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# Latest measurements of beauty quark production at HERA

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The latest results of beauty quark production measurements at HERA are presented. New measurements have been obtained both in the photoproduction and the deep inelastic scattering regimes. The results were compared with the NLO QCD calculations.

## 1. Introduction

Production of heavy quarks is a fascinating tool to understand the nucleon structure as well as the underlying QCD parton dynamics. In addition production of $b$ quarks is a source of background for many searches for new physics at existing and future colliders. The high $b$ mass ($M_b \gg \Lambda_{QCD}$) should provide a solid basis for a perturbative calculation. Nevertheless, so far discrepancies between the experimental cross section measurements and the NLO QCD calculation have been found.

The experimental procedure often relies on the measurement of the transverse momentum $p_T^{rel}$ of the muon produced in the semi-leptonic decay with respect to the axis of the closest jet. This spectrum is harder for $b$ quarks than for $c$ quarks and, therefore, allows a statistical separation of the signal from the background. Additional information such as lifetime measurements provided by silicon detectors can also be used. An alternative tag is given by the coincidence of $D^*$ mesons and muons which provide sensitivity to the region of low transverse $b$ quark momenta and is less affected by background.

The recent experimental results obtained at the HERA collider are reviewed in both the photoproduction ($Q^2 \sim 0$ GeV$^2$) and the Deep Inelastic Scattering (DIS: $Q^2 > 1$ GeV$^2$) kinematic regimes.

## 2. Open Beauty in Photoproduction

When the exchanged photon has small virtuality ($Q^2$) the time-scale of the interaction is such that its hadronic structure can be revealed. Photoproduction at HERA can therefore be similar to the processes at hadron colliders and supplies complementary information. Both ZEUS and H1 already published results on $b$ photoproduction [1–3]. The ZEUS experiment has now measured the differential cross sections of beauty photoproduction using events with at least two jets and a muon in the final state [4]. The luminosity used is almost three times larger than in the previous measurements. The fraction of events from $b$ decays has been extracted using the $p_T^{rel}$ method. The kinematic region is defined by $Q^2 < 1$ GeV$^2$, $0.2 < y < 0.8$, $p_T^{Jet1(2)} > 7(6)$ GeV, $|\eta^{Jet1(2)}| < 2.5$, $p_T^{\mu} > 2.5$ GeV and $-1.6 < \eta^{\mu} < 2.3$ [1]. Figure 1 shows a comparison between the measured differential cross section and a NLO QCD calculation for different regions of the muon pseudorapidity. The QCD prediction was calculated using the program `FMNR` [5]. The hadronization is modeled by a Peterson function and the spectrum of the semi-leptonic muon momentum was extracted from `PYTHIA` [6]. The bands around the NLO prediction show the results obtained by varying the $b$ quark mass as well as the renormalization and factorization scales. The measured cross sections are a factor 1.4 larger than the central NLO prediction but compatible with it within the experimental and theoretical uncertainties.

In addition, a dijet cross section ($ep \to b\bar{b}X \to jet\ jet\ X$) has been determined using `PYTHIA` to extrapolate to the unmeasured part

[1] $\eta = -\ln(\tan\theta/2)$ is the pseudorapidity, where $\theta$ is the polar angle measured with respect to the proton beam direction.

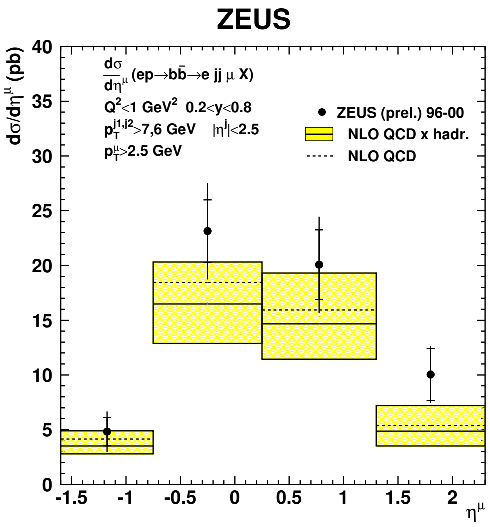


Figure 1. Differential cross section of beauty photoproduction as a function of the muon pseudorapidity compared with NLO QCD calculations.

of the muon kinematics and to correct for the branching ratio. For this measurement a different data sample has been used with looser cuts on the transverse momentum of the muon at large pseudorapidities. The result is $\sigma^{dijet} = 733 \pm 61 \pm 104$ pb while the NLO QCD prediction is $381^{+117}_{-78}$ pb, corresponding to a data excess of a factor of two.

## 3. Open Beauty in DIS

First results in the DIS region have been already released by the H1 collaboration [7]. Thanks to the high luminosity in the new ZEUS measurement [8] differential distributions have been measured for the first time in DIS. Events were selected by requiring the presence of at least one muon in the final state and at least one jet in the Breit frame[2]. A total visible cross section of $\sigma^{vis} = 38.7 \pm 7.7^{+6.1}_{-5.0}$ pb was measured for the reaction $ep \to eb\bar{b}X \to e\ jet\ \mu\ X$ in the kinematic region defined by: $Q^2 > 2$ GeV$^2$, $0.05 < y < 0.7$, $p^\mu > 2$ GeV, $30° < \theta^\mu < 160°$ and one jet in the Breit frame with $E_T^{Breit} > 6$ GeV and $-2 < \eta^{Lab} < 2.5$. Also for this measurement the $p_T^{rel}$ method was applied. This result has been compared with a NLO QCD calculation implemented in the HVQDIS program [9], after folding the $b$ quark momentum spectrum with a Peterson fragmentation function and subsequently with a spectrum of the semi-leptonic muon momentum extracted from RAPGAP [10]. The NLO QCD prediction is $28.1^{+5.3}_{-3.5}$ pb which agrees with the measured value within the errors. The differential cross section as a function of $Q^2$ compared to the NLO calculation is shown in Fig. 2. The

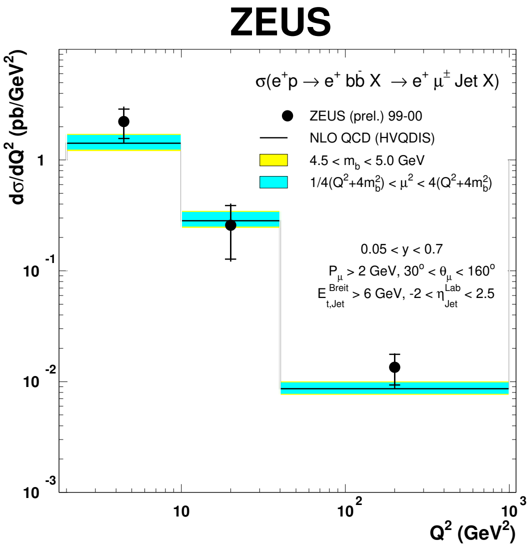


Figure 2. Differential beauty cross section as a function of $Q^2$ compared with the NLO QCD calculations.

prediction of the Monte Carlo program CASCADE [11], which implements a calculation based on the CCFM evolution equations [12] and uses a $k_T$-dependent gluon density, is 35 pb which is in very good agreement with the measurement. In addition, the simulation gives a good description of the measured differential cross sections.

## 4. $D^* - \mu$ correlations

The separation of charm and beauty contributions to the signal can also be performed by

[2] In the Breit frame, defined by $\vec{\gamma} + 2x\vec{P} = \vec{0}$, where $\vec{\gamma}$ is the momentum of the exchanged photon, $x$ is th Bjorken scaling variable and $\vec{P}$ is the proton momentum, a purely space-like photon and a proton collide head-on.

exploiting the charge and angle correlations of the $D^*$ meson and of the muon in the reaction $ep \to eb\bar{b}X \to eD^*\mu X$. Of particular interest is the configuration in which the muon and the $D^*$ originate from the same parent $B$-meson yielding unlike charge sign $D^* - \mu$ pairs produced in the same hemisphere.

Using this strategy and performing a likelihood fit on the kinematic distributions H1 has extracted the cross sections of beauty and charm production in the kinematic region defined by $p_T^{D^*} > 1.5$ GeV, $|\eta^{D^*}| < 1.5$, $p_T^{\mu} > 1$ GeV, $|\eta^{\mu}| < 1.74$ and $0.05 < y < 0.75$ [13]. The measured values, which confirm previous results, are respectively $\sigma^b_{vis} = 380 \pm 120 \pm 130$ pb and $\sigma^c_{vis} = 720 \pm 115 \pm 245$ pb which are well above LO+parton shower Monte Carlo expectations.

A similar analysis has been conducted by ZEUS [14] whose selection has been optimized for decays of $b$ quarks. The beauty cross section, measured in a slighty different phase space ($p_T^{D^*} > 1.9$ GeV, $|\eta^{D^*}| < 1.5$, $p_T^{\mu} > 1.4$ GeV, $-1.75 < \eta^{\mu} < 1.3$), is $\sigma^b_{vis} = 214 \pm 52^{+96}_{-84}$ pb. The result is in good agreement with the the H1 measurement once the same cuts are applied. In order to compare the measured cross section with NLO QCD predictions a photoproduction-enriched sample has been selected by applying the cuts $Q^2 < 1$ GeV$^2$ and $0.05 < y < 0.85$. Furthermore, the measurement is restricted in a $b$ quark rapidity range $\zeta^b < 1$ where the distributions of the Monte Carlo program used to extrapolate agree with the respective `FMNR` spectra within $\pm 15\%$. The result for the extrapolated cross section is $\sigma_{\gamma p \to b(\bar{b})X} = 15.1 \pm 3.9^{+3.8}_{-4.7}$ nb while the NLO prediction of `FMNR` for this reaction is only $5.0^{+1.7}_{-1.1}$ nb.

## 5. Conclusions and outlook

The understanding of the $b$ quark production mechanism is an outstanding puzzle in QCD. A set of new visible cross sections of beauty production, defined close to the detector acceptance, have been measured at HERA. The results are about a factor 1.4 higher than the NLO QCD predictions but consistent within the experimental and theoretical uncertainties both in the photoproduction and the DIS regions. An excess of measured cross sections over the NLO QCD prediction is observed when attempts are made to extrapolate cross sections to regions which are not directly measured by the detectors.

The HERA collider is now starting a new phase of operation at higher luminosities. Together with the enhanced $b$-tagging capabilities of the new H1 and ZEUS vertex detector and tracking triggers more precise and differential measurements can be expected within the next five years.

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