Beauty in ep collisions

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Recent results from the ZEUS and H1 collaborations at HERA on open beauty production in ep interactions at (300–318) GeV centre–of–mass energy are presented. Cross section measurements obtained from inclusive lepton analyses as well as from the study of $D^*\mu$ correlations are discussed and compared with QCD predictions.

1. INTRODUCTION

Measurements of beauty production in high-energy ep collisions probe proton and photon structure as well as the mechanisms of the hard subprocesses underlying ep interactions. They are considered an excellent testing ground for perturbative QCD calculations, where the high b quark mass ensures the presence of a hard scale.

The production of beauty quarks is predominantly gluon–induced. Figure 1(a) shows the leading order (LO) *photon–gluon fusion* diagram, where a photon emitted by the electron and a gluon coming from the proton form a beauty quark–antiquark pair. The exchange of a quasi–real photon (*photoproduction*, γp) dominates over large photon virtualities (*deep inelastic scattering*, DIS). Processes for which only a fraction $x_\gamma < 1$ of the photon's momentum enters the hard subprocess signal the partonic substructure of the photon and are therefore called *resolved photon interactions*, in contrast to *direct processes* where

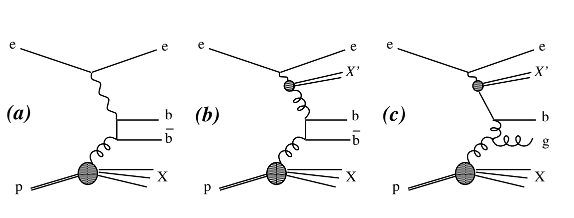

Figure 1. Examples for quark–level beauty production diagrams: (a) photon–gluon fusion, (b) gluon–gluon fusion and (c) beauty excitation in the photon.

$x_\gamma = 1$. Two examples for resolved photon interactions are given in Figure 1(b) and (c).

The beauty production cross section is two and three orders of magnitude smaller than charm and total cross sections respectively. Perturbative QCD calculations of the partonic process, assuming the b quark to be dynamically produced in the hard subprocess (*massive* approach), are available in next–to–leading order (NLO) and yield cross sections which are about a factor 1.4 higher than corresponding LO results. The connection to the hadron level is provided by fragmentation functions which are extracted from e^+e^- annihilation data. The dominant contributions to the error on the theoretical prediction arises from the uncertainty on the b quark mass and the choice of factorisation and renormalisation scales in the calculation. Monte Carlo (MC) simulations used in present analyses are based on LO matrix elements and parton showers, using, except for the CCFM–based CASCADE program, a DGLAP–like parton evolution.

In the following, results on beauty production obtained by the H1 and ZEUS experiments at the HERA collider for ep interactions at a centre–of–mass energy of $\sqrt{s} = (300 - 318)$ GeV are reviewed. All measurements are performed in the semi–leptonic decay channel. Most of them are using muons or electrons in di–jet events, but recently also results based on the study of correlations between identified muons and D^* mesons have become available. While earlier analyses provided total cross sections within suitably defined visible ranges in photoproduction and DIS, larger data sets now allow the production dynamics to be investigated in a more differential way.

2. LEPTON ANALYSES IN γp

2.1. Photon 2001 status

The first observation of open beauty production at HERA [1] was based on an inclusive muon analysis of H1 data recorded in 1996. Here, the transverse muon momentum p_t^{rel} relative to an associated jet was used as observable, thus exploiting the large beauty mass. A later preliminary H1 measurement [2] detected beauty hadrons in addition via their long lifetime by reconstructing the signed muon impact parameter δ, cf. Figure 2. In both cases, photoproduction cross sections for the process $ep \to b\bar{b}X \to \mu X'$ were extracted in a visible range defined by the event and muon kinematics. The results significantly exceeded the NLO QCD prediction obtained from the FMNR program [3].

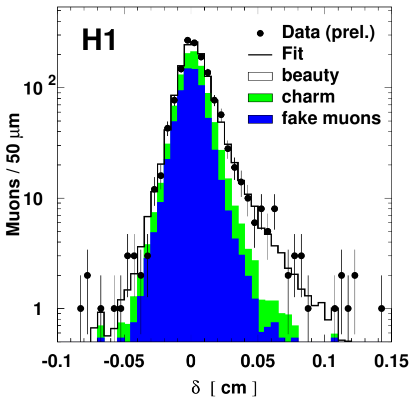

Figure 2. Signed impact parameter distribution for identified muons in the H1 data, together with the fit result for the sample decomposition into signal and background sources.

The ZEUS collaboration published an electron p_t^{rel} analysis [4], which included an extrapolation of the measured beauty photoproduction cross section to the parton level. The resulting cross section for the process $ep \to bX$ in a visible range defined by the event and b quark kinematics was found to be somewhat above the result of a corresponding FMNR calculation. In addition, preliminary ZEUS results in the muon channel [5] provided a first look at differential beauty cross sections as a function of the transverse momentum and the pseudorapidity of the muon.

The measurements sketched above were based on data corresponding to an integrated luminosity $\mathcal{L}$ of 21 pb^{-1} and 39 pb^{-1} for H1 and ZEUS respectively. Since then, a preliminary measurement of beauty photoproduction [6] has become available using a significantly larger data set. This is discussed in the following section.

2.2. New results

The ZEUS collaboration has measured beauty photoproduction using the semi–muonic decay of beauty hadrons within jets.

From data recorded in the years 1996–2000 corresponding to $\mathcal{L} = 98$ pb^{-1}, a γp sample is obtained by rejecting events in which the scattered electron is found in the main detector, thus effectively requiring the photon virtuality Q^2 to be less than 1 GeV^2. In addition, the event inelasticity is restricted to the range $0.2 < y < 0.8$. Jets are reconstructed using the longitudinally invariant k_t algorithm [7], and events with at least two jets of transverse momentum $p_t^{jet1(2)} > 7(6)$ GeV and pseudorapidity $|\eta^{jet}| < 2.5$ are selected. Muon candidates are selected by applying cuts on the momentum and pseudorapidity, cf. Table 1, which ensure a good acceptance for muons that reach the outer muon chambers.

Table 1
Muon selection cuts

pseudorapidity	(transverse) momentum
$-1.6 < \eta^\mu < -0.9$	$p^\mu > 2.5$ GeV
$-0.9 < \eta^\mu < +1.3$	$p_t^\mu > 2.5$ GeV
$+1.5 < \eta^\mu < +2.3$	$p_t^\mu > 1$ GeV, $p^\mu > 4$ GeV

A signal fraction in the selected data of about 25% is extracted by fitting the shape of the muon p_t^{rel} distribution, cf. Figure 3. The input MC samples for beauty, charm and light flavour production are obtained from the PYTHIA event generator [8] and include both direct and resolved photon processes. Using PYTHIA to extrapolate for the unmeasured part of the muon kinematics and to correct for the branching ratio of the decay $b \to \mu$ yields a total di–jet cross section of

$$\sigma = [733 \pm 61(\text{stat.}) \pm 104(\text{syst.})] \text{ pb} \qquad (1)$$

for the process $ep \to b\bar{b} \to jjX$. This is about a factor 2 above the corresponding NLO QCD

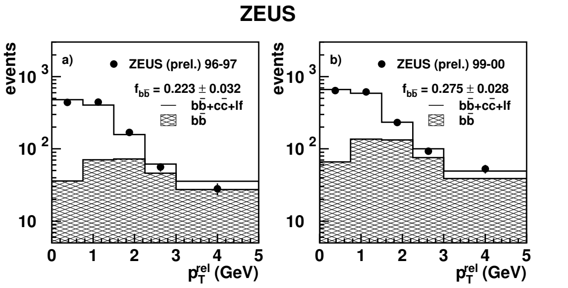

Figure 3. Muon p_t^{rel} distribution for ZEUS data recorded in (a) 1996–96 and (b) 1999–2000, together with the fit result for the sample decomposition into signal (hatched) and background.

(FMNR) result of (381^{+117}_{-78}) pb. In the calculation, the b quark mass is set to to $m_b = 4.75$ GeV. The factorisation and renormalisation scales are chosen as $\mu_f^2 = \mu_r^2 = p_{t,b}^2 + m_b^2 := m_T^2$. The uncertainty is estimated from a simultaneous variation of m_b by ± 0.25 GeV and $\mu_{f,r}$ between $m_T/2$ and $2m_T$.

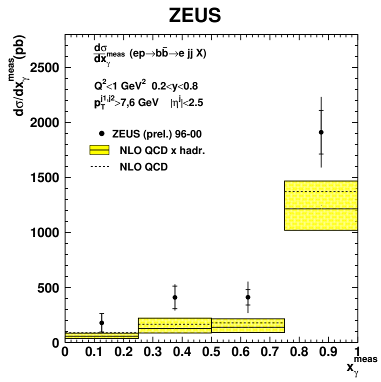

Figure 4. Measured $d\sigma/dx_\gamma^{\mathrm{meas}}$, compared to NLO QCD based on parton–level jets (dashed line) and hadron–level corrected jets (full line).

Differential cross sections are measured by extracting the signal fraction from a p_t^{rel} fit in each bin of the selected variable. Figure 4 shows the cross section as a function of the fraction of $(E - p_z)$ of the hadronic system carried by the two leading jets,

$$x_\gamma^{\mathrm{meas}} = \frac{(E-p_z)_{\mathbf{jet1}} + (E-p_z)_{\mathbf{jet2}}}{(E-p_z)_{\mathrm{hfs}}}\,, \qquad (2)$$

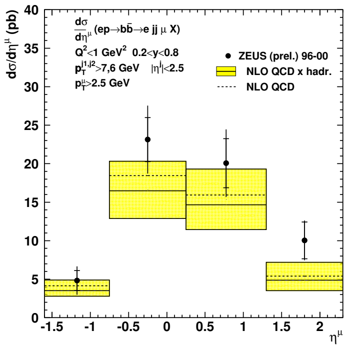

Figure 5. Measured $d\sigma/d\eta^\mu$, compared to the NLO QCD prediction.

together with NLO QCD predictions. In the LO picture, x_γ^{meas} reconstructs the fraction x_γ of the photon momentum taking part in the hard interaction. The tail of the distribution towards low x_γ^{meas} signals the contribution from resolved photon processes. The excess of the measured cross section over the prediction is found not to be restricted to a particular x_γ^{meas} region.

Requiring in addition $p_t^\mu > 2.5$ GeV and $-1.6 < \eta^\mu < 2.3$, the QCD expectation[1] is found to be a factor 1.4 below, but within the experimental and theoretical uncertainties compatible with, the measured cross section. In this restricted kinematic range, differential muon cross sections are measured as a function of η^μ (see Figure 5) and p_t^μ.

3. LEPTON ANALYSES IN DIS

3.1. Photon 2001 status

For the first (preliminary) measurement [9] of beauty production in the deep inelastic scattering regime, H1 used a muon sample selected from di–jet data corresponding to $\mathcal{L} = 11$ pb^{-1}. The visible muon cross section $\sigma\left(ep \to b\bar{b}X \to \mu X\right)$, determined from a combined (δ, p_t^{rel}) fit, was found to significantly exceed the theoretical predictions.

[1] Here, the FMNR program is used in combination with the Peterson fragmentation function ($\epsilon = 0.0035$). The muon momentum spectrum from the beauty hadron decay is obtained from PYTHIA.

3.2. New results

In a new preliminary analysis [10], ZEUS has measured the DIS process $ep \to b\bar{b} \to e\mu jX$ based on an integrated luminosity of 60 pb^{-1}. In events with a high–energy scattered electron and an identified muon, jets are reconstructed using the longitudinally invariant k_t algorithm in the Breit frame. The muon is required to be contained in a jet with $E_t^{\mathrm{Breit}} > 4$ GeV.

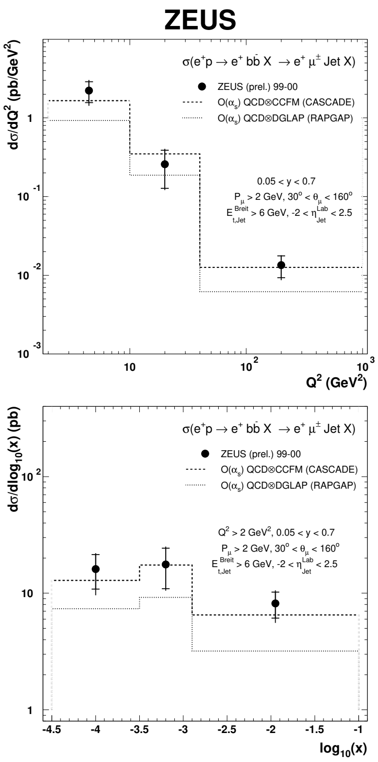

Figure 6. Measured $d\sigma/dQ^2$ (top) and $d\sigma/d\log(x)$ (bottom), compared to the RAPGAP (dotted line) and CASCADE (dashed line) prediction.

In a visible range defined by $Q^2 > 2$ GeV^2, $0.05 < y < 0.7$, a muon with momentum $p > 2$ GeV and polar angle $30° < \theta < 160°$ and at least one jet with $-2 < \eta < 2.5$ and $E_t^{\mathrm{Breit}} > 6$ GeV, the signal contribution to the selected data is determined from a p_t^{rel} fit to be $[25 \pm 5(stat.)]\,\%$, which translates into a visible

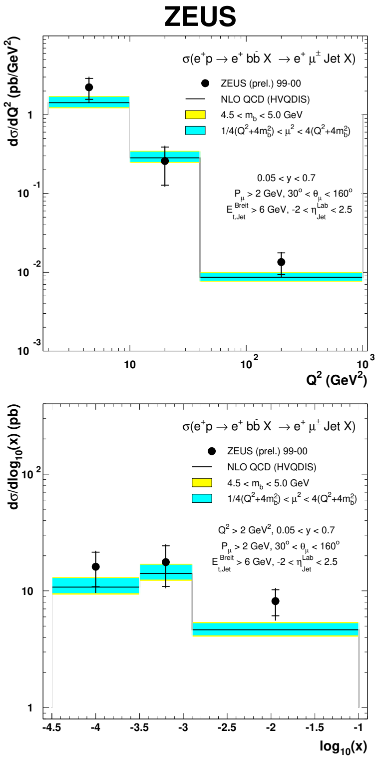

Figure 7. Measured $d\sigma/dQ^2$ (top) and $d\sigma/d\log(x)$ (bottom), compared to NLO QCD (HVQDIS).

beauty cross section of

$$\sigma = \left[38.7 \pm 7.7(\mathrm{stat.})^{+6.1}_{-5.0}(syst.)\right] \text{ pb} . \qquad (3)$$

This is somewhat above, but within the experimental and theoretical uncertainties in agreement with, the NLO QCD prediction of $28^{+5.3}_{-3.5}$pb. Here, the QCD calculation is performed with the HVQDIS [11] program, using $m_b = 4.75$ GeV, $\mu_f^2 = \mu_r^2 = Q^2 + 4m_b^2$, in combination with the Peterson fragmentation function ($\epsilon = 0.002$) and a muon momentum spectrum extracted from the RAPGAP MC program [12]. The error is estimated by varying the scales $\mu_{f,r}$ by a factor of 2 and the mass m_b between 4.5 and 5 GeV.

In addition, differential beauty cross sections as a function of Q^2 and $x = Q^2/ys$ are measured and compared to QCD predictions from LO MC programs (see Figure 6) and NLO calculations (cf. Figure 7). The NLO predictions agree with the data. While the DGLAP–based RAPGAP program underestimates the measured cross sections, CASCADE [13], which uses a CCFM-like parton evolution, is in good agreement with the data.

4. $D^*\mu$ CORRELATION ANALYSES

The increased data samples make it possible to go beyond inclusive lepton analyses and study beauty production in a more exclusive way.

Requiring a reconstructed D^* meson candidate strongly suppresses light–flavour backgrounds. With an additional lepton in the event, the signal can be extracted from the lepton charge and flight direction with respect to the D^* meson. While $c\bar{c}$ background events are expected to yield an unlike–charged D^*–lepton pair in opposite hemispheres, for beauty production also other combinations are possible. Unlike-sign D^*–lepton pairs in the same hemisphere are of particular interest. Here, the D^* meson and the lepton stem from the same beauty hadron, and the D^*–lepton invariant mass is constrained not to exceed the B mass. D^*–lepton correlation analyses do not rely on a jet requirement and, therefore, provide information on beauty production also in the low p_t regime close to the kinematic limit.

Preliminary H1 [14] and ZEUS [15] results based on a D^*–muon tag are summarised in the following.

4.1. H1

From data corresponding to an integrated luminosity of 91 pb^{-1}, events with at least one D^* meson, reconstructed via the decay $D^{*\pm} \to D^0\pi_s^\pm \to K^\mp\pi^\pm\pi_s^\pm$, and at least one muon are selected, requiring $p_t^{D^*} > 1.5$ GeV, $|\eta^{D^*}| < 1.5$, $p_t^\mu > 1$ GeV, $|\eta^\mu| < 1.75$ and $0.05 < y < 0.75$. The decomposition of this sample into charm and beauty production is determined from a fit to the distribution of $\Delta M = m_{K\pi\pi_s} - m_{K\pi}$, which is performed simultaneously in four different correlation regions defined by like and unlike–sign $D^*\mu$ pairs in the same and opposite γp rest frame hemispheres respectively. After subtracting explicitly light flavour backgrounds as estimated from LO MC simulation, the fit result translates into a visible $D^*\mu$ production cross sections which exceeds the prediction from the AROMA MC program [16] by a factor of 1.8 for charm and a factor of 3.6 for beauty. A comparison of measured differential cross sections as a function of the $D^*\mu$ transverse momentum, rapidity, invariant mass and azimuthal angle difference to the AROMA prediction, scaled according to the above result, is shown in Figure 8. Good agreement is found in all cases.

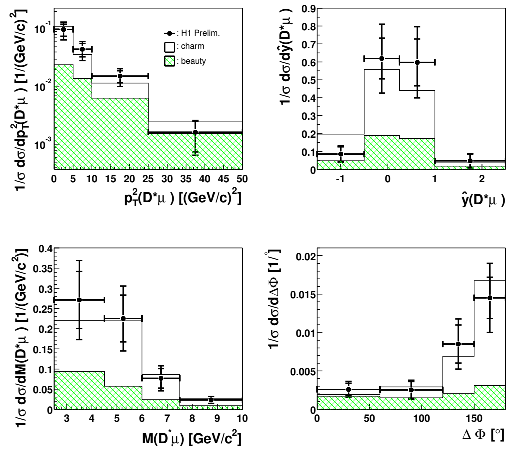

Figure 8. Normalised visible $D^*\mu$ cross sections, as a function of the $D^*\mu$ p_t, rapidity, invariant mass and azimuthal angle difference.

4.2. ZEUS

The ZEUS collaboration has performed a similar measurement using an integrated luminosity of 114 pb^{-1}.

Figure 9 shows the ΔM distribution for like–sign and unlike–sign $D^*\mu$ events and two different regions of the D^*–muon distance $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, together with the result of a fit to the ΔR distribution. The extracted signal fraction in the data corresponds to a visible $D^*\mu$ cross section which is well above the LO MC prediction and in agreement with the above H1 result.

Restricting the measurement to the photoproduction regime ($Q^2 < 1\,\mathrm{GeV}^2$, $0.05 < y < 0.85$), an extrapolation with the PYTHIA MC program yields a parton–level cross section for the process $\gamma p \to b(\bar{b})X$ of

$$\sigma = \left[15.1 \pm 3.9(\mathrm{stat.})^{+3.8}_{-4.7}(syst.)\right]\ \mathrm{nb}\ . \qquad (4)$$

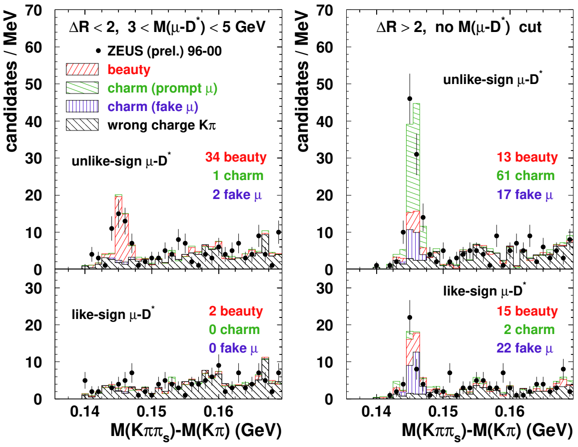

Figure 9. ΔM distribution for four different regions of phase space, together with the decomposition into signal and background contributions as determined from the ΔR fit.

Here, the beauty quark rapidity has been restricted to $\hat{y}^{b(\bar{b})} < 1$. The corresponding NLO QCD prediction of $5.0^{+1.7}_{-1.1}$ nb from FMNR (with $m_b = 4.75$ GeV and $\mu_f^2 = \mu_r^2 = Q^2 + p_{t,b}^2$) underestimates the measurement significantly.

5. SUMMARY

New preliminary results on open beauty production at HERA, based on new data and additional channels, have recently become available. Analyses of semi–muonic beauty decays within jets yield improved γp and DIS measurements, including for the first time differential cross sections in DIS. The increased statistics also make it possible to perform first double tag analyses in the D^*–muon channel, which extend the experimental sensitivity into the low p_t region.

All beauty cross sections measured by H1 and ZEUS are found to be above the NLO QCD expectation. Not in all cases the excess is significant, though, the new ZEUS DIS result agreeing with the prediction within the errors. It should be noted that the different measurements use various different kinematic ranges and cross section definitions, which makes a direct comparison difficult. There are indications, that extracting visible cross sections in a kinematic range corresponding to the the actual experimental acceptance, thus avoiding large extrapolations based on LO MC simulations, improves the agreement with the NLO QCD prediction.

Future analyses, using further increased data sets, upgraded detectors and possibly a larger variety of experimental methods, will provide additional input on the way to a precise quantitative understanding of beauty production in high–energy ep collisions.[2]

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[2] Shortly after this conference, new preliminary H1 results [17] on beauty photoproduction became available. Here, a combined (δ, p_t^{rel}) analysis of muons within jets ($\mathcal{L} = 48$ pb^{-1}) yields a visible cross section which is 1.5σ above the NLO prediction and in good agreement with the corresponding ZEUS measurement [6].