Beauty production in DIS and the measurement of $F_2^{b\bar{b}}$ at ZEUS

Marcello Bindi, on behalf of the ZEUS Collaborations

University and INFN of Bologna - Department of Physics
Viale Berti Pichat,6/2 - 40127 - Bologna - Italy

Beauty production has been measured in DIS regime with the ZEUS detector at HERA. Beauty was reconstructed using its semi-leptonic decay into muons. The beauty signal was separated from the background using lifetime information, the transverse momentum of the muon with respect to the axis of the associated jet and the missing transverse momentum parallel to the muon direction. Differential cross sections were measured and compared to next-to-leading order QCD predictions. The beauty contribution to the proton structure function F_2, $F_2^{b\bar{b}}$, was extracted and compared with theoretical predictions using different parameterisations of the proton PDFs.

1 Introduction

The measurement of beauty production in deep inelastic scattering (DIS) provides a stringent test of quantum chromodynamics (QCD) since the large b quark mass provides a hard scale that makes perturbative calculations applicable. At leading order, beauty quark is produced in DIS via boson–gluon fusion (BGF) ($\gamma^* g \to q\bar{q}$). From the total cross section for beauty production, the contribution to the proton structure function F_2, $F_2^{b\bar{b}}$, can be extracted and compared to NLO QCD predictions. Since these predictions are sensitive to the gluon density of the proton, the measurement can help in constraining it.

Beauty production in DIS has been previously studied in events with muons and jets [1] and from lifetime information [2]. The existing data are generally in good agreement with next-to-leading-order (NLO) QCD predictions. The largest differences were observed in the muon analyses [1], where in certain kinematic regions the measured beauty cross section was about two standard deviations above the theoretical expectation.

A new ZEUS analysis [3], that is a simultaneous measurement of beauty and charm production using semi-leptonic (SL) decays into muons, is presented here. The fractions of muons originating from beauty, charm and light flavours (LF) are extracted by exploiting three discriminating variables: the muon impact parameter, the muon momentum component transverse to the associated jet axis and the missing transverse momentum, which is sensitive to the neutrino from SL decays. The analysis focuses on data with large squared four-momentum exchange at the electron vertex, $Q^2 > 20$ GeV^2. The cross sections for muons from beauty and charm decays are measured for muon transverse momenta $p_T^\mu > 1.5$ GeV and pseudorapidities $-1.6 < \eta^\mu < 2.3$ as a function of p_T^μ, η^μ, Q^2, and of the Bjorken scaling variable x and compared to QCD predictions. The muon cross sections, measured in bins of x and Q^2, are used to extract the heavy quark contributions to the proton structure function F_2 which are compared to previous results and to QCD predictions.

The data used in this analysis were collected with the ZEUS detector during 2005 running period when HERA collided electrons with energy $E_e = 27.5$ GeV with protons with $E_p =$ 920 GeV corresponding to a centre-of-mass energy $\sqrt{s} = 318$ GeV. The corresponding integrated luminosity was $\mathcal{L} = 126.0 \pm 3.3$ pb^{-1}.

2 Theoretical predictions

The results of this analysis have been compared to NLO calculations at next-to-leading order ($O(\alpha_s^2)$) in the fixed flavour number scheme (FFNS) in which only light flavours are present in the proton and heavy quarks (HQ) are produced in the interaction. The calculation has been performed with the HVQDIS program [4]. The renormalisation and factorisation scales were set to $\mu_R^2 = \mu_F^2 = Q^2 + 4m_q^2$ and the quark masses to $m_c = 1.5$ GeV and $m_b = 4.75$ GeV. The PDFs were obtained by repeating the ZEUS-S [5] PDF fit in the FFNS with quark masses set to the same values as in the HVQDIS calculation.

The partonic results were interfaced to a model of HQ fragmentation into weakly decaying heavy hadrons and of the decay of heavy hadrons into muons. The hadron momentum was obtained by scaling the quark momentum according to the fragmentation function of Peterson et al. [6]: $\epsilon_c = 0.055$ for charm and $\epsilon_b = 0.0035$ for beauty. The branching ratios were set to $\mathcal{B}(c \to \mu) = 0.096 \pm 0.004$ and $\mathcal{B}(b \to \mu) = 0.209 \pm 0.004$ [7].

The uncertainty on the theoretical predictions was evaluated by independently varying μ_R and μ_F by a factor two; by varying the HQ masses simultaneously to $(m_c, m_b) = (1.3, 4.5), (1.7, 5.0)$ Gev in the calculation and in the PDF fit; by varying the proton PDFs by their experimental uncertainty and by varying the fragmentation parameters within $0.04 < \epsilon_c < 0.12$ and $0.0015 < \epsilon_b < 0.0055$. The total theoretical uncertainty, obtained by adding in quadrature the effects of each variation, is dominated for the beauty case by the variation of μ_R and of the mass m_b.

3 Selection cuts, fits and cross sections

A sample of muon in DIS was selected with

$$(E-P_Z)_{\rm total} \subset [40, 80] \text{ GeV} \qquad y_e = 1 - E_e'(1-\cos\theta_e)/(2E_e) < 0.7 \tag{1}$$

$$y_{\rm JB} = (E-P_Z)_{hadronic}/(2E_e) > 0.01 \quad Q_\Sigma^2 = (E_e' \sin\theta_e)^2/(1 - y_\Sigma) > 20 \text{ GeV}^2, \tag{2}$$

where $y_\Sigma = (E-P_Z)_{hadronic}/(E-P_Z)_{\rm total}$, and θ_e is the electron polar angle. These cuts restricted the accessible inelasticity $y = Q^2/(xs)$ and Q^2 to $0.01 < y < 0.7$ and $Q^2 > 20$ GeV^2. The DIS variables x and Q^2 were reconstructed using the Σ estimators Q_Σ^2 and $x_\Sigma = Q_\Sigma^2/(s y_\Sigma)$. To remove background events with isolated muons ($\gamma\gamma \to \mu^+\mu^-$, J/ψ and Υ decays) and residual cosmic muons, an anti-isolation cut was applied by requiring that the hadronic energy in a cone of radius 1 in the $\eta - \phi$ plane around the muon candidate, excluding the muon itself, was $E^{\rm iso} > 0.5$ GeV. A jet associated to the muon is required with $P_T^{jet} > 2.5$ GeV. After the above selections, the final sample contained 11126 muons.

The fractions of muons originating from charm, beauty or LF events are determined by fitting a combination of MC distributions to the measured three-dimensional distribution of the following discriminating variables [8] that are sensitive to different aspects of HQ decays:

- $p_T^{\rm rel}$, the muon momentum component transverse to the axis of the associated jet, $p_T^{\rm rel} = |\mathbf{p}^{\,\mu} \times \mathbf{p}^{\,\rm jet}|/|\mathbf{p}^{\,\rm jet}|$.
- δ, the distance of closest approach of the muon track to the centre of the interaction region in the X, Y plane. A positive sign is assigned to δ if the muon track crosses the axis of the associated jet in the jet hemisphere, negative otherwise. Muons from

decays of long-lived heavy quarks tend to have positive δ while tracks originating from the primary interaction have a symmetric δ distribution around zero, corresponding to the experimental resolution.

- $p_T^{\mathrm{miss}||\mu}$, the missing transverse momentum parallel to the muon direction. The $p_T^{\mathrm{miss}||\mu}$ distribution has a positive tail of events containing semileptonic HQ decays due to the presence of the neutrino.

A control sample of inclusive DIS data, selected similarly to the muon sample but without any muon requirement, is used to test the quality of the simulation of these variables. The control sample is dominated by LF events, containing, according to MC, about (1%) b events.

The global charm and beauty fractions resulting from the fit are $f_c = 0.456 \pm 0.029$(stat.) and $f_b = 0.122 \pm 0.013$(stat.) with a correlation coefficient $\rho_{cb} = -0.43$. The distributions of p_T^μ, η^μ, p_T^{jet}, $E - P_Z$, Q^2_Σ and x_Σ for the data and for the MC samples normalised according to the fit are shown in Figure 1.

The distributions of the three discriminating variables are shown in Fig. 2 (a-c) togheter with the distribution of p_T^{rel} for a signal-enriched subsample (Fig. 2 - d).

The visible cross section for muons from beauty decays in the kinematic region $Q^2 > 20\ \mathrm{GeV}^2$, $0.01 < y < 0.7$, $p_T^\mu > 1.5 GeV$ and $-1.6 < \eta^\mu < 2.3$

$$\sigma^b = \ 63 \pm \ 7(\mathrm{stat.})\ ^{+18}_{-11}(\mathrm{syst.})\ \mathrm{pb}$$

has to be compared with the NLO QCD cross section obtained with Hvqdis of $\sigma^b = 33 \pm 5$ pb. The beauty cross section is 2.3 (1.9) standard deviations above the central (upper) Hvqdis result. The differential cross sections as a function of p_T^μ, η^μ, Q^2, and x are compared in Fig. 3 to the NLO QCD predictions based on Hvqdis. The predictions from Rapgap MC are also shown, normalised according to the result of the global fit. The tendency of the beauty cross section to lie above the central NLO prediction is concentrated at low p_T^μ and low Q^2. The MC gives a good description of the shape of all the differential cross sections.

4 Extraction of $F_2^{q\bar{q}}$

The relation between heavy quark contributions to the proton structure functions, $F_2^{q\bar{q}}$, $F_L^{q\bar{q}}$ and the double differential cross section in x and Q^2 for the production of the quark q is:

$$\frac{d^2\sigma^{q\bar{q}}}{dx\, dQ^2} = \mathcal{K}\ \left[F_2^{q\bar{q}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{q\bar{q}}(x,Q^2) \right] = \mathcal{K}\ \tilde{\sigma}^{q\bar{q}}(x,Q^2,s),$$

where $\mathcal{K} = Y_+(2\pi\alpha^2_{\mathrm{em}})/(xQ^4)$ and $Y_+ = 1+(1-y)^2$. The muon cross sections, σ^q, measured in bins of x and Q^2, were used to extract $F_2^{q\bar{q}}$ at a reference points in the x, Q^2 plane by:

$$F_2^{q\bar{q}}(x,Q^2) = \sigma^q \frac{F_2^{q\bar{q},\mathrm{th}}(x,Q^2)}{\sigma^{q,\mathrm{th}}},$$

where $F_2^{q\bar{q},\mathrm{th}}(x,Q^2)$ and $\sigma^{q,\mathrm{th}}$ were calculated at NLO in the FFNS using the Hvqdis program. This procedure contains several corrections: the extrapolation from the restricted muon kinematic range ($p_T^\mu > 1.5GeV, -1.6 < \eta^\mu < 2.3$) to the full muon phase space; the $q \to \mu$ branching ratio; the correction for the longitudinal structure function $F_L^{q\bar{q}}$ and the correction from a bin-averaged cross section to a point value (bin centring).

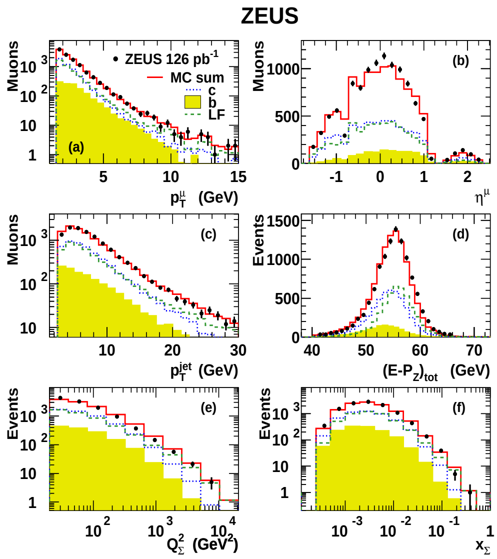

Figure 1: Distributions of (a) p_T^μ, (b) η^μ, (c) $p_T^{\rm jet}$, (d) $(E-P_Z)_{\rm tot}$, (e) Q^2_Σ and (f) x_Σ for the selected sample of muons in DIS. The data (points) are compared to the MC expectation (solid line) with the c (dotted line), b (shaded histogram) and light flavours,(dashed line), LF, components.

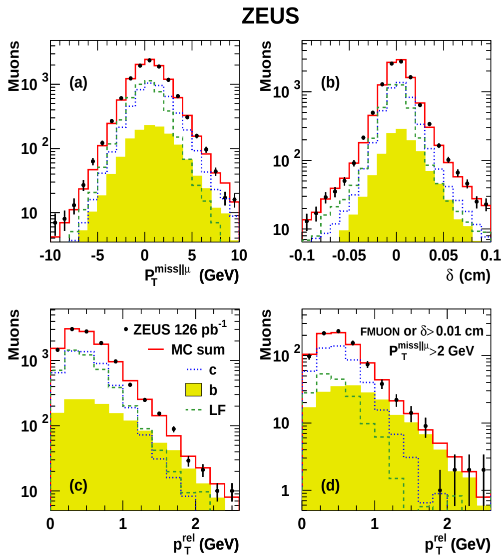

Figure 2: Distributions of (a) $p_T^{\rm miss||\mu}$, (b) δ, (c) $p_T^{\rm rel}$ for the selected sample of muons in DIS, and of (d) $p_T^{\rm rel}$ for a signal-enriched subsample with $p_T^{\rm miss||\mu} > 2$ GeV and either a muon in FMUON or $\delta > 0.01$ cm.

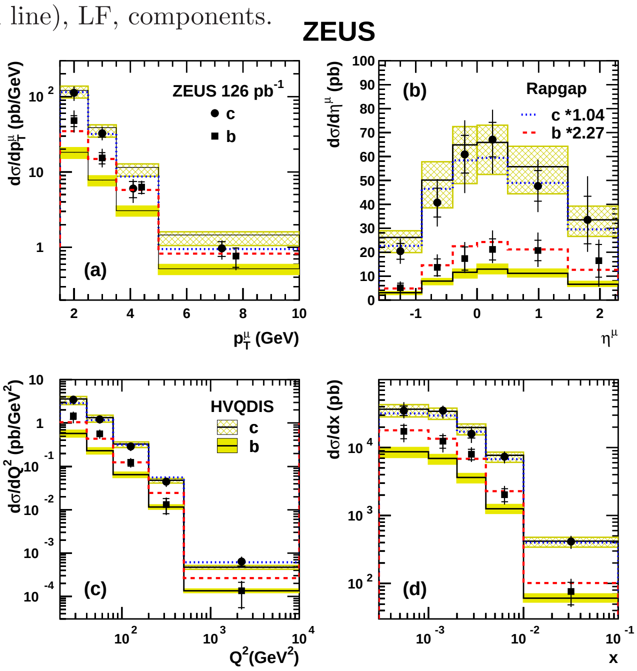

Figure 3: Differential muon cross sections for c and b as a function of (a) p_T^μ, (b) η^μ, (c) Q^2, and (d) x. The bands show the NLO QCD predictions (HVQDIS) and the corresponding uncertainties. The differential cross sections from RAPGAP are also shown.

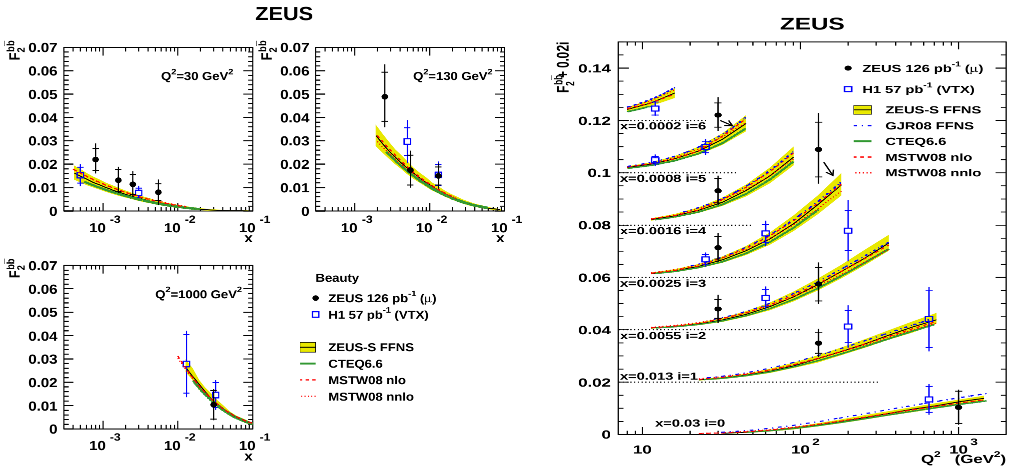

Figure 4: On the left $F_2^{b\bar{b}}$ as a function of x (filled symbols) is compared to previous results (open symbols). On the right $F_2^{b\bar{b}}$ (filled symbols) as a function of Q^2 for fixed x values is presented. The curves with the relative bands represent the NLO QCD predictions in the FFNS using the ZEUS-S PDF fit with their uncertainty.

The largest uncertainty is related to the extrapolation to the full muon phase space. The theoretical uncertainty in the extraction of $F_2^{q\bar{q}}$ was evaluated by varying the HVQDIS parameters as explained in Section. 2 and by using a different PDF set (CTEQ5F). The theoretical uncertainty in the extraction of $F_2^{b\bar{b}}$ is 5%.

Figure 4 shows the extracted $F_2^{b\bar{b}}$ from this analysis and also a previous H1 result [2], corrected to the reference Q^2 values used in the present analysis. The two data sets are in good agreement. At high Q^2 the precision of the present measurement is similar to that of the H1 data . In the same Figure the extracted $F_2^{b\bar{b}}$ as functions of Q^2 for fixed values of x is shown, compared to previous results corrected to the same reference x used in the present analysis. Different QCD calculation are also shown. For $Q^2 \geq 60$ GeV^2 the present results are of comparable or higher precision than those previously existing.

References

[1] ZEUS Coll, S. Chekanov et al, Phys. Lett. **B 599**, 173 (2004)
H1 Coll, A. Aktas et al, Eur. Phys. J. **C 41**, 453 (2005)

[2] H1 Coll, A. Aktas et al, Eur. Phys. J. **C 40**, 349 (2005)
H1 Coll, A. Aktas et al, Eur. Phys. J. **C 45**, 23 (2006)

[3] ZEUS Coll, S. Chekanov et al, arXiv:0904.3487v1 [hep-ex] submitted ot EPJ C

[4] J. Smith and W.L. van Neerven, Nucl. Phys. **B 374**, 36 (1992)
B.W. Harris and J. Smith, Nucl. Phys. **B 452**, 109 (1995)
B.W. Harris and J. Smith, Phys. Lett. **B 353**, 535 (1995). Erratum-ibid **B 359** (1995) 423

[5] ZEUS Coll, S. Chekanov et al, Phys. Rev. **D 67**, 012007 (2003)

[6] C. Peterson et al, Phys. Rev. **D 27**, 105 (1983)

[7] Particle Data Group, W.-M. Yao et al, J. Phys. **G 33**, 1 (2006)

[8] M. Bindi, *Measurement of the Charm Production Cross Section in DIS Events at HERA*. PhD Thesis, Università di Bologna, Report DESY-THESIS-2008-026, 2008