Heavy quark production and spectroscopy at HERA

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Heavy flavour production and spectroscopy are key components of the HERA physics programme. I will summarise a selection of the recent results obtained by the H1 and ZEUS collaborations. The production of excited charm mesons and J/ψ will be discussed as well as measurements of b quark cross-sections in photoproduction. The status of searches for exotic bound states and the D^*p resonance will be updated.

1. INTRODUCTION

Heavy flavour production in $e^{\pm}p$ collisions at HERA provides a good testing ground of perturbative Quantum Chromodynamics (pQCD) as the high quark mass provides a hard scale. Furthermore, other hard scales such as Q^2, the virtuality of the exchanged boson, or p_t, the transverse momentum of the heavy quark, allow resummation techniques to be tested. Measurements of production rate and kinematic properties of heavy quark bound states such as charmonium also give direct access to the non-perturbative part of the production process. New theoretical models can also be tested by searches for exotic bound states like the D^*p resonance.

Different kinematic variables are used to describe the ep interaction at HERA: Q^2, the Bjorken scaling variable, x, and the inelasticity, y. Until 1997 HERA ran at a centre-of-mass energy of $\sqrt{s} = 300\,\text{GeV}$. This energy was increased to $\sqrt{s} = 320\,\text{GeV}$ for data taken from 1998 onwards. Due to improvements of the detector and accelerator during a break in the data taking, the available dataset is split into two periods. In the HERA I period from 1996 until 2000 about $130\,\text{pb}^{-1}$ and between 2003 and 2007 of HERA II about $400\,\text{pb}^{-1}$ per experiment were collected.

The kinematic range of the analysed data can be separated in the following two regimes: photoproduction (γp), where the exchanged photon in the process is almost real, and deep inelastic scattering (DIS), where the exchanged photon is virtual. Experimentally, γp is defined by the scattered electron not being in the acceptance region of the detector, corresponding to a cut $Q^2 \lesssim 1\,\text{GeV}^2$.

2. THEORY

There are different approaches for the calculation of heavy flavour production in next-to-leading order perturbative QCD. The massive approach assumes no initial charm or beauty in the proton (or photon). Heavy flavours are only generated dynamically from the gluon distribution. This approach is particularly valid if the heavy quark mass is of the order of other hard scales like Q^2 or the transverse momentum p_t of the heavy quarks. In the massless approach, the leading-logarithmic and next-to-leading logarithmic terms for example in $\alpha_s \log Q^2/m^2_{c,b}$ are resummed. This approach assumes the heavy quark to be massless and is therefore only valid if other quantities like Q^2 or p_t provide the dominant scale. Models using the k_T factorisation approach [1] are based on non-collinear parton dynamics based on the CCFM [2] evolution equations. In heavy quark bound states like charmonium, only the production of the $c\bar{c}$ pair can be described in pQCD, whereas the formation of the J/ψ bound state which occurs at long distances has to be described by phenomenological models. In the framework of non-relativistic QCD (NRQCD) [3] so-called colour singlet (CS) and colour octet (CO) states coexist. In the spectroscopy of heavy quark bound states containing only one heavy quark, Heavy Quark Effective Theory (HQET) is used to predict the production and decay properties.

3. BEAUTY IN PHOTOPRODUCTION

An important test of pQCD is provided by open heavy flavour production. In Figure 1 the measurements of the beauty cross section in photoproduction of both the H1 and the ZEUS collaborations are shown as a function of the b quark transverse momentum, p_T. The analyses used different datasets, techniques and decay channels providing independent measurements cross-checking each other. The different measurements agree well with each other and are in reasonable agreement with the NLO prediction from FMNR[4]. They cover a wide range in p_T^b giving a consistent picture of b quark photoproduction.

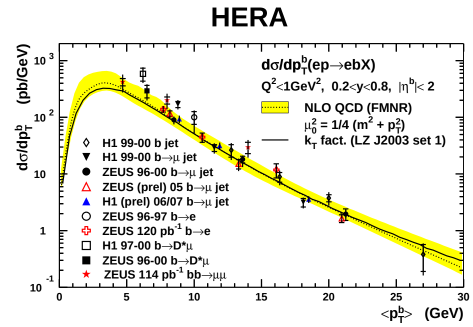

Figure 1: Cross sections for beauty production as a function of p_T^b from various decay channels.

4. INELASTIC J/ψ PRODUCTION

At HERA, the charmonium state J/ψ is produced predominantly by the boson gluon fusion (BGF) process. The theoretical models which are used to compare with the measurements follow either the DGLAP evolution or use the k_T factorisation approach. After the heavy quark pair ($c\bar{c}$) is produced at short distances, the formation of the J/ψ bound state is described by non-perturbative long distance matrix elements (LDME). In the NRQCD models, contributions from both CS and CO states are predicted; one aim of the measurements is the extraction of their relative contributions. The H1 collaboration measured inelastic J/ψ production with decays to $\mu^+\mu^-$ in the photoproduction region using $\sim 166\text{pb}^{-1}$ from the 2006-2007 data, complementing their previous measurement in the DIS region [5]. In Figure 2 the differential cross section as a function of p_T^2 is shown and compared with Monte Carlo predictions and the CS calculations at leading order (LO) and at next-to-leading order (NLO). The scaled CASCADE [2] Monte Carlo, which uses the k_T factorisation in the colour changing flavour mode, is able to reproduce the slope better than the scaled EPJPSI [6] Monte Carlo, following the DGLAP evolution. While the CS LO calculation is not able to describe the data, there is a good agreement with the NLO calculation within the large normalisation uncertainties. As the CS provides a generally good description of the data when using the k_T factorisation or calculations at higher orders, no significant colour octet contribution is required, although there are still large normalisation uncertainties on the prediction.

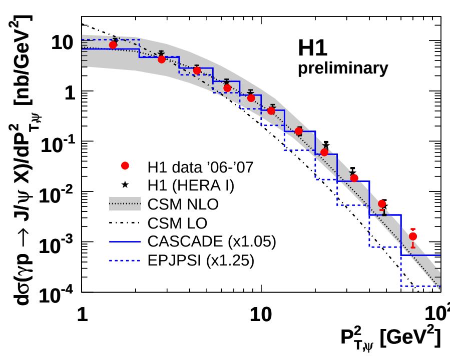

Figure 2: Differential cross section as a function of $p_{T,\psi}^2$ in the (γp) regime

In order to reduce the effect of the normalisation uncertainty, polarisation measurements are an important testing ground for the NRQCD predictions. Normalised quantities can be measured using helicity parameters to characterise the decay angular distributions. A measurement of the J/ψ helicity [7] has been performed by the ZEUS collaboration using the complete HERA statistics ($\sim 470\text{pb}^{-1}$). The angular distributions of the $J/\psi \to l^+l^-$ decay can be parametrised as $\frac{d^2\sigma}{d\Omega dy} \propto 1 + \lambda(y)\cos^2\Theta + \mu(y)\sin 2\Theta\cos\phi + \frac{1}{2}\nu(z)\sin^2\Theta\cos^2\phi$ [8]. The following integrated helicity formulae are used, depending on the chosen reference frame:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\Theta dz} \propto 1 + \lambda(z)\cos^2\Theta,$$
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\phi dz} \propto 1 + \frac{\lambda(z)}{3} + \frac{\nu(z)}{3}\cos^2\phi,$$

where θ is the angle between the μ^+ vector in the J/ψ rest frame and the z axis, and ϕ is the azimuthal angle in the x-y plane of the μ^+ vector in the J/ψ rest frame.

Figure 3 shows the measurement of the helicity parameter ν as a function of the inelasticity z. In addition to the NRQCD predictions two different predictions following the k_t factorisation approach are compared with the measurement. The LO NRQCD predictions (BKV) [8] do not describe the dependency of this parameter well, whereas the prediction including the CO contribution seems to be favoured within the large uncertainties. The other two predictions (Baranov) [9], predict a small negative polarisation and are always below the measurement. In this scheme where only CS contributions have been taken into account two different parametrisations of unintegrated gluon distributions have been used. The CS model with k_T factorisation gives predictions that are more similar to CS+CO compared to the CS only prediction. To distinguish between the different theoretical contributions the large variation between the calculations has to be understood and it would be good if the theoretical predictions could be improved and made available at NLO.

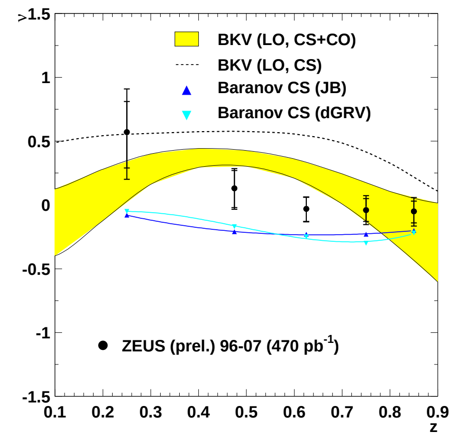

Figure 3: Helicity parameter, ν, as a function of the inelasticity, z

5. SPECTROSCOPY

The large charm production cross section at HERA permits measurements to be made of excited charm and charm-strange mesons. The production of excited charm and charm-strange mesons is observed by the ZEUS collaboration using the full HERA I dataset corresponding to an integrated luminosity of $\sim$ 126pb^{-1} [10]. The following decay channels were investigated:

$$\begin{aligned} D_1(2420)^0 &\to D^{*\pm}\pi^{\mp} \\ D_2^*(2460)^0 &\to D^{*\pm}\pi^{\mp} \\ &\to D^{\pm}\pi^{\mp} \\ D_{S1}(2536)^0 &\to D^{*+}K_s^0 \\ &\to D^{*0}K_s^+ \end{aligned}$$

Figure 4 shows the $M(D^{*+}\pi_a)$ and $M(D^+\pi_a)$ distributions for the charm meson candidates reconstructed in the given decay channels. The measured masses of the observed mesons have been found to be in reasonable agreement with the world average values. In addition to the masses also the widths, helicity and the relative branching fractions could be extracted. The measured D_1^0 width is $\Gamma(D_1^0) = 53.2 \pm 7.2(\text{stat.})^{+3.3}_{-4.9}(\text{syst.})$ MeV which is above the world average value of 20.4 ± 1.7 MeV. A larger S-wave admixture at ZEUS with respect to that in measurements with restricted phase space could explain the differences as already a small S-wave admixture could have sizeable contributions to the D_1^0 width. The measured value for the helicity parameter of $h(D_1^0) = 5.9^{+3.0}_{-1.7}(\text{stat.})^{+2.4}_{-1.0}(\text{syst.})$ has to be compared with the prediction of the HQET for a pure S-wave ($h = 0$) and a pure D-wave ($h = 3$). For the charm-strange meson D_{s1}^+ the measured parameter is $h(D_{s1}^+) = -0.74^{+0.23}_{-0.17}(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})$ which is inconsistent with the prediction for a pure D-wave and more than two standard deviations away from the prediction for a pure S-wave. So the measurement suggests a significant contribution of both D-wave and S-wave amplitudes to the $D_{s1}(2536)^+ \to D^{*+}K_S^0$ decay. In addition, a search for the radially excited charm meson $D^{*'}(2640)^{\pm}$has been made, which was reported by DELPHI as a narrow resonance in the final state $D^{*\pm}\pi^+\pi^-$ at 2637 MeV. In the inspected mass range no signal was observed and according to the expected mass and width the following limit at (95% confidence level) was extracted: $f(c \to D^{*'+}) \cdot \mathcal{B}_{D^{*'+} \to D^{*+}\pi^+\pi^-} < 0.4\%$.

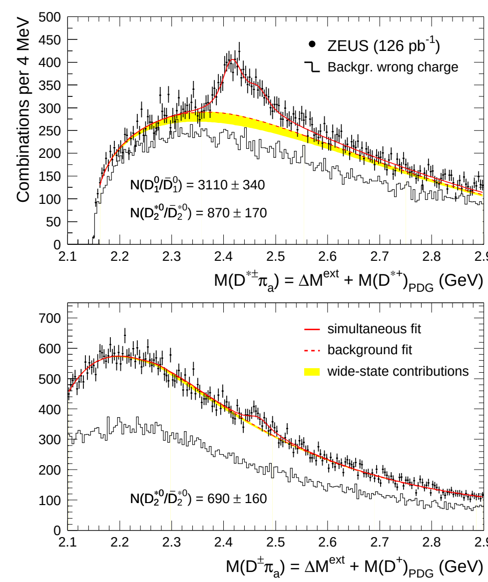

Figure 4: $M(D^{*+}\pi_a)$ and $M(D^+\pi_a)$ distributions for the $D_1(2420)^0$ and the $D_2^*(2460)^0$ candidates.

6. D*p RESONANCE

The H1 collaboration observed a narrow signal in the D^*p channel at $M(D^*p) = 3099 \pm 3(\text{stat.}) \pm 5(\text{syst.})$ MeV in the HERA I dataset [11]. This signal was interpreted as an anti-charm baryon with a minimal constituent quark composition of $uudd\bar{c}$ with a relative contribution of $\frac{N(D^*p)}{N(D^*)} \sim 1\%$ in the identified D^* meson sample. In contrast to this, no evidence was found by the ZEUS [12] collaboration. Using the full HERA dataset H1 does not confirm the observation. The data of 2004 to 2007 correspond to an integrated luminosity of $348\,\text{pb}^{-1}$ and thus increase the available statistics by a factor of ~ 4. In contrast to the previous analysis of the D^*p final state no dE/dx requirements were used for particle identification. A detailed description of the event selection can be found in [13]. The mass spectrum was reconstructed both for the HERA II dataset as well as for the HERA I dataset using the new selection criteria. Figure 5 shows the reconstructed invariant mass for the D^*p candidates separately for the two datasets. In the reanalysed HERA I dataset the previously reported signal is reproduced. Under the assumption of the width from the HERA I measurement there is no excess in the HERA II data visible. The upper limit at a 95 % confidence limit was calculated to be $\frac{N(D^*p)}{N(D^*)} \sim 0.1\%$.

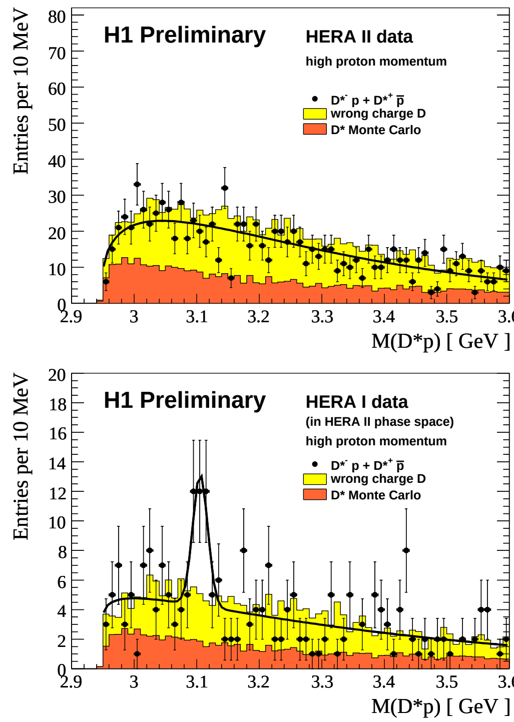

Figure 5: Distribution of $M(D^*p$ in the HERA I (bottom) and HERA II (top) data samples.

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