Heavy Flavour Production at HERA

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The production of hadrons containing a heavy quark is one of the most sensitive tests of QCD. At HERA, besides the investigation of production models incorporating multi-scale dependence, the production of heavy flavored hadrons is used to constrain the parton distribution functions, with important implications for LHC physics. Recent measurements by H1 and ZEUS experiments have been obtained using the HERA II data set and various tagging techniques for both photoproduction and Deep Inelastic Scattering. The results are in agreement with theoretical calculations. The DIS data have been combined recently to obtain a precise determination of the charm contribution to the proton structure function F_2.

1. The HERA Collider

The HERA accelerator as the first lepton-proton collider in the world offered a unique testing ground for studies of the proton structure. It operated since 1992 and was closed in 2007. The machine collided electrons or positrons with energy of 27.5 GeV, with protons, of energy 820 to 920 GeV. The resulting center-of-mass energy was 300 or 318 GeV respectively. The two collider experiments, H1 and ZEUS, collected data corresponding to an integrated luminosity about 0.5 fb^{-1} per experiment.

2. Kinematics of ep interactions

The electron-proton interaction is described by a set of Lorenz-invariant kinematic variables: the squared center-of-mass energy of the ep system:

$$s = (P + k)^2, \quad (1)$$

the photon virtuality given by the squared momentum transfer:

$$Q^2 = -q^2 = -(k - k')^2, \quad (2)$$

the Bjørken scaling variable:

$$x = \frac{q^2}{2P \cdot q}, \quad 0 \leq x \leq 1, \quad (3)$$

and the inelasticity - the relative energy transfer in the proton rest frame:

$$y = \frac{P \cdot q}{P \cdot k}, \quad 0 \leq y \leq 1, \quad (4)$$

where P, q, k and k' denote the four-momenta of the proton, the mediated boson, and the in- and outgoing lepton, respectively.
The momentum transfer phase space is devided into two kinematic regimes. In photoproduction (PhP), where $Q^2 \approx 0$ GeV^2, the angle of the scattered electron is too small for the electron to be observed. At larger Q^2 - Deep Inelastic Scattering (DIS) - defined usually by $Q^2 > 1$ GeV^2, the electron is scattered enough to enable its detection.

3. Motivation

Heavy quark production at HERA is dominated by the Boson Gluon Fusion process, in which a gluon from the proton and a virtual photon from the electron produce a heavy quark pair. This process is well suited for the study of the strong interaction. In this presentation we focus on the main aspects:
- comparison of heavy flavour cross sections with perturbative QCD predictions, which is possible due to the hard scale of the heavy quark mass in DIS and PhP.
- measurements of the heavy quark $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ contribution to the structure function F_2 can be used for a more precise determination of proton parton density functions, which is of great importance for the Large Hadron Collider.

4. The theoretical models

Beside the masses of the heavy quarks, additional scales can be introduced by the transferred momentum Q^2 and by the transverse momentum p_T of the produced quarks, which can lead to large logarithms in the calculation, spoiling the convergence of the perturbative expansion.

There exist two distinct approaches in the treatment of this multi-scale problem in pQCD production of heavy quarks. In the massive model heavy quarks are only produced perturbatively in the hard interaction. Terms representing higher order collinear gluon radiations, are not resummed. In the massless scheme heavy quarks are treated as active partons in the proton, which allows resummation to all orders. It is expected that these approaches are applicable for different scales - massive for low and medium, and massless for high Q^2 and p_T.

Mixed schemes interpolate between the massive and massless description. They provide the correct threshold behaviour at low Q^2, p_T and heavy quark densities for large Q^2, p_T^2

5. Heavy Quark detection in the H1 and ZEUS experiments

The following tagging techniques of heavy quarks are most commonly used in HERA analyses:

5.1. Full Reconstruction

In this method the invariant mass of the decaying heavy hadron is reconstructed by using tracking chamber and vertex detector information of the charged particles from the decay. The number of signal events is determined from the resonance spectrum, above a non-resonant combinatorial background. This technique is limited at HERA to the charm measurements.

5.2. Semileptonic decays

The signature provided by semileptonic decays of heavy quarks is mainly used at HERA for b-quark analyses. The identification of electrons is achieved by using their energy loss in the drift chambers as well as the energy deposit in the calorimeter, while muons are identified by using their minimally ionising particle signature in the calorimeter and muon chambers.

In order to extract the relative contributions from beauty, charm and light flavour quarks in a sample, observables which reflect the different lifetimes and masses are used. In the p_T^{rel} method the transverse momentum of the lepton relative to the direction of the jet axis, p_T^{rel}, is used. The impact parameter is defined as the distance of closest approach of a track to the primary vertex.

5.3. Inclusive lifetime method

This technique, utilising lifetime information of long-living heavy hadrons is not restricted to specific decay channels, hence yields higher statistics. Significances of the tracks from a secondary vertex as well as secondary vertex significances are used. The track significance is defined as impact parameter divided by its resolution. The secondary vertex significance is the distance between primary and secondary vertices projected onto the estimated quark direction and devided by its error.

6. Results

6.1. Charm in photoproduction

The H1 collaboration measured the charm quark production using a sample with an integrated luminosity 93 pb^{-1} [1]. Events in the kinematic region of $Q^2 < 2$ GeV^2 have been selected requiring a D^* in the golden decay $D^{*+} \rightarrow D^0\pi^+ \rightarrow K\pi^+\pi^+$, with the presence of two jets. The D^* meson, to which one of the jets is associated, and the other jet, tagging another hard parton in the process, have been selected in the central detector region of pseudorapidity $|\eta| <1.5$. The transverse momenta fulfil $p_T(D^*) > 2.1$ GeV and $p_T(otherjet) > 3.5$ GeV for the D^* and the other jet respectively.

The differential cross sections of $p_T(D^*jet)$, $\eta(D^*jet)$ as well as $p_T(otherjet)$, $\eta(otherjet)$ have been measured and compared to MC@NLO predictions, in which NLO matrix elements calculations are matched with MC parton showering [2]. Fig. 1 present pseudorapidity spectra of jets. The central value of the prediction is below the data. The pseudorapidity of the other

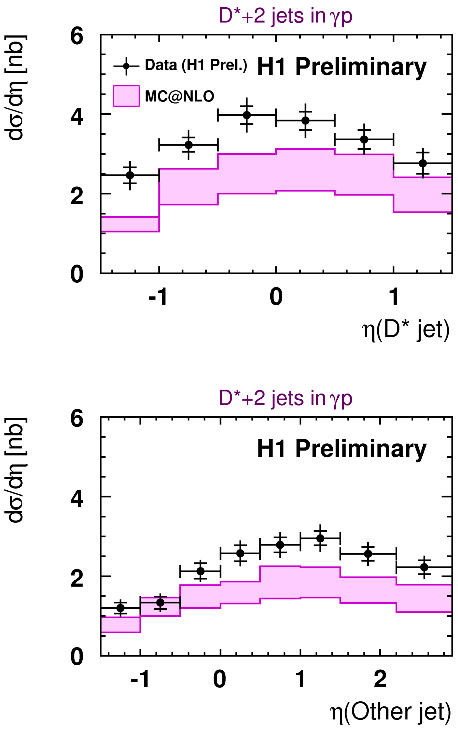

Figure 1. Cross section as a function of η of the D^*-jet and the other jet at H1 D^* in γp analysis.

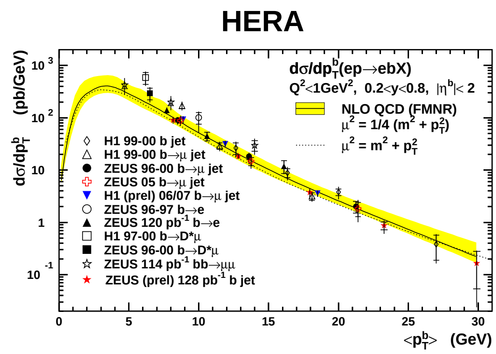

Figure 2. Beauty production cross section as function of the p_T of b-quark. Data are compared with an NLO prediction. [3]

jet is shifted forward with respect to the D^* jet, which indicates that the other jet can originate from another parton: light quark or gluon. This is reasonably described by the prediction.

6.2. Beauty in photoproduction

Using the inclusive method of the secondary vertex reconstruction, the ZEUS collaboration performed a measurement of b quark photoproduction, with an integrated luminosity of 126 pb^{-1} [3]. The measured cross sections of p_T and η of the jets are reasonably well described by the NLO predictions in the massive scheme [4]. The measurement have been compared with previous H1 and ZEUS measurements (see fig. 2), which used different tagging methods, datasets and decay channels. They are in good agreement with each other as well as in reasonable agreement with the NLO prediction for the full b-quark transverse momentum p_T spectrum.

6.3. Charm in Deep Inelastic Scattering

Charm production at high Q^2 has been measured at the H1 experiment [5]. For this purpose D^* mesons of pseudorapidity $|\eta| < 1.5$ and

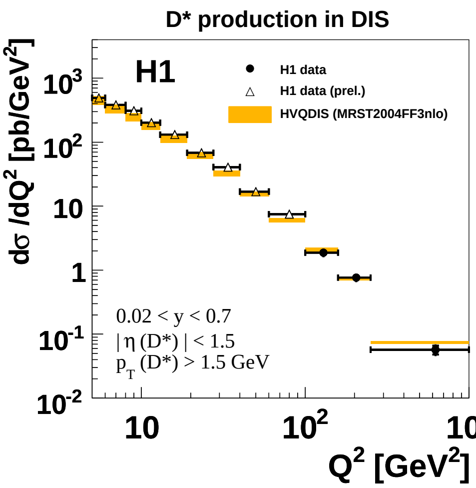

Figure 3. D^* production cross section as a function of Q^2 compared to an NLO prediction [5].

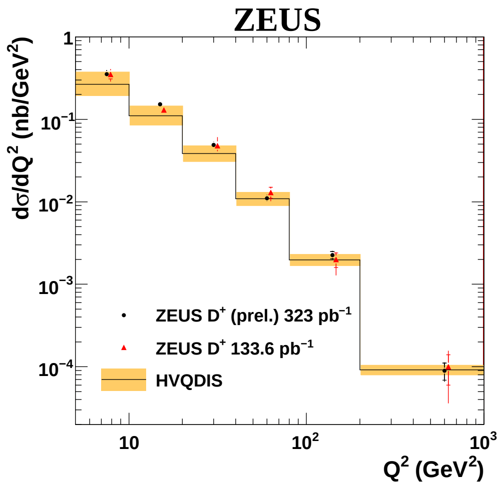

Figure 4. D^+ production cross section (circles) as a function of Q^2 compared to an NLO prediction (band) and previous measurement (triangles).

$p_T(D*) < 1.5$ GeV were reconstructed in the golden decay channel. The measurement was based on the full HERA II statistics, corresponding to an integrated luminosity of 351 pb^{-1}. The differential cross sections, measured with a precision of about 20%, have been compared with the CASCADE and RAPGAP MC, which do not describe the data well. However, the measurement is in good agreement with massive scheme NLO pQCD predictions provided by HVQDIS [6] program (see fig. 3).
The same feature can also be seen in the ZEUS full HERA II measurement (fig. 4), in which D^+ mesons have been reconstructed in the decay $D^+ \rightarrow K^-\pi^+\pi^+$ in the kinematic range of $1.5 < Q^2 < 1000$ GeV^2, and $|\eta(D^+)| < 1.6$. In this measurement a secondary vertex technique has been used, which lead to a significant reduction of background and improvement of precision compared to previous ZEUS measurements.

6.4. Charm and beauty in Deep Inelastic Scattering

Measurements of charm and beauty hadrons decaying into muons were performed by the ZEUS experiment for the 2005 data, corresponding to an integrated luminosity of 126 pb^{-1} [8]. The measurements were performed in the phase space region of $Q^2 > 20$ GeV^2. The differential cross sections have been measured as a function of Q^2 and x, as well as the transverse momentum p_T^μ (see fig. 5) and pseudorapidity η^μ of the muon. The measurements are in good agreement for charm and reasonable agreement for beauty, compared to the next-to-leading order massive scheme predictions by the HVQDIS program. The tendency of the beauty cross section to lie above NLO predictions at low p_T and low Q^2, is also observed in the $b \rightarrow \mu$ analysis [9] of the HERA I data sample. The data are alse compared to RAPGAP MC prediction, which describe the shapes of the p_T^μ distributions reasonably well.

6.5. Beauty in DIS

The inclusive beauty measurement performed by the ZEUS Collaboration, and based on the full HERA II data sample (corresponding to the integrated luminosity of 354 pb^{-1}) [10] is more precise than the muon analyses. Events with at

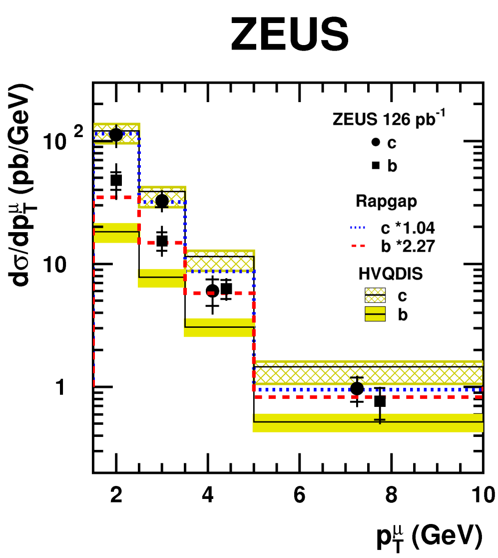

Figure 5. Charm and beauty cross section as a function of p_T of the muon in the ZEUS analysis compared to various predictions [9]

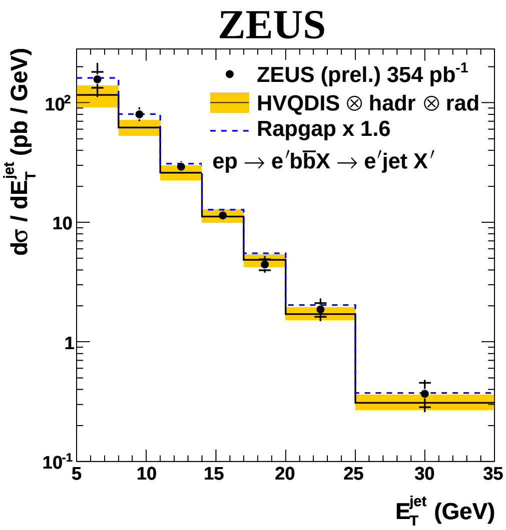

Figure 6. Differential cross section of an inclusive beauty production in DIS as a function of E_T.

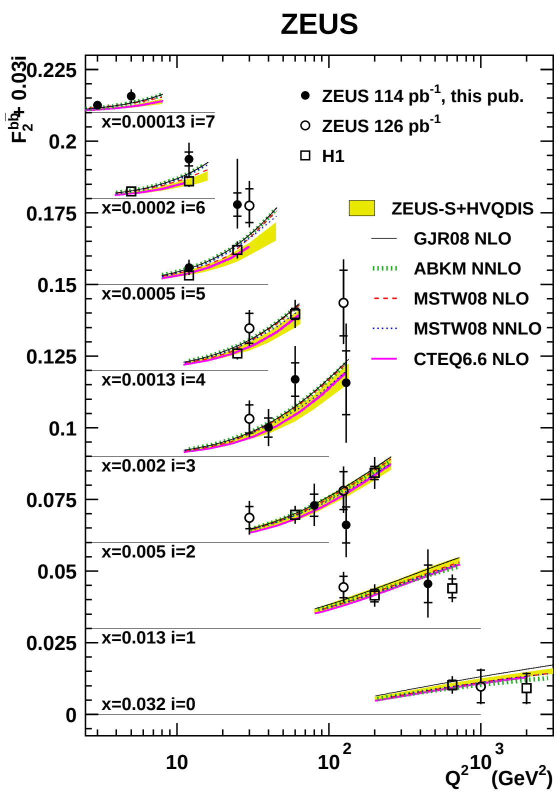

Figure 7. $F_2^{b\bar{b}}$ measurements at HERA compared to pQCD predictions.

least one jet with transverse energy $E_T > 5$ GeV^2 in the acceptance region of $-1.6 < \eta < 2.2$ have been selected. The secondary vertices were reconstructed using well measured tracks, which were associated to the jet. The measured differential cross sections are in agreement with massive NLO predictions for wide ranges of Q^2 and E_T of the jet (fig. 6).

7. Charm ($F_2^{c\bar{c}}$) and beauty ($F_2^{b\bar{b}}$) contributions to the proton structure function F_2

Identifying heavy flavour provides the possibility of studying charm contributions ($F_2^{c\bar{c}}$) to the structure function F_2, connected with the charm cross section by the relation:

$$\frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2^{c\bar{c}} - y^2F_L^{c\bar{c}}], \quad (5)$$

and similarly for beauty. The terms from the longitudinal structure function $F_L^{c\bar{c}}$ are small.

Because heavy flavours are likely to be produced in the hard scattering and not in the subsequent hadronisation of the struck parton, precise theoretical predictions can be performed for $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$. Using the charm contribution $F_2^{c\bar{c}}$ to the proton structure function F_2 in the PDF fit together with the inclusive cross section extracted from the data will allow to test the sensivity to the charm quark mass - one of the important parameters of the QCD predictions.

7.1. $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$ measurements

Fig. 7 presents the comparison of the three latest $F_2^{b\bar{b}}$ measurements with the different massive and mixed scheme predictions [9]. The results of the different measurements are compatible, and in agreement with predictions.

The $F_2^{c\bar{c}}$ results have been lately combined by

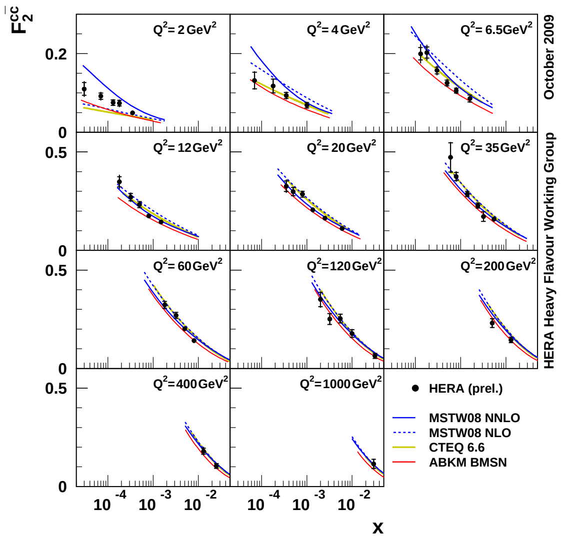

Figure 8. Combined $F_2^{c\bar{c}}$ result compared to different pQCD predictions.

the H1 and ZEUS collaborations [11] obtaining a precision of about 5-10%. Fig. 8 presents the combined results compared to different pQCD predictions. The precision of the data is higher than the variation between the predictions of different models. The combined $F_2^{c\bar{c}}$ measurement can be included in the global PDF fit, which will further constrain the fit parameters.

8. Conclusions

Measurements of charm and beauty production in Deep Inelastic Scattering and photoproduction at HERA have been presented. NLO pQCD predictions in the massive scheme have been found to describe the data well up to large virtualities Q^2. The determination of the charm and beauty contribution to the proton structure function has been performed. The precision of charm measurement allows tests of different treatment of heavy flavour in the determination of the parton density functions of the proton. The inclusion of the combined $F_2^{c\bar{c}}$ results into the global fit can constrain PDF fit parameters, which is important for more precise cross section predictions at the Large Hadron Collider [12].

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