either a flat (CTEQ2MF\cite{32}) or steep (GRV\cite{12}) gluon distribution. The error bands reflect the uncertainties due to variation of the charm mass in the calculation (between 1.3 and 1.7 GeV).

$F^{c\bar{c}}_2$ is defined irrespective of the production mechanism, but the predominant mechanism is again boson gluon fusion. Other contributions – scattering off a possible intrinsic charm content of the proton, or gluon splitting into $c\bar{c}$ pairs – are expected to be small, as supported by earlier muoproduction data\cite{1} and recent $e^+e^-$ results\cite{33}. Therefore $F^{c\bar{c}}_2$ is an almost purely gluonic observable and can provide powerful constraints on the proton structure.

\section{Conclusion}

New results in the area of hidden and open charm are emerging from the experiments ZEUS and H1 at HERA. Elastic $J/\psi$ production exhibits a very clean experimental signature, and in some models it offers a temptingly high sensitivity to the gluon density in the proton. However, the theoretical discussion on how to assess the model uncertainties has not yet settled. Inelastic $J/\psi$ production is found in agreement with next-to-leading order QCD. The measured elasticity distribution at HERA disfavors large color octet contributions.
Figure 5: Charm contribution $F_2^c$ to the proton structure function. The curves are two different structure function parameterizations, the error bands reflect the uncertainties due to variation of the charm mass.
Charmed mesons have been measured in photoproduction and deep inelastic scattering. The total cross section $\sigma(\gamma p \rightarrow c\bar{c})$ is subject to large extrapolation uncertainties. H1 had a first look at rapidity and $p_\perp$ distributions, they are in rough agreement with NLO QCD. First evidence for diffractive charm photoproduction has been presented. In DIS, a first measurement of the charm contribution $F_2^{c\bar{c}}$ to the proton structure has been made at HERA.

Charm production at HERA thus allows to test and extend our understanding of heavy quark production in terms of QCD, and it holds the promise of providing direct determinations of the gluon density in the proton in the near future. The results presented here demonstrate that this is progressing well along a variety of ways.

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