$F_2^{b\bar{b}}$ from the ZEUS HERA-II Data

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Beauty production in deep inelastic scattering with events in which a muon and a jet are observed in the final state has been measured with the ZEUS detector at HERA II using an integrated luminosity of 39 pb^{-1}. The fraction of beauty quarks in the data was determined using the distribution of the transverse momentum of the muon relative to the jet. The cross section for beauty production was measured in the kinematic range $Q^2 > 4$ GeV^2, $0.05 < y < 0.7$ and requiring a muon with $p_T^\mu > 1.5$ GeV and $\eta^\mu > -1.6$ and a jet with $E_T^{jet} > 5$ GeV and $-2 < \eta^{jet} < 2.5$. Differential cross sections in Q^2, p_T^μ, η^μ, p_T^{jet} and η^{jet} are compared to theory. Furthermore $F_2^{b\bar{b}}$, the beauty contribution to the structure function F_2, is obtained and compared to theoretical predictions.

1 Introduction

This paper reports the first ZEUS measurement at HERA II of beauty production in deep inelastic scattering (DIS), in the reaction with at least one jet and one muon in the final state: $ep \rightarrow e\ b\bar{b}\ X \rightarrow e\ jet\ \mu\ X'$. The analysis described here measures in an extended kinematic region compared to the previous ZEUS analysis of HERA I data [2] and uses a combination of multiple detector components for muon identification. This allows a lower muon transverse momentum threshold and a higher detection efficiency to investigate these regions of phase space further.

Due to the large b-quark mass, muons from semi-leptonic b-decays usually have high values of p_T^{rel}, the transverse momentum of the muon with respect to the axis of the closest jet. For muons from charm decays and in events induced by light quarks, where some of the produced hadrons are misidentified as muons, the p_T^{rel} values are lower. Therefore, the fraction of events from b-decays in the data sample can be extracted by fitting the p_T^{rel} distribution of the data to Monte Carlo (MC) simulations of the processes producing beauty, charm and light quarks. In this analysis a total visible cross section, and differential cross sections are compared to leading order (LO) plus parton shower (PS) MC predictions and next-to-leading-order (NLO) QCD calculations. Furthermore the beauty contribution to the proton structure function F_2 is measured for different Q^2 and x values and compared to theoretical predictions.

2 Data sample and selection

The data used in this measurement were collected during the 2003-2004 HERA II running period, where a proton beam of 920 GeV collided with a positron beam of 27.5 GeV, corresponding to an integrated luminosity of 39.1 pb^{-1}. A detailed description of the ZEUS detector can be found elsewhere [3].

Events were selected by requiring the presence of at least one muon and one jet in the final state. The final sample was selected in four steps: 1) inclusive DIS event selection, requiring a well reconstructed outgoing positron with energy greater than 10 GeV, $Q^2 > 4$ GeV^2 and

inelasticity $0.05 < y < 0.7$. 2) Muon finding, using different components of the ZEUS detector, yielding an efficiency of about 80% at high momentum. Cuts on $p_T^\mu > 1.5$ GeV and $\eta^\mu > -1.6$ were applied. 3) Jet finding with hadronic final-state objects, using the k_T cluster algorithm (KTCLUS) [4]. Selected events contained at least one jet with $E_T^{jet} > 5$ GeV within the detector acceptance $-2 < \eta^{jet} < 2.5$. 4) Muon-jet association, requiring a jet and a muon within a cone of $R = \sqrt{\delta\phi^2 + \delta\eta^2} < 0.7$.
The final data sample contained 4734 events. To correct the data for detector acceptance and to extract the beauty fraction, the RAPGAP 3 MC simulation [5] was used to generate signal (beauty) and background (charm) events. RAPGAP is a generator based on LO matrix elements, with higher-order QCD radiation simulated in the leading-logarithmic approximation. The hadronisation is simulated using the Lund string model as implemented in JETSET [6]. The background from light flavours was simulated using DJANGO [7]. It has been checked on a hadronic background sample of data and MC, that the DJANGO MC describes the shape of the p_T^{rel} distribution reasonably well. Some small differences are treated as a contribution to the systematic error.

3 Experimental Method

3.1 Extraction of the b-signal

The light flavour and charm quark MC samples were mixed according to their relative luminosities and the b-quark sample was added according to the beauty fraction determined from the p_T^{rel} analysis. Figure 1 shows the p_T^{rel}-distribution as measured in the ZEUS detector for the data and MC. To determine the beauty fraction in the data, the contribution from light flavour plus charm, and beauty, were allowed to vary and fitted to the data using the χ^2-method. The obtained beauty fraction is $f_{beauty} = 21 \pm 2\%$(stat.). The sum of the MC contributions shown in Fig. 1 describes the data well.
Using this method, the total visible cross section, differential cross sections in Q^2, p_T^μ, η^μ, p_T^{jet} and η^{jet} and double differential cross sections $d^2\sigma_{meas}^{b\bar{b}\to\mu}/dxdQ^2$ can be obtained.

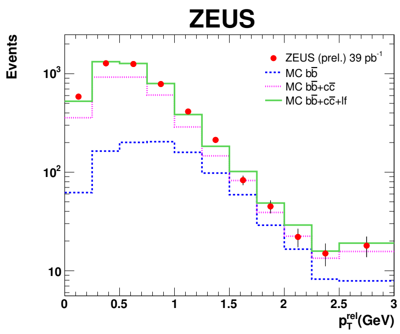

Figure 1: Measured p_T^{rel}-distribution for the data and fitted MC.

3.2 Calculation of $F_2^{b\bar{b}}$

In order to obtain $F_2^{b\bar{b}}$, the beauty contribution to F_2, cross sections in bins of Q^2 and x have been measured. The inclusive double differential cross section at low to medium Q^2 can be expressed in terms of structure functions:

$$\frac{d^2\sigma^{ep}}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\Big(\big[1 + (1-y)^2\big] F_2(x, Q^2) - y^2 F_L(x, Q^2)\Big).$$

If the small contribution from F_L is neglected, the inclusive cross section is proportional to $F_2(x, Q^2)$. In complete analogy, the cross section of events containing a $b\bar{b}$-pair ($ep \to b\bar{b}X$)

is proportional to $F_2^{b\bar{b}}(x,Q^2)$.
The reduced b-cross section is defined as:

$$\tilde{\sigma}^{b\bar{b}}(x,Q^2) = \frac{d^2\sigma^{b\bar{b}}}{dxdQ^2}\frac{xQ^2}{2\pi\alpha^2(1+(1-y)^2)}$$

where $\tilde{\sigma}^{b\bar{b}}(x,Q^2)$ is calculated using the fixed flavour number scheme (FFNS) NLO. In terms of the measured double differential cross section, the reduced cross section is given as:

$$\tilde{\sigma}^{b\bar{b}}_{meas}(x,Q^2) = \tilde{\sigma}^{b\bar{b}}_{NLO}(x,Q^2)\frac{d^2\sigma^{b\bar{b}\to\mu}_{meas}}{dxdQ^2}\Bigg/\frac{d^2\sigma^{b\bar{b}\to\mu}_{NLO}}{dxdQ^2}$$

using the ratio of measured to calculated double differential cross sections for the reaction $ep \to e\ b\bar{b}\ X \to e\ jet\ \mu\ X'$. The extrapolation factor from the measured to the full phase-space lies between 6 for low Q^2 and 3 at high Q^2. This includes the extrapolation of the p_T^b and η^b spectrum, fragmentation and decay kinematics for jet and μ and the η and p_T cuts on the muon and the jet. The branching fraction of $b\bar{b}$ to μ of 0.3924 is not included in these extrapolation factors.

4 Results

A total visible cross section of $\sigma_{b\bar{b}} = 77.1 \pm 7.8(\text{stat.}) \pm^{9.6}_{14.9}$ (syst.) pb was measured for the reaction $ep \to e\ b\bar{b}\ X \to e\ jet\ \mu\ X'$ in the kinematic region defined by: $Q^2 > 4\ \text{GeV}^2$, $0.05 < y < 0.7$, $p_T^\mu > 1.5\ \text{GeV}$, $\eta^\mu > -1.6$ and one jet with $E_T^{jet} > 5\ \text{GeV}$ and $-2 < \eta^{jet} < 2.5$ associated to the muon. The systematic uncertainty is the quadratic sum of different individual uncertainties coming from the muon-efficiency correction, p_T^{rel}-shape for light flavours, ratio of light flavours to charm, energy scale and luminosity uncertainty. This result was compared to a NLO QCD calculation from HVQDIS [8], which uses the FFNS, 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 [5]. A mixture of direct ($b \to \mu$) and indirect ($b \to c \to \mu$ and $b \to \tau \to \mu$) b-hadron decays to muons has been used. The b-quark mass was set to $m_b = 4.75$ GeV and the renormalisation and factorisation scales to $\mu = \sqrt{p_T^2 + 4m_b^2}$. The CTEQ5F4 parton densities [9] have been used. The NLO QCD prediction is $\sigma_{NLO} = 32.9 \pm 3.3$ pb, where the error has been estimated by varying the scale μ by a factor of 2 and 1/2 and the mass m_b between 4.5 and 5.0 GeV. The measured total cross section is about 2σ higher than the NLO prediction. The differential cross sections were measured in the same kinematic range as the total visible cross section by repeating the fit of the p_T^{rel}-distribution in each bin. Differential cross sections as a function of Q^2, p_T^μ, η^μ, p_T^{jet} and η^{jet} are shown in [1]. In all distribution the data are

PDF	Order	Scheme	μ^2	M_b(GeV)
MRST04	α_s^2	VFNS	Q^2	4.3
MRST NNLO	α_s^3	VFNS	Q^2	4.3
CTEQ6.5	α_s^2	VFNS	$Q^2 + M^2$	4.5
HVQDIS+CTEQ5F3	α_s^2	FFNS	$p_T^2 + 4M^2$	4.75

Table 1: PDF schemes and parameters, the first three are taken from [14, 15].

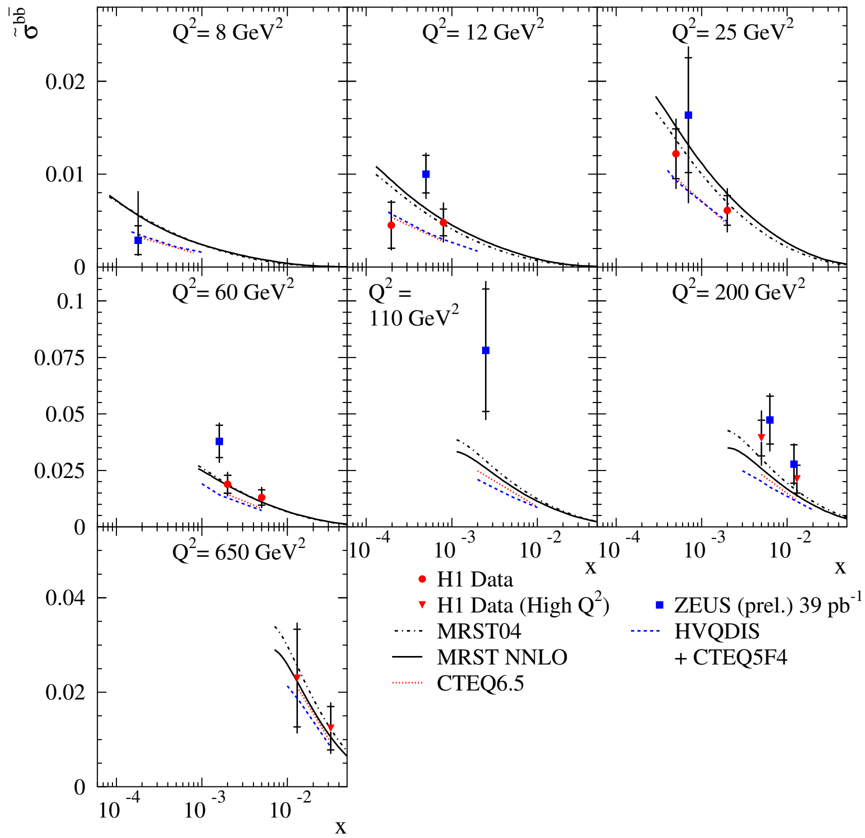

Figure 2: The measured reduced cross section shown as a function of x for different values of Q^2, together with measurements from H1 [10]. Different QCD predictions (see Tab.1) are also shown.

described in shape by the MC and by the NLO QCD calculation. The constant factor between the normalisation of the data and the NLO QCD calculations in these distributions reflects the 2σ difference seen in the total cross section. The $F_2^{b\bar{b}}$ measurements are shown in Figure 2 together with values from H1 [10]. The HVQDIS + CTEQ5F4 prediction and other predictions from NLO calculations using the variable flavour number scheme (VFNS) with different parameters (see Table 1) are shown. The ZEUS data lie above the H1 data, but are compatible within uncertainties. The large spread between the theory curves is partially caused by the use of different scales (see Tab. 1) and partially by the different treatment of the flavour threshold within VFNS between the MRST [11] and CTEQ6.5 [12, 13] predictions.

5 Conclusions

The production of beauty quarks in the deep inelastic scattering (DIS) process $ep \rightarrow e\ b\bar{b}\ X \rightarrow e\ jet\ \mu\ X'$ has been measured with the ZEUS detector at HERA II. The total visible cross section is 2σ higher than the NLO prediction. Differential cross sections $d\sigma/dQ^2$, $d\sigma/dp_T^\mu$, $d\sigma/d\eta^\mu$, $d\sigma/dp_T^{jet}$ and $d\sigma/d\eta^{jet}$ were measured. In all distributions the data are described in shape by the MC and by the NLO QCD calculation. $F_2^{b\bar{b}}$ results agree with results from H1, where a very different method was used to obtain $F_2^{b\bar{b}}$, with similar uncertainties. The measured values of $F_2^{b\bar{b}}$ are found to be described by perturbative QCD predictions within the large uncertainties.

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