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HEAVY QUARK PRODUCTION AT HERA

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Recent measurements of the charm and beauty production in ep collisions at HERA are presented. Heavy-quark tagging methods used by the ZEUS and H1 experiments are described. Cross section results are compared with NLO QCD predictions and in general the data are well described by the calculations. A determination of the charm and beauty contributions to the proton structure function is also presented. The comparison with NLO QCD predictions shows reasonable agreement. A comparison of the result on the beauty contribution to the structure function with a NNLO calculation is also shown, although the errors are currently too large to discriminate between theories.

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1. Introduction

Heavy quarks (c and b quarks) are produced at HERA prodominantly by the process known as boson-gluon fusion, where a photon emitted by the electron interacts with a gluon in the proton producing a $b\bar{b}$ or $c\bar{c}$ pair. The measurements of such interactions are directly sensitive to the gluon density in the proton. Also, perturbative calculations of these processes should be reliable since the virtuality Q^2 of the exchanged photon and the large mass of the produced quark, in the case of photoproduction, provides a hard scale. Hence, the study of heavy quark production at HERA is a stringent test of the perturbative quantum chromodynamics (QCD).

The perturbative QCD calculations are performed in two different ways. The first is known as the massive approach [1] in which the c and b quarks have mass and are not part of the structure functions but are rather produced perturbatively in the hard interaction. This method is most appropriate for the region $Q^2 \sim m_Q^2$ but tends to break down for $Q^2 >> m_Q^2$ due to the appearance of divergent corrections from $\log(Q^2/m_Q^2)$ terms. In this region, it is expected that the massless approach [2] is more suitable where the heavy quarks are considered as active flavours in the proton and photon and are fragmented into heavy quarks after the hard interaction.

In the following sections, recent H1 and ZEUS measurements of the process described above are presented. The results are compared with NLO predictions calculated using the massive approach. The programs used to compute these predictions are HVQDIS [3] in the case of deep inelastic scattering (DIS) measurements, defined as $Q^2 > 1\mathrm{GeV}^2$ and FMNR [4] in the case of measurements made in the photoproduction regime, defined as $Q^2 \sim 0$ GeV^2.

The data used in these measurements were collected using the H1 [5] and ZEUS [6] detectors. In all but one of the results presented, the events analysed are the result of collisions of 920 GeV protons and 27.5 GeV electrons or positrons in the HERA collider after the luminosity upgrade of 2001. The other uses events from when HERA operated with protons at 820 GeV. During this upgrade period a silicon microvertex detector (MVD) [7] was installed in the ZEUS detector. This detector component and the existing vertex detector in H1 allow accurate heavy-flavour measurements based on lifetime tagging to be made by both experiments. The various methods used to tag heavy quarks, which use these vertex detectors at HERA, will also be discussed.

2. Resonance tagging methods

2.1. $D^{\pm}$ and other charm hadron cross sections

In addition to the usual resonance tagging method for charmed mesons [8], a cut can be made on the decay length significance, defined as $S_l = l/\sigma_l$ where l is the decay length and σ_l is the error on the decay length. This method was employed in the ZEUS measurement [9] of D meson cross sections and enhances the signal to background ratio significantly as can be seen in Fig. 1. This measurement was carried out using 135 pb^{-1} of data collected by the ZEUS detector between 2004 and 2005. The $D^{*\pm}$ cross section as a function of Q^2 can also be seen in Fig. 1. The data are compared with the NLO QCD predictions implemented in the HVQDIS program. The cross section measurements are reasonably well described by the NLO calculation. The cross section measured previously [8] at ZEUS using HERA I data is also shown on the plot and a decrease in error can be seen when using the improved tagging technique. These techniques can now be used to extend the kinematic region of the measurement, and the $D^{*\pm}$ data can be used to extract the charm contribution to the structure function F_2. These data can also be combined with other charm data to constrain the gluon density in the proton.

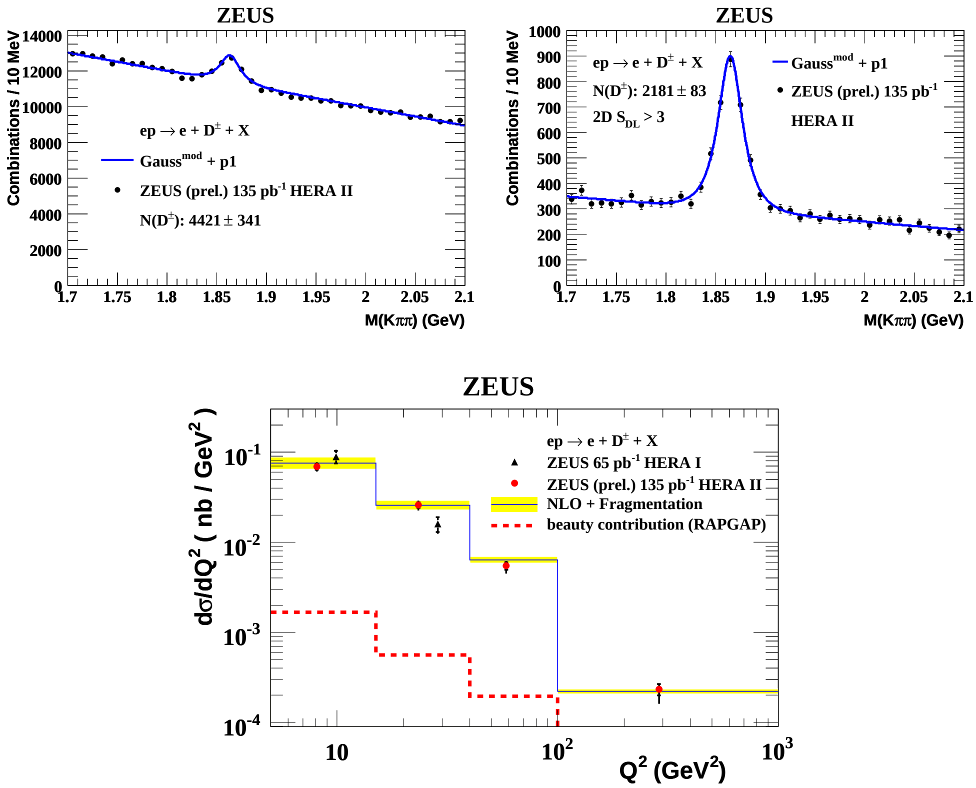

Fig. 1. Left: ZEUS measurement of the mass distribution of the D^0 meson candidates without (top) and with (bottom) a cut on the decay length significance and χ^2/ndf. Right: Differential $D^{*\pm}$ cross section as a function of Q^2, as measured by ZEUS, compared to the NLO QCD calculation of HVQDIS.

2.2. $D^{*\pm}$ production in DIS at low Q^2

In general previous results have observed good agreement between data and NLO predictions in both the DIS and photoproduction regimes. In a recent ZEUS measurement [10], the transition region between DIS and photoproduction was probed. The measurement was carried out using 81 pb^{-1} of data collected between 1998 and 2000. The kinematic region is defined by $0.02 < y < 0.85$ (y being the inelasticity of the event), $0.05 < Q^2 < 0.7$ GeV^2, $1.5 < p_T(D^*) < 9.0$ GeV and $|\eta(D^*)| < 1.5$. The differential cross sections were measured as a function of Q^2, y, $p_T(D^*)$ and $\eta(D^*)$ but are not shown here. The results were compared with theoretical predictions computed both in the DIS regime by the HVQDIS program and in the photoproduction regime by the FMNR program. The two predictions agree well in this region and both describe the data well. The data were also plotted with the DIS and photoproduction measurements as shown Fig. 2. The measurement presented here is consistent with the cross section measured in both DIS and photoproduction. The data were fitted with a function

$$\sigma(Q^2) = \frac{SM^2}{Q^2 + M^2} ,$$

where S is the photoproduction cross section at $Q^2 = 0$ and M^2 is the scale at which the γp cross section changes from the photoproduction value to the DIS $1/Q^2$ behaviour. This function gives a good description of the data over the whole Q^2 range when $S = 823 \pm 63$ nb and $M^2 = 13 \pm 2$ GeV^2.

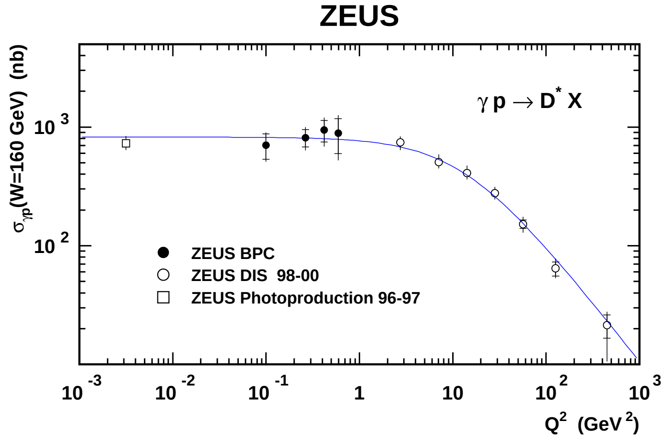

Fig. 2. γp cross section for $D^{\pm}$ production in DIS at low Q^2 as measured by ZEUS shown with previous photoproduction and DIS measurements.

3. Decay tagging methods

The charm and beauty decays can be tagged by identifying a lepton which is produced in the semileptonic decay of heavy quarks. Two variables can be used to discriminate between different quark decays. The first is the relative transverse momentum, $p_T^{\rm rel}$, of the lepton with respect to the heavy flavour hadron which for experimental purposes is approximated to the direction of the associated jet. This variable can be used to discriminate between beauty and charm decays since the mass of the beauty quark is larger and therefore it has a harder $p_T^{\rm rel}$ spectrum. The second variable is the signed impact parameter (δ) which is defined as the transverse distance of closest approach of a track to the primary vertex. This variable reflects the lifetime of the quark and hence can be used to discriminate between charm and beauty decays and the decays of light quarks. The sign allows a statistical disentanglement of detector resolution effects from the effects of the decay lifetime of the heavy hadron. By fitting template distributions from Monte Carlo simulations of these variables to data, the beauty and/or charm fraction in the data can be extracted and used to calculate cross sections.

3.1. *Beauty photoproduction*

The combination of the methods described in Section 3 can be a powerful tool in the tagging of beauty quarks. Such a method was used by the ZEUS collaboration in a recent measurement [11] of beauty photoproduction in the semileptonic decay channel into muons in dijet events. Total and differential cross sections were measured in the kinematic region defined by $Q^2 < 1$ GeV^2, $0.2 < y < 0.8$, $p_T^{\mathrm{jet}1,2} > 7, 6$ GeV, $-1.6 < \eta^{\mathrm{jet}} < 2.3$, $p_T^{\mu} > 2.5$ GeV and $|\eta^{\mu}| < 1.5$. Figure 3 shows the differential cross section as a function of muon p_T measured as described and also the previous ZEUS measurement [12] which used the p_T^{rel} method alone. The data are compared to a NLO QCD prediction computed with the FMNR program. The differential cross section as a function of η^{μ} was also measured but is not shown here. Good agreement is observed with the calculations over the p_T^{μ} and η^{μ} regions considered. In Fig. 3, a compilation of HERA beauty cross section measurements can be seen. In the past, some measurements [13, 14] have observed beauty cross sections to be larger than the theoretical predictions. The new measurements are in agreement with the NLO calculations.

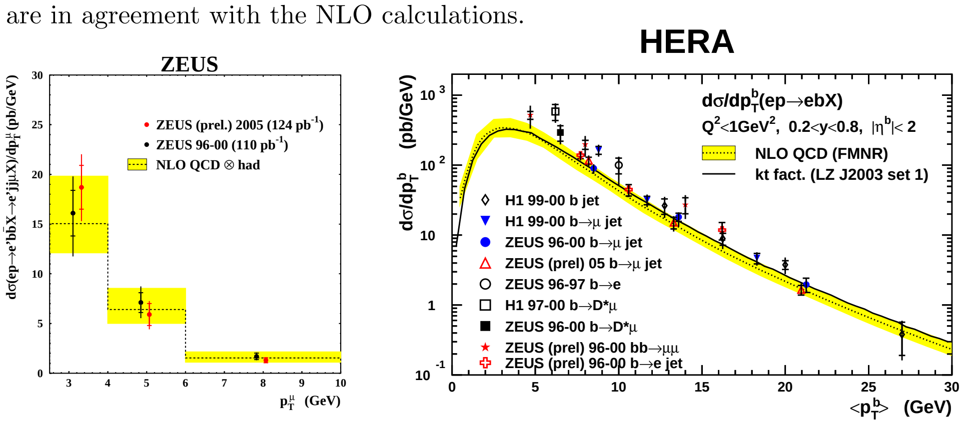

Fig. 3. Left: ZEUS measurement of differential cross sections as a function of the transverse momentum of the muon, p_T^{μ}, from semi-leptonic b decay. Right: Compilation of HERA measurements of the differential cross section for b-quark production as a function of the b-quark transverse momentum p_T^b for b-quark pseudorapidity.

3.2. *Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$*

A recent H1 measurement [15] of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ also used a procedure based on the impact parameter method. Instead of tagging the heavy quarks with a lepton, all tracks were used. The variables S_1 and S_2 are defined as the impact parameter significance $(\delta/\sigma(\delta))$ of the track with the highest and second highest significance, respectively, where δ is the impact parameter and $\sigma(\delta)$ is the error on the impact parameter. A simultaneous fit of these distributions permits the extraction of both the beauty and charm fractional content of the data sample. The fractions in each $x - Q^2$ interval, where x is the usual Bjorken scaling variable, were converted to cross section measurements. This was then extrapolated to obtain the charm and beauty contributions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ to the structure function F_2 which is related to the total DIS cross section by

$$\frac{d^2\sigma^{\mathrm{ep}}}{dQ^2 dx} = \frac{2\pi\alpha^2}{Q^4 x} \cdot (1 + (1-y)^2) \cdot F_2(x, Q^2)\,,$$

where y is the inelasticity variable.

This measurement was carried out using 54 pb^{-1} of H1 electron data collected in 2006 and was made in the kinematic region defined as $12 \le Q^2 \le 650$ GeV^2. Figure 4 shows some results of this measurement. Values of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ are shown at fixed values of x as a function of Q^2 as determined in this analysis, in previous

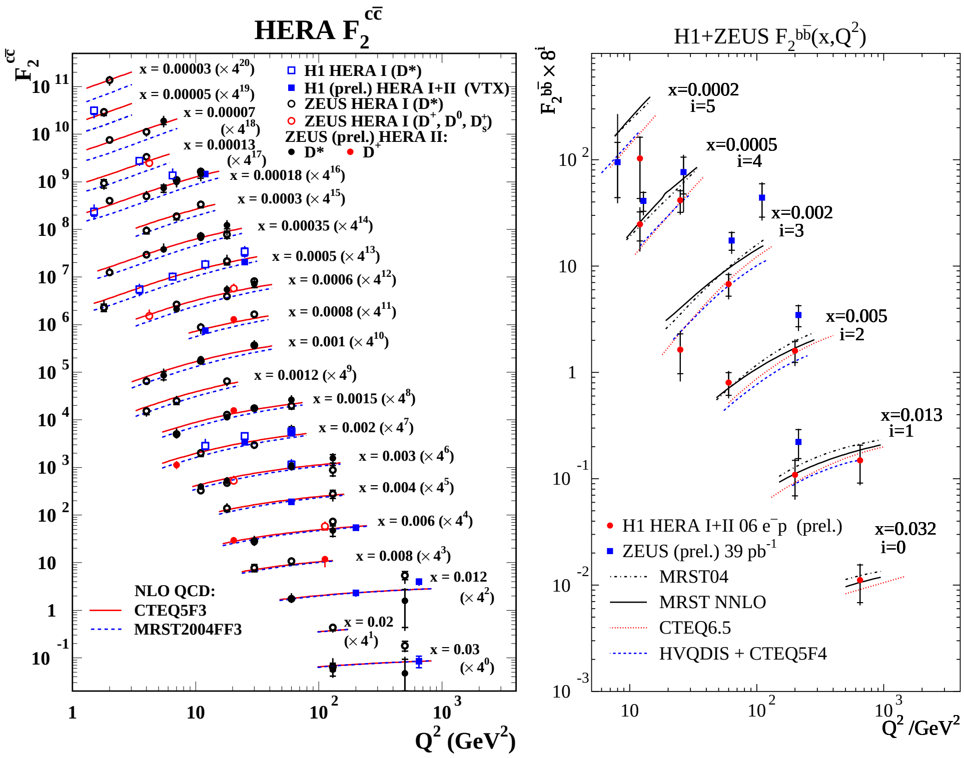

Fig. 4. Measured $F_2^{c\bar{c}}$ (left) and $F_2^{b\bar{b}}$ (right) as a function of Q^2 for various values of x.

H1 analyses and as measured by ZEUS. The $F_2^{b\bar{b}}$ measurement was made using weighted average of published HERA I data and the HERA II data from 2006. The data are compared with QCD predictions from MRST [16] and CTEQ [17] at NLO and also with a NNLO prediction in the case of $F_2^{b\bar{b}}$. In general, the results for $F_2^{c\bar{c}}$ are reasonably well described by the NLO predictions, however, at low x there are notable differences between the two theoretical predictions. The measurements of $F_2^{b\bar{b}}$ agree reasonably well between the H1 and ZEUS collaborations despite being produced using different methods. The ZEUS result uses the $p_T^{\text{rel.}}$ method to tag the beauty quarks. The experimental errors are, however, too large to distinguish between different theoretical calculations.

4. Conclusions

Recent results for charm and beauty production in ep collisions at HERA have been presented and compared with NLO QCD calculations. A measurement has been made by the ZEUS collaboration of $D^{*\pm}$ production in the DIS regime at low Q^2 which is described well by two calculations, designed for the DIS (HVQDIS) and photoproduction (FMNR) regions. By exploiting the precision of the vertex detectors of the H1 and ZEUS experiments, new measurements have been made of $D^{\pm}$ and other charm hadron cross sections, beauty cross sections and the charm and beauty contributions to the structure function F_2. These measurements are reasonably well described by NLO QCD predictions and by a NNLO prediction.

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TVORBA TEŠKIH KVARKOVA U HERI

Predstavljamo nedavna mjerenja tvorbe kvarkova šarma i ljepote u ep sudarima u HERI. Opisujemo metode označavanja teških kvarkova koje se primjenjuju u mjerenjima ZEUS i H1. Ishodi za udarne presjeke uspoređuju se s predviđanjima NLO QCD, a eksperimentalni i teorijski podaci su u dobrom skladu. Predstavljamo također određivanje doprinosa šarma i ljepote protonskoj strukturnoj funkciji. Usporedba s predviđanjima NLO QCD pokazuje dobro slaganje. Dajemo i usporedbu ishoda za doprinos ljepote strukturnoj funkciji s računima NNLO, iako su sada pogreške prevelike da bi se razlikovale teorije.