Charm Production at HERA

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Selected recent measurements of charm quark production in lepton-proton collisions performed at HERA by the experiments H1 and ZEUS are reviewed. The experimental results are compared in detail with theoretical predictions, based on QCD calculations in both leading order and next-to-leading order perturbative approaches. No large deviations from the expectations were observed within the theoretical uncertainties.

Results on inelastic leptoproduction of J/ψ mesons are directly compared with predictions based on NRQCD/factorisation approaches. A search for colour octet processes predicted within this approach is conducted in many regions of phase space, but no unambiguous evidence has been found.

1. Introduction

One of the main interests in studying heavy flavours (HF) at the HERA $e-p$ collider is the investigation of the production mechanisms and detailed comparisons with theoretical predictions, in particular with perturbative QCD calculations, and extended studies of non-perturbative phenomena.

The kinematics of HF production is described by three independent variables, the centre-of-mass energy $\sqrt{s}$, the photon four-momentum squared $q^2 = -Q^2$ and either one of the scaling variables $y = (q \cdot P/l \cdot P)$, the inelasticity of the ep-interaction, or Bjorken-x, $x = Q^2/(2P \cdot l)$. Here P and l denote the four-momentum of the proton and the electron[1], respectively. The $\gamma - p$ centre-of-mass energy squared is given by $W_{\gamma p}^2 = W^2 \approx y \cdot s - Q^2$.

The results presented here are based upon data recorded by the H1 [1] and ZEUS [2] collaborations during 1996 through 2000, with an $e-p$ centre-of-mass energy $\sqrt{s} = 300$ GeV and 318 GeV, in the kinematic regimes of photoproduction ($Q^2 \approx 0$) and deep inelastic scattering (DIS, at large Q^2).

[1]Hereafter, a reference to electron implies a reference to either electron or positron. Most of the results shown were obtained in positron-proton collisions.

2. Open Charm Production

2.1. Production Mechanism and Theories

The description of open charm production is based on perturbative QCD (pQCD). At HERA charmed quarks are produced predominantly by the direct *photon gluon fusion* (BGF) process $\gamma g \rightarrow c\bar{c}$, where a real or virtual photon emitted by the electron and a gluon from the proton generate a $c\bar{c}$ pair. In photoproduction, resolved photon interactions contribute as well and lead to the notion of a photon structure function. However, beyond this LO *only the sum* of direct and resolved processes is a well-defined quantity. The heavy quarks then hadronise and are either detected as "open states", i.e., in final states with charmed hadrons, or alternatively as "hidden states", such as J/Ψ .

One of the QCD calculations in NLO of interest here, is the *massive approach* [3], which is a fixed order (FO in α_s) pQCD calculation with a massive charm quark. The massive calculations are expected to break down for large scales $p_T \gg m_c$ because no large-p_T resummation is done.

Recently, for the photoproduction regime, an extended approach has become available. This so-called "matched calculation" (FONLL) [4] complements the FO-calculations by adding next-to-leading log (NLL) correction terms.

The available Monte Carlo simulation programs are based on the LO processes (BGF and resolved in some cases). Traditionally, they are based on DGLAP-evolution equations and leading-log parton showers, such as the implementations AROMA, HERWIG and PYTHIA.

2.2. Inclusive D-meson Production

D mesons are identified in the H1 and ZEUS detectors by exclusive reconstruction of the relevant decay chains $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$, $D_s \rightarrow \phi\pi$ and $D^+ \rightarrow K^-\pi^+\pi^+$ in the *visible* kinematic regions limited in $p_t(D)$ and rapidity $\hat{y}(D)$.

The single differential production cross section distributions measured by ZEUS [5] are shown in Fig. 1 for $Q^2 < 1$ GeV^2, $\mid \hat{y}(D) \mid < 1.6$, $1.9 < p_t(D) < 20$ GeV and $130 < W < 285$ GeV.

Overlaid are the predictions by the NLO QCD calculations[2], in FO [3] (solid) and in FONLL [4] (dotted). In general the ZEUS data are reasonably well reproduced by both FO and FONLL, which are very similar in shape. However, the predictions tend to be below the data, slightly more so in the case of FONLL. There remain some discrepancies in the forward region, the clarification of which requires more studies.

H1 studied the inclusive production of D-mesons in DIS [6] based on about 48 pb^{-1} of data taken in 1999 and 2000. Inclusive production cross sections are measured for the vector D^{*+} and for the pseudoscalar mesons D^0, D_S and, for the first time at HERA, also D^+. The long lifetimes of the pseudoscalar mesons lead to a separation of their production and decay vertices, which is exploited to distinguish signal and background processes and to substantially improve the signal qualities. This is illustrated in Fig. 2(top), which shows the D^+ signal with and without a vertex separation significance requirement. The resulting single differential distribution for the

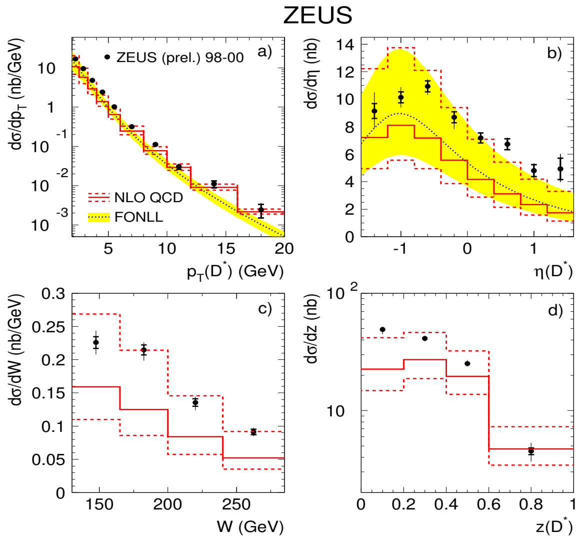

Figure 1. Single differential D^* photoproduction cross sections compared with FO and FONLL QCD calculations; central choice of QCD predictions are given by solid (FO) and dotted (FONLL) histograms, with the bounds indicated separately for FO (dashed) and FONLL (band).

D^+-channel are presented in Fig. 2 for the visible kinematic range of $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$, $|\eta_{D^*}| < 1.5$ and $p_{t\ D^*} > 2.5$ GeV.

The LO QCD predictions (Aroma MC) overlaid in Fig. 2 (dark band) show rather good agreement with the measurements.

2.3. Studies of fragmentation

The question of the universality of non-perturbative fragmentation effects has been addressed by both ZEUS and H1. ZEUS studied the distribution of the energy fraction $z = (E+p_L)[D]/(E+p_L[jet])$ in D^*-meson photoproduction [7]. Within the framework of the LO simulation (in Pythia) complemented by a Peterson fragmentation parametrisation, a direct comparison allowed the extraction of an optimal fragmentation parameter $\epsilon_{Pete} = (0.064 \pm 0.006^{+0.011}_{-0.008})$, that compares pretty well with values measured in e^+e^-. H1 measured several differential cross section distributions [6] that allowed the determination of ratios of various D-meson quark and spin states, and subsequent comparisons with the numbers observed at e^+e^--colliders.

[2]The renormalisation scale μ_r, the hadron and photon factorization scales μ_{Fh} and $\mu_{F\gamma}$ are customarily given relative to the charm quark mass m_c. Here the values are: $\mu = m_T = \sqrt{m_c^2 + p_t^2}$; and $\mu_r = \mu; \mu_{Fh} = \mu_{F\gamma} = 2\mu$.

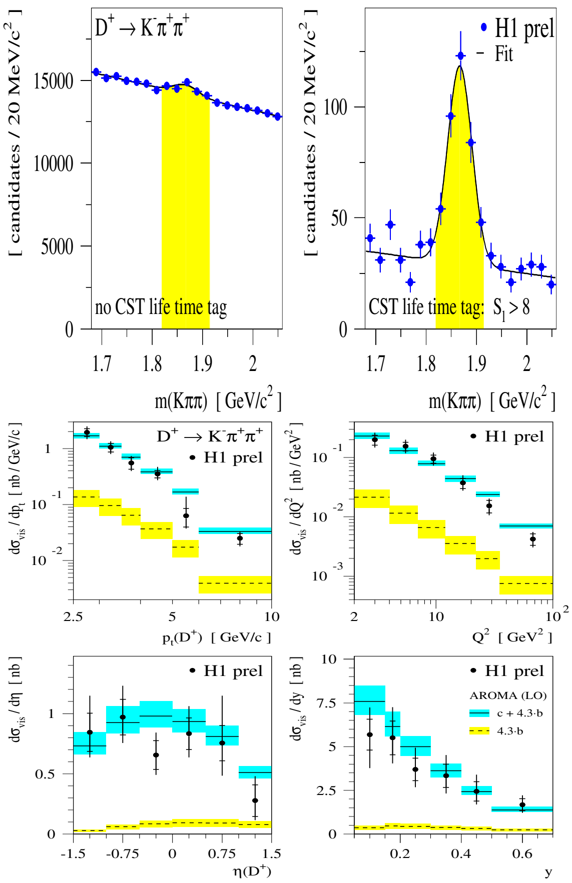

Figure 2. H1 data: D^+ signal signal enhancement (top) by a vertex separation significance requirement; differential D^+ production cross sections (bottom: solid dots), compared with the LO predictions (dark band).

All these measurements support the hypothesis that the charm fragmentation process is universal, e.g., the results from e^+e^- can be applied to ep-processes.

3. Inelastic Charmonium Production

One of the main interests in the leptoproduction of J/Ψ mesons is a clarification of its production process.

Experimentally, inelastic production processes are selected by means of the *inelasticity* variable $z \equiv \frac{q \cdot P_\psi}{q \cdot P}$, where P_ψ is the four-momentum of the J/ψ meson. The J/ψ mesons are identified by their decays to lepton pairs.

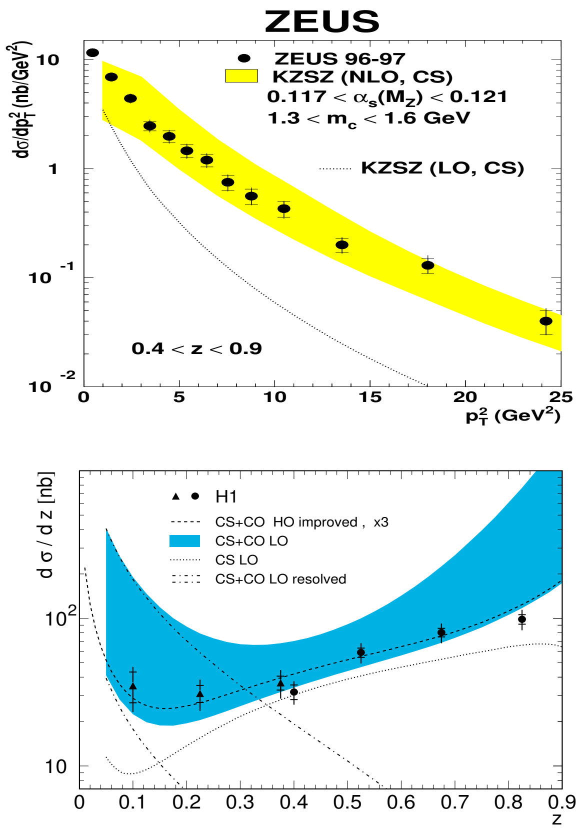

Figure 3. Inelastic J/ψ photoproduction cross-sections measured as functions of $p_t^2(J/\Psi\ )$ by ZEUS (top) and z by H1 (bottom). Overlaid are the predictions based on and NLO (top) and LO (bottom) QCD calculations.

In the theoretically favoured NRQCD/ factorization approach [9], the cross section is described by $\sigma(\gamma p \to J/\psi X) = \sum \langle \mathcal{O}[n] \rangle \cdot \hat{\sigma}(\gamma p \to c\bar{c}[n] X)$, where $\langle \mathcal{O}[n] \rangle$ are the NRQCD long distance matrix elements (LDME) and $\hat{\sigma}$ the short distance coefficients, calculable in pQCD, with n being the quantum numbers of the colour state, ${}^{2S+1}L_J$.

This NRQCD-approach contains both the traditional colour-singlet model [10,11] (CSM) and the colour-octet model [12] (COM) where the transition from the coloured $c\bar{c}$ state produced in the hard sub-process to the colour-singlet final state proceeds non-perturbatively.

Since CO-contributions $\langle \mathcal{O}[8] \rangle$ are believed to be universal, they can be determined with data at e.g. the Tevatron [13] and applied to HERA data. Thus a measure of these CO-contributions at HERA provides a very sensitive test for the consistency of the model.

The p_T^2-dependence of the cross sections have been measured by both H1 [15,16] and ZEUS [17]. As an example the results by ZEUS are shown in fig 3 (top) and compared with both LO and NLO predictions [10,11,14] within the CSM. The LO contribution alone is too low, whereas the NLO calculations describe the data pretty well within the (rather large) theoretical uncertainties, indicated by the band.

Differential cross section $d\sigma/dz$ measured by H1 are shown in Fig. 3 (bottom) for a large z-range ($z > 0.1$), and compared with LO theoretical calculations within the NRQCD/factorization framework [14]. Direct photon contributions as well as resolved processes are included and shown separately. At z above 0.3 direct photon contributions dominate and the CO contribution is dominant at $z \geq 0.6$. In order to describe the shape, the addition of CO contributions helps, as does a specific choice of quite small LDMEs, however the normalisations are still too low calling for large k-factors.

The number of parameters entering these comparisons is large, and thus the presently available measurements do not allow one to distinguish between different models yet.

4. Summary and Conclusions

The production of charm quarks in ep-collisions at HERA has been studied by identifying charm in the form of D- and J/ψ-mesons. In the overall picture, the hard nature of the charm production process appears to be firmly established, and thus yields reasonable predictions for the total production rates. The shape of differential distributions is in general reasonably well predicted by the pQCD calculations, with possible exceptions at large η-values, although the predictions tend to be below the data.

In the case of inelastic J/Ψ meson production, the NLO calculations based on NRQCD/factorization with colour-singlet contributions alone describe the data well within errors, thus exhibiting no indications of colour-octet contributions.

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