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Measurement of beauty production in deep inelastic scattering at HERA

ZEUS Collaboration

Abstract

The production of beauty quarks in the deep inelastic scattering (DIS) process $e^+p \rightarrow e^+ + \mu^\pm + \mathrm{jet} + X$ has been measured with the ZEUS detector at HERA using an integrated luminosity of $60\,\mathrm{pb}^{-1}$. Events with a muon and at least one jet in the Breit frame with transverse energy greater than $6\,\mathrm{GeV}$ were selected. The fraction of beauty quarks in the data was determined using the distribution of the transverse momentum of the muon relative to the closest jet. The cross section for beauty production was measured in the kinematic range $Q^2 > 2\,\mathrm{GeV}^2$, $0.05 < y < 0.7$ and the muon was restricted to the region of polar angle $30^\circ < \theta < 160^\circ$ and momentum $p > 2\,\mathrm{GeV}$. The result is compared with next-to-leading-order QCD predictions.

1 Introduction

Reactions involving heavy quarks can be used to test Quantum Chromorodynamics (QCD) and to probe the proton and photon structure. The large charm (c) and especially beauty (b) quark masses provide a hard scale that ensures perturbative QCD (pQCD) is applicable and makes such calculations more reliable than for light quarks. The b-production cross sections were measured first in proton-antiproton collisions at CERN [1] and at Tevatron [2] and, more recently in two-photon interactions at LEP [3] and electron-proton (ep) scattering at HERA [4,5]. For all the measurements, except the early CERN data [1], the measured b-production cross sections lie significantly above QCD expectations calculated up to next-to-leading order (NLO) in the strong coupling constant, α_s.

This paper reports the first ZEUS measurement of beauty production in deep inelastic scattering (DIS), in the reaction with at least one hard jet in the Breit frame [6] and a muon in the final state:

$$e^+p \to e^+ + \text{jet} + \mu^\pm + X.$$

In the Breit frame, defined by $\boldsymbol{\gamma} + 2x\boldsymbol{P} = 0$, where $\boldsymbol{\gamma}$ is the momentum of the exchanged photon, x is the Bjorken scaling variable and $\boldsymbol{P}$ is the proton momentum, a purely space-like photon and a proton collide head-on. In this frame, any final-state particle with a high transverse momentum is produced by a hard interaction.

Due to the large b-quark mass, muons from semi-leptonic b decays usually have high values of $p_T^{\rm rel}$, which is the transverse momentum of the muon with respect to the axis of the closest jet. In the case of muons coming from charm decays and in events induced by light quarks, where some of the produced hadrons are misidentified as muons ("fake muons"), the $p_T^{\rm rel}$ values are low. Therefore, the fraction of events from b-decays in the data sample can be extracted by fitting the $p_T^{\rm rel}$ 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, $\sigma_{b\bar{b}}$, and differential cross sections as a function of the photon virtuality Q^2, $d\sigma/dQ^2$, and as a function of the Bjorken scaling variable x, $d\sigma/d\log_{10}(x)$ are measured and compared to leading-order (LO) and NLO QCD calculations.

2 Analysis

The data used in this measurement were collected during the 1999-2000 HERA running period, where a proton beam of 920 GeV collided with a positron beam of 27.5 GeV, corresponding to an integrated luminosity of $(60 \pm 1)\,\text{pb}^{-1}$. The reconstruction of observables characterising the event topology and kinematic variables was based on combined information from the compensating uranium scintillator calorimeter (CAL) [7], the central tracking detector (CTD) [8], the small angle rear tracking detector (SRTD) [9], the barrel and rear muon chambers (BMUON and RMUON) [10] and the luminosity monitor [11].

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. The final sample was selected in four steps: 1) inclusive DIS event selection, 2) muon finding, 3) jet finding and 4) muon-jet association.

1. DIS events were selected by requiring a well reconstructed outgoing positron with energy greater than 10 GeV, $Q^2 > 2\,\mathrm{GeV}^2$ and inelasticity $0.05 < y < 0.7$, where $y = Q^2/xs$. Additionally, the reconstructed event vertex had to lie within 50 cm of the interaction point.

2. Muons were identified by requiring a reconstructed segment both in the inner and outer part of BMUON and RMUON chambers, where the rear direction is defined by the incoming positron[1]. The muon chambers measure the impact position and the momentum of the muon track. The reconstructed muons are then matched in space and momentum with a track found in the CTD, with a χ^2 of the matching required to be smaller than 15. This cut rejects background from muons coming from $K^\pm$ and $\pi^\pm$ decays and from fake muons produced in hadronic showers in the CAL. In addition, a cut on the muon momentum, $p^\mu > 2\,\mathrm{GeV}$, was applied and a cut on the muon polar angle θ^μ, $30^\circ < \theta^\mu < 160^\circ$, was applied.

   The reconstruction efficiency of the muon chambers was estimated separately for BMUON and RMUON using an independent sample of di-muon events.

3. Hadronic final-state objects, reconstructed from tracks and energy deposits in the calorimeter, were boosted to the Breit frame and clustered into jets using the k_T cluster algorithm (KTCLUS) [12] in its longitudinally invariant inclusive mode [13] with the E_T recombination scheme. Reconstructed muons were included in the clustering procedure. Selected events had at least one jet with $E_T^{\mathrm{Breit}} > 6\,\mathrm{GeV}$ and within the detector acceptance $-2 < \eta^{\mathrm{LAB}} < 2.5$, where η^{LAB} is the pseudorapidity[2] in the laboratory frame.

4. The muons in the sample were associated with a jet using the KTCLUS information, where the associated jet was not necessarily the jet satisfying the cuts above. To ensure a good reconstruction of the associated jet, it was required to have transverse energy in the Breit frame $E_T^{\mathrm{Breit}} > 4\,\mathrm{GeV}$.

After all selection cuts, the final data sample contains 836 events.

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the centre of HERA. The coordinate origin is at the nominal interaction point.

[2] The pseudorapidity is defined as $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$, where the polar angle, θ, is measured with respect to the proton beam direction.

To correct the results for acceptance and to extract the beauty fraction, the RAPGAP2.08 Monte Carlo (MC) simulation [14] was used. RAPGAP is a generator based on leading-order (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 [15].

The light-flavour and charm-quark RAPGAP samples were mixed according to the relative luminosities and the b-quark sample was added according to the beauty fraction determined from the $p_T^{\rm rel}$ analysis.

Figure 1 shows the $p_T^{\rm rel}$ distribution as measured in the ZEUS detector for the data, light-plus-charm and beauty MC contributions. The distribution is peaked at low $p_T^{\rm rel}$, where the decays of hadrons containing charm and light quarks dominate. At higher $p_T^{\rm rel}$, the distribution falls less steeply than that expected for light and charm contributions alone. The data are consistent with a significant contribution from b quarks. To determine the beauty fraction in the data, the contribution from light-plus-charm flavours and beauty were allowed to vary, and the best mixture was extracted using a binned maximum-likelihood method. The measured beauty fraction, $f_{\rm beauty}$, is $(25 \pm 5)\%$, where the error is statistical. The sum of the MC contributions shown in Fig. 1 describes the data well.

Figure 2 shows the comparison between the data and the MC simulation with respect to various variables describing properties of the measured muon and the associated jet. Here, the relative fractions of the contributions from beauty and light plus charm quarks have been fixed by the procedure described above. The MC agrees reasonably well with the measured distributions. This demonstrates that the RAPGAP MC can be reliably used to calculate the detector-acceptance corrections.

3 Results

The total visible cross section, $\sigma_{b\bar{b}}$, was determined in the kinematic range $Q^2 > 2\,{\rm GeV}^2$, $0.05 < y < 0.7$ with a muon with $p^\mu > 2\,{\rm GeV}$ and $30^\circ < \theta^\mu < 160^\circ$ and one jet in the Breit frame with $E_T^{\rm Breit} > 6\,{\rm GeV}$ and $-2 < \eta^{\rm LAB} < 2.5$. The measured cross section is

$$\sigma_{b\bar{b}}(e^+p \rightarrow e^+b\bar{b}X \rightarrow e^+{\rm jet}\ \mu^\pm X) = 38.7 \pm 7.7\ ({\rm stat.})^{+6.1}_{-5.0}({\rm syst.})\,{\rm pb}.$$

The biggest contribution to the systematic uncertainty comes from the muon reconstruction efficiency and from the $p_T^{\rm rel}$ fit procedure.

The NLO QCD predictions were evaluated using the HVQDIS program [16, 17]. Fragmentation of b-quarks into hadrons was performed using the Peterson function [18] with $\epsilon = 0.002$, as recently suggested [19]. The semi-leptonic decay of b-hadrons was modeled using a parameterisation of the muon momentum spectrum extracted from RAPGAP. A mixture of direct ($b \to \mu$) and indirect ($b \to c \to \mu$) b-hadron decays to muons was used. The b-quark mass was set to $m_b = 4.75\,\mathrm{GeV}$ and the renormalisation and factorisation scales to $\mu = \sqrt{Q^2 + 4m_b^2}$. The CTEQ5F4 parton densities [20] were used. The cross section was determined using the sum of the branching ratios of direct and indirect decays of b hadrons into muons, which was fixed to 0.22, as implemented in JETSET [15]. The NLO QCD prediction is $28^{+5.3}_{-3.5}$ pb, where the error was estimated by varying the scale μ by a factor of 2 and the mass m_b between 4.5 and 5.0 GeV and adding the respective contribution in quadrature. An additional uncertainty introduced by varying the Peterson parameter ϵ by ± 0.001 is of the order of 3-4 %. The measured total cross section is somewhat above but agrees with the NLO prediction within the experimental and theoretical uncertainties. The program CASCADE [21] implements the LO calculations based on the CCFM [22] evolution equations, which implement the resummation of $\log(1/x)$ factors in the low-x limit. CASCADE is based on unintegrated gluon densities fitted to the HERA proton-structure-function data. The LO CASCADE program gives a prediction of 35 pb, which is also in good agreement with the measurement presented here.

Figure 3 shows the ratio of the b-production cross section measured at HERA for both photoproduction and DIS to theoretical NLO QCD calculations.

The differential cross sections were calculated in the same restricted kinematic range as the total cross section by repeating the fit of the p_T^{rel} distribution in each bin. Figures 4 and 5 show the differential cross sections as functions of Q^2 compared to the NLO and LO QCD calculations, respectively. Figures 6 and 7 show the differential cross sections as functions of x compared to the NLO and LO QCD calculations, respectively. The NLO predictions agree with the data. The LO QCD prediction folded with the DGLAP evolution (RAPGAP MC) underestimates the measured cross sections. CASCADE is in good agreement with the data.

4 Conclusions

The production of beauty quarks in the deep inelastic scattering (DIS) process $e^+p \to e^+ + \mu^\pm + \mathrm{jet} + X$ has been measured with the ZEUS detector at HERA. The NLO QCD predictions agree with the measured total cross section and differential cross sections $d\sigma/dQ^2$ and $d\sigma/d\log_{10}(x)$ within the experimental and theoretical uncertainties. The LO QCD calculation in the DGLAP scheme underestimates the measured cross sections. CASCADE is in good agreement with the data.

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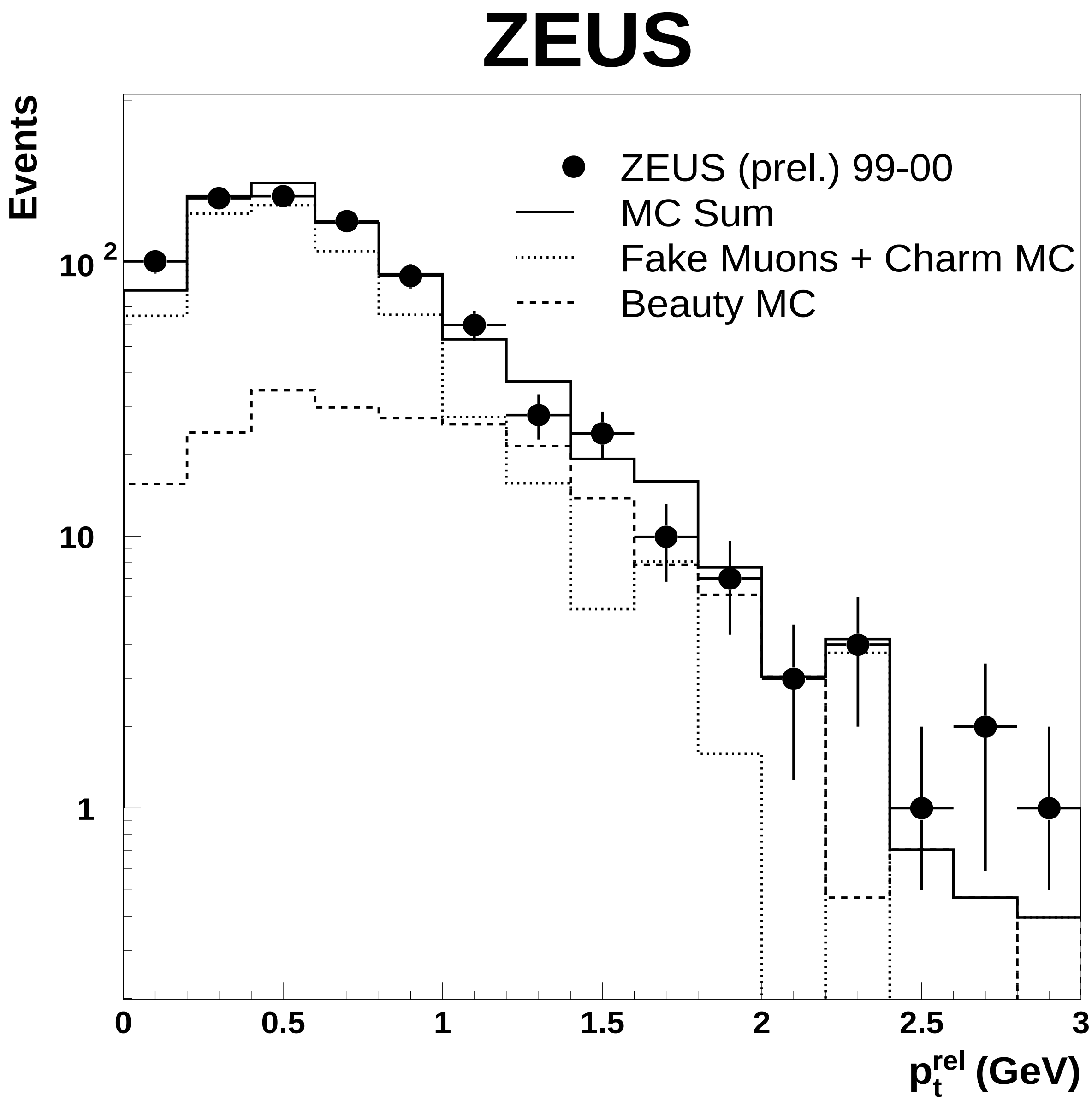

Figure 1: *Measured $p_T^{\rm rel}$ distribution for the data and MC. The fitted contribution (see Section 3) from beauty quarks (dashed histogram) and from light-plus-charm quarks (dotted histogram) are shown separately. The solid line corresponds to the sum of all MC contributions added as described in Section 3. The data points are plotted with the statistical uncertainties only.*

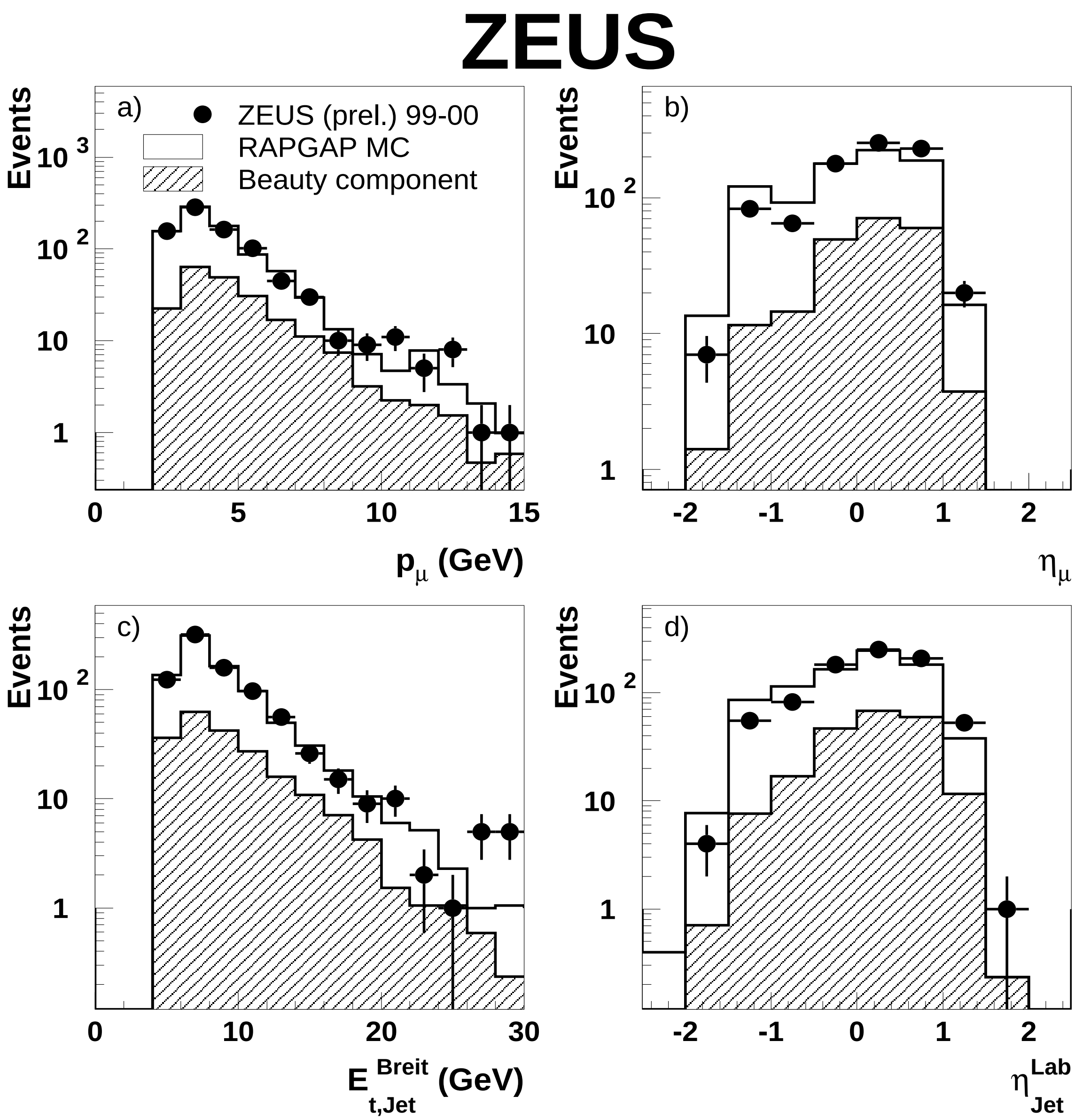

Figure 2: *Data (dots) and RAPGAP MC (solid line) distributions after the final event selection for a) momentum of the muon, b) pseudorapidity of the muon, c) transverse energy in the Breit frame and d) pseudorapidity in the laboratory frame of the associated jet. The solid line represents all MC contributions according to the percentage given by the fit (see Section 3), while the hatched histograms show the contribution from b quarks. The error bars are statistical only.*

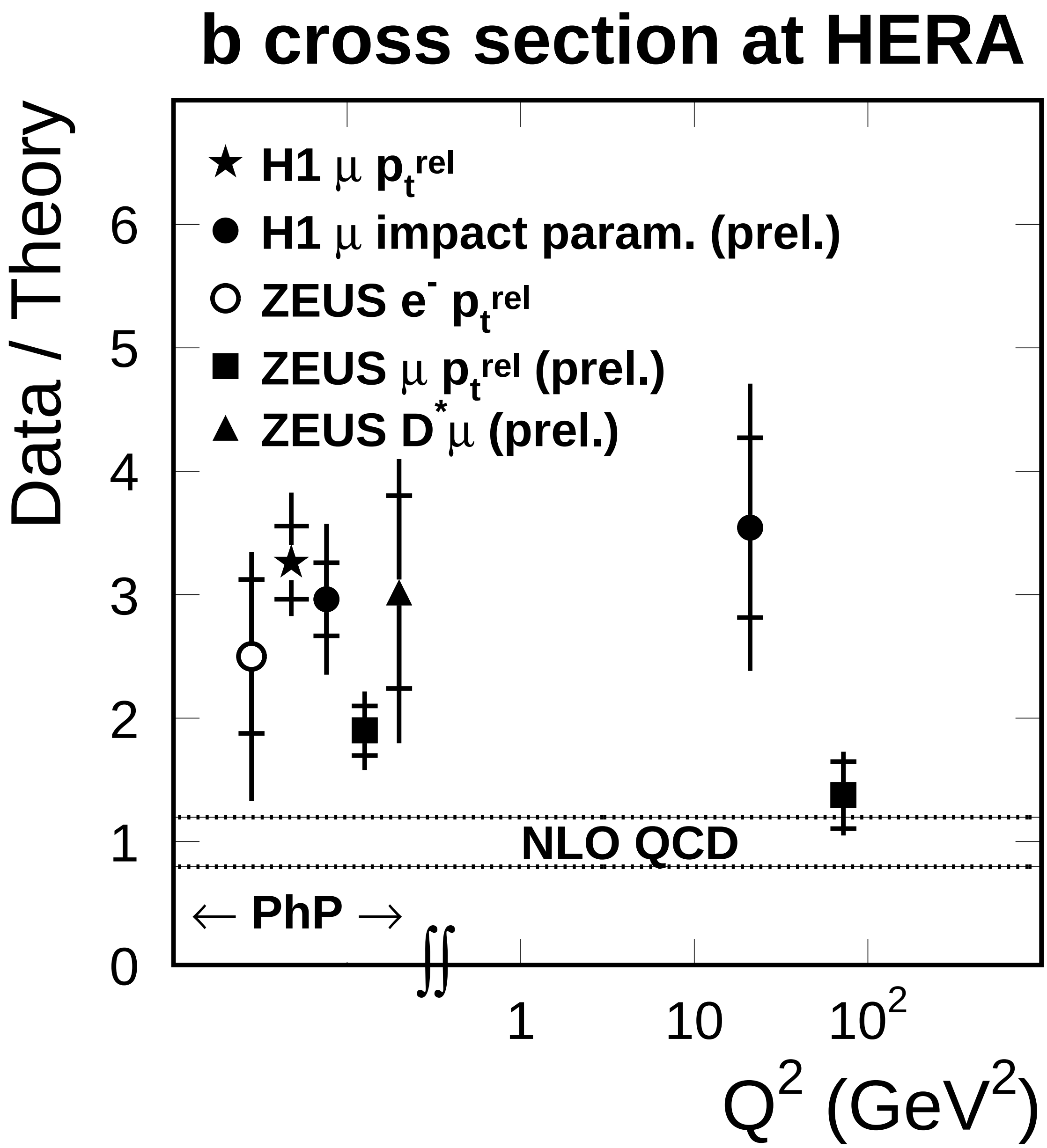

Figure 3: *Ratio of measured b-production cross section at HERA to NLO QCD expectations as a function of Q^2. Open squares correspond to the new ZEUS Preliminary results for DIS (this paper) and photoproduction with the p_T^{rel} method [23]. Triangle represents the photoproduction measurement using the D^*+muon tag [24]. The error bars on the data points indicate the statistical uncertainty on the measurement (inner error bars) and the quadratic sum of the statistical and systematic uncertainties of the measurement added in quadrature (outer error bars). The dotted band corresponds to the NLO QCD prediction with a generic uncertainty of 20%.*

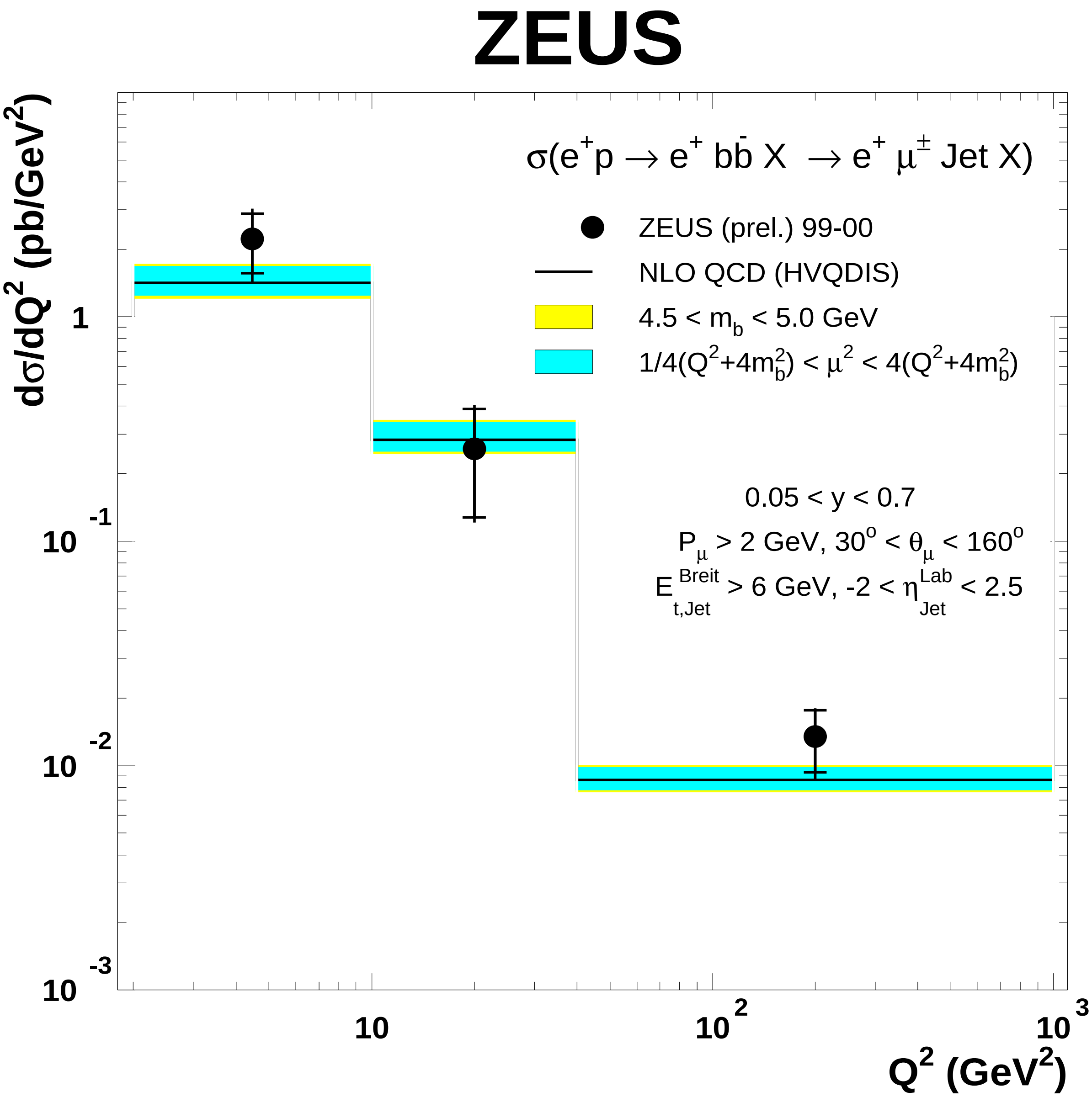

Figure 4: *Differential beauty cross section as a function of Q^2 for events with at least one jet reconstructed in the Breit frame and a muon, compared to the NLO QCD calculations. The error bars on the data points correspond to the statistical uncertainty (inner error bars) and to the statistical and systematic uncertainty added in quadrature (outer error bars). The shaded bands show the uncertainty of the theoretical prediction coming from the variation of the renormalisation and factorisation scale, μ, and the b-quark mass, m_b.*

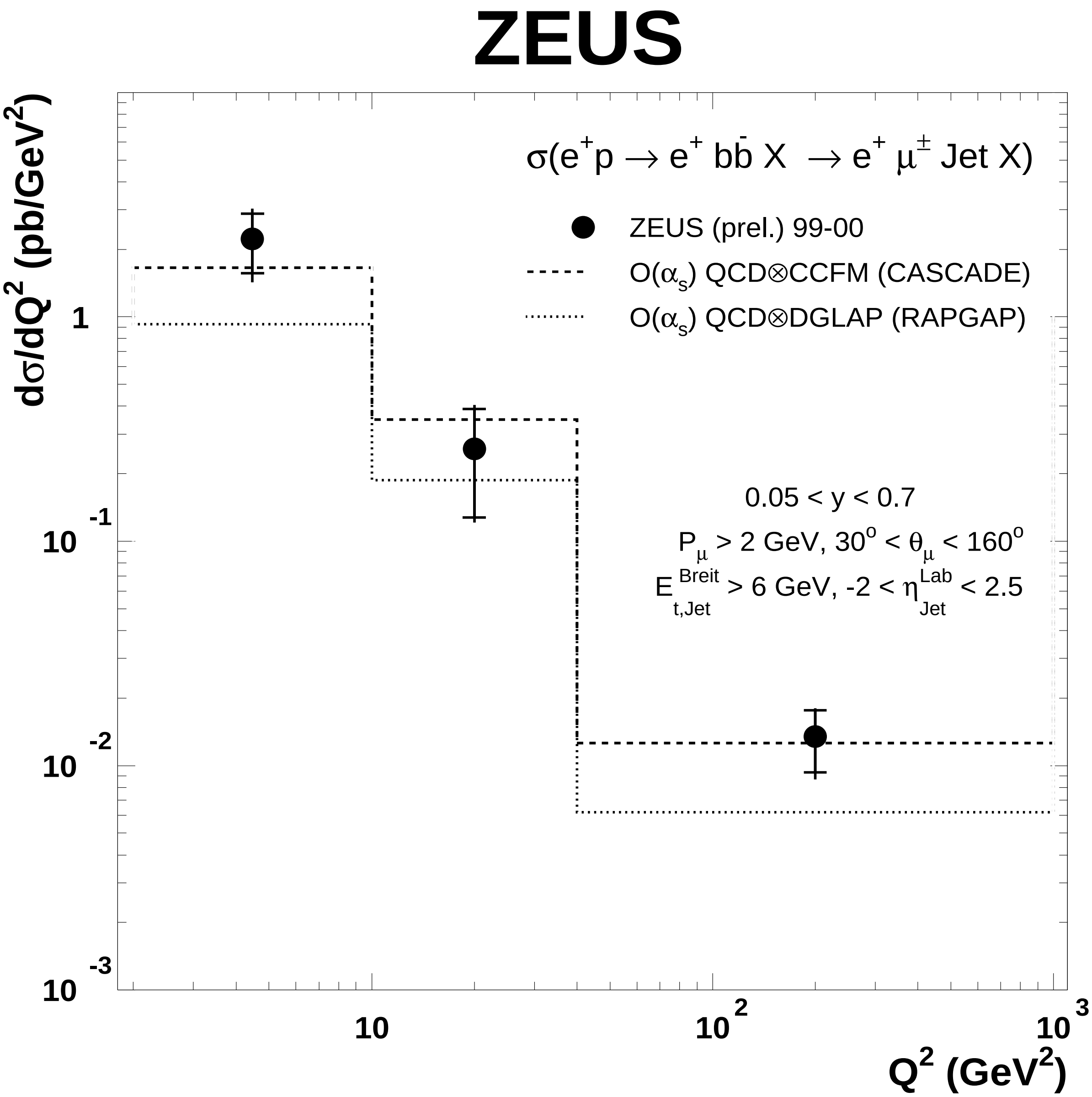

Figure 5: *Differential beauty cross section as a function of Q^2 for events with at least one jet reconstructed in the Breit frame and a muon, compared to the LO QCD calculations folded with DGLAP evolution (dotted line) and to the LO CASCADE prediction with CCFM evolution (dashed line). The error bars on the data points correspond to the statistical uncertainty (inner error bars) and to the statistical and systematic uncertainty added in quadrature (outer error bars).*

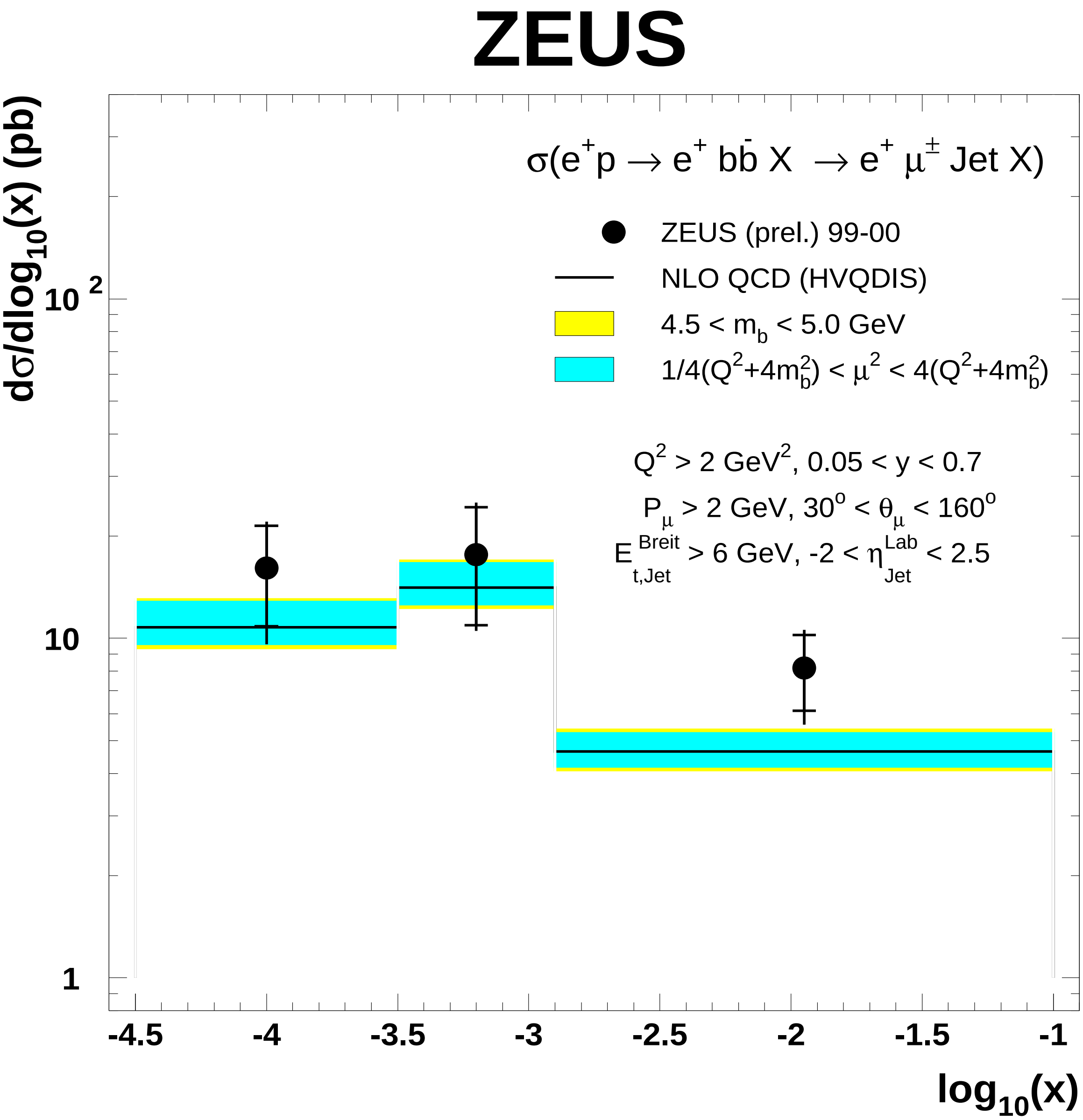

Figure 6: *Differential beauty cross section as a function of x for events with at least one jet reconstructed in the Breit frame and a muon, compared to the NLO QCD calculations. The error bars on the data points correspond to the statistical uncertainty (inner error bars) and to the statistical and systematic uncertainty added in quadrature (outer error bars). The shaded bands show the uncertainty of the theoretical prediction coming from the variation of the renormalisation and factorisation scale, μ, and the b-quark mass, m_b.*

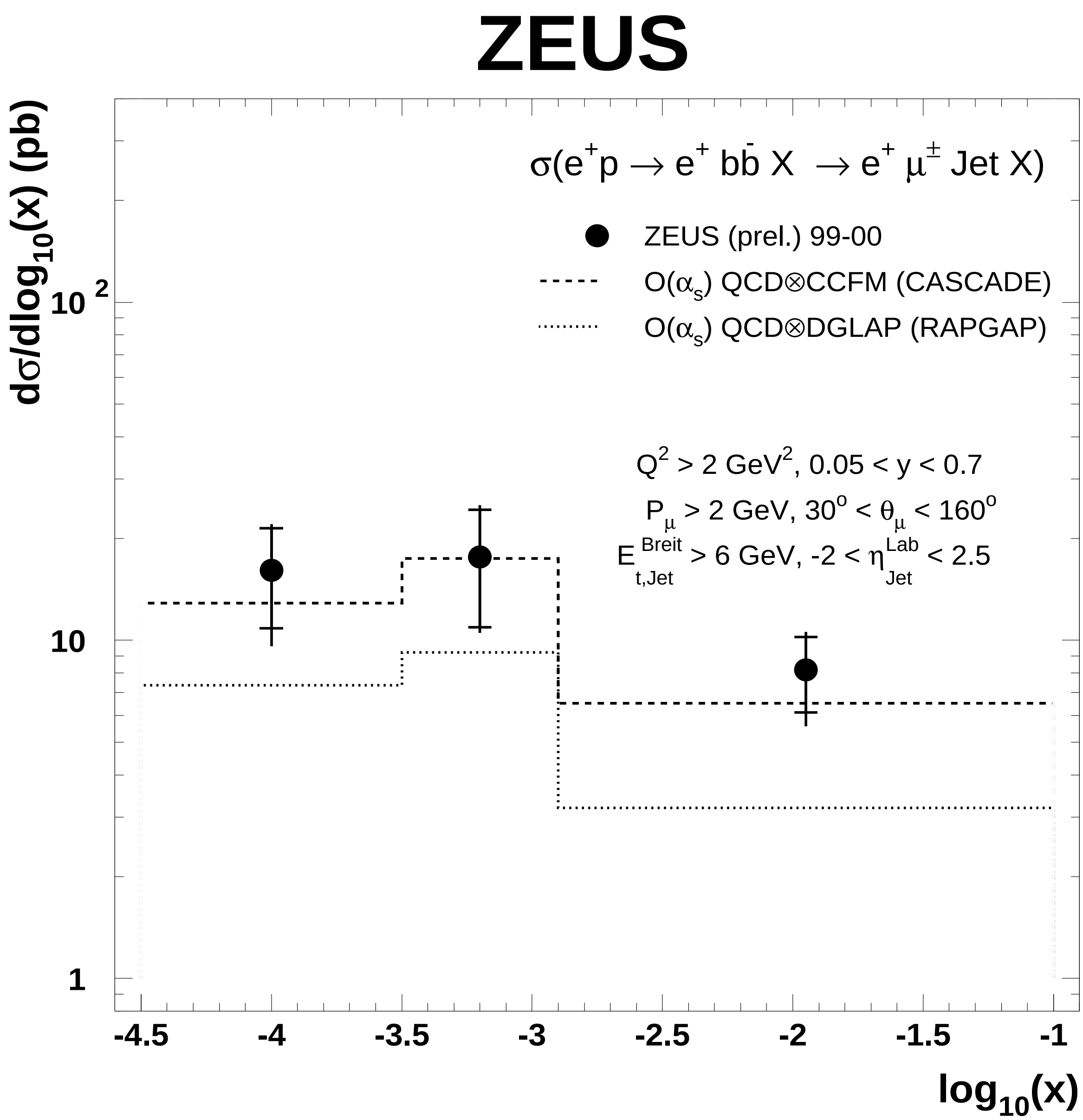

Figure 7: *Differential beauty cross section as a function of x for events with at least one jet reconstructed in the Breit frame and a muon, compared to the LO QCD calculations folded with DGLAP evolution (dotted line) and to the LO CASCADE prediction with CCFM evolution (dashed line). The error bars on the data points correspond to the statistical uncertainty (inner error bars) and to the statistical and systematic uncertainty added in quadrature (outer error bars).*