BEAUTY PRODUCTION AT HERA

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A review is given on beauty production at HERA. Many new results have recently become available based on various tagging techniques and covering altogether a wide kinematic phase space in photon virtualities and b quark transverse momenta. Differential beauty production cross sections are presented and compared to perturbative QCD predictions. The first measurements of the structure function $F_2^{b\bar{b}}$ are shown.

1. Introduction

The dominant beauty production mechanism at HERA is photon gluon fusion (PGF), which is shown in the left diagram in figure 1. The total

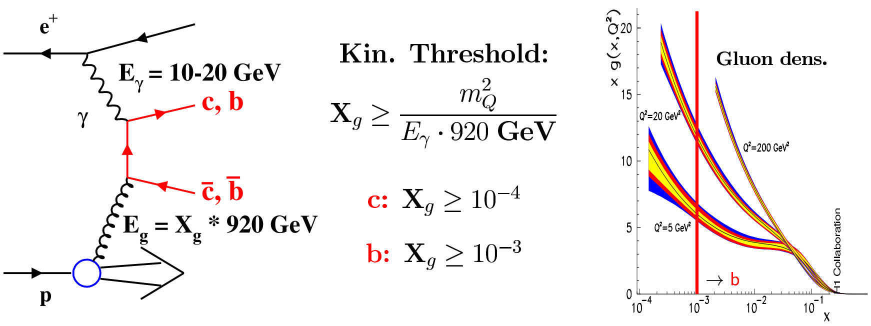


Figure 1. Comparison of kinematical thresholds for charm and beauty production at HERA in terms of the minimum proton momentum fraction x_g of the gluon that enters the hard interaction. The left plot shows the PGF process where the energies are indicated that enter the heavy quark pair production process. The threshold formula for x_g in the middle of the figure is calculated from $(x_g p + q)^2 \approx 2x_g pq = 4x_g E_\gamma E_p \geq (2m_Q)^2$, where p and q are the four vectors of the proton and photon, respectively. The right plot shows the gluon density in the proton as determined from scaling violations of F_2. The vertical line indicates the minimum fraction $X_g = 10^{-3}$ for beauty production at HERA.

production rates of light, charm and beauty quarks at HERA scale roughly like

$$\sigma_{uds} : \sigma_c : \sigma_b \sim 2000 : 200 : 1.$$

The strong suppression of beauty events is mostly due to the limited kinematic phase space, as illustrated in figure 1. To produce two beauty quarks in the PGF process a minimal proton momentum fraction of the gluon of 10^{-3} is needed, while for charm the threshold is one order of magnitude lower. A further suppression factor of *four* for beauty production relative to charm production is due the smaller electric charge of down type quarks compared to up type quarks.

Since the last Ringberg workshop in 2003 a wealth of new beauty production measurements have become available at HERA, which will be summarised here. The results are based on a variety of tagging methods and cover in total a large kinematic phase space of photon virtualities $0 < Q^2 < 1000$ GeV^2 and b quark transverse momenta $0 < p_T < 30$ GeV.

2. Theory

Since the large b mass provides a hard scale, rendering a small α_s, it would be expected that beauty production can be accurately calculated using perturbative QCD (pQCD). Calculations are available in Next to Leading Order (NLO) in the massive scheme, where the b quark mass is fully taken into account. For photoproduction the program FMNR [1] is used and for deep inelastic scattering (DIS) HVQDIS [2]. In the massive scheme, u, d and s are the only active flavours in the proton and the photon, and charm and beauty are produced dynamically in the hard scattering as shown in figure 1. These predictions are expected to be reliable for the largest part of the kinematic phase space at HERA. However, at very large transverse momenta $p_{t,b} \gg m_b$ or photon virtualities $Q^2 \gg m_b^2$, the predictions of the massive scheme are expected to become unreliable due to neglected higher order terms in the perturbation series of the form $[\alpha_s \ln(p_{t,b}^2/m_b^2)]^n$ or $[\alpha_s \ln(Q^2/m_b^2)]^n$, which appear to any order n and represent collinear gluon radiation from the heavy quark lines. In this kinematic range, the massless scheme can be used, in which charm and beauty are treated as active flavours in both the proton and also in the hadronic structure of the photon, in addition to u, d and s. The kinematics of the heavy quarks is treated massless in this scheme, mass effects are taken into account as effective cutoffs for the dynamic evolution of the heavy quarks in the proton and photon parton density functions. In this scheme the above higher order terms are resummed to all orders. Unfortunately there are at the present time no results from massless scheme calculations available which could be compared to the HERA beauty measurements. Results are available from mixed scheme calculations, which apply the massive (massless) scheme for small (large) high transverse momenta and photon virtualities with suitable interpolations in intermediate regions. The measurements of the proton structure function $F_2^{b\bar{b}}$, presented below, are compared to the mixed scheme predictions from MRST [3] and CTEQ [4] in NLO and to the first Next to Next to Leading Order (NNLO) calculation, provided by MRST [5].

3. Overview of measurements and used tagging techniques

The table below gives an overview of the beauty measurements presented in this review. The analyses are ordered with respect to the minimum b quark transverse momentum p_T which is probed and the covered range of the photon virtuality Q^2. Note, that the numbers in the table are only approximative values.

$Q^2 \longrightarrow$

$p_T \downarrow$

	Photoprod. $Q^2 \approx 0$	**DIS** $Q^2 \geq 1$ **GeV**^{2}	**DIS** $Q^2 \geq 150$ **GeV**^{2}
> 0 **GeV**	$\mu\mu$ $D^*\mu$	**Incl. Lifet.**	**Incl. Lifet.**
> 6 **GeV**	μ+**Jets**	μ+**Jet**	μ+**Jet**
> 11 **GeV**	**Incl. Lifet.**		

The following tagging techniques are applied:

- (μ+Jets): The measurements [6,7,8] use events with a muon from semileptonic b decay associated to a jet. The separation of beauty events from charm and light quark background is based on the large b quark mass, leading to large transverse momenta p_t^{rel} of the muon with respect to the axis of the associated jet. In [8] the long lifetime of the b quark is additionally exploited, leading to relatively large displacements of the muon track from the primary vertex.
- (Incl. Lifet.) The inclusive lifetime measurements [9,10,11] are based on the displacements of charged tracks from beauty decays from the primary vertex. Events are selected with at least one charged track measured with high quality in the vertex detector.

- ($\mu\mu$, $D^*\mu$) The double tag measurements use events with two muons [12] or with one muon and a fully reconstructed D^{*+} [13,14]. The separation of the beauty events from the background exploits the charge correlations ($\mu\mu$) or charge and angular correlations ($D^*\mu$) between the two particles.

All presented measurements are based on HERA I data. The achieved experimental accuracies are $\geq 20\%$ for inclusive measurements and for differential bins sometimes only $\sim 50\%$.

4. Results

The results section is ordered as follows: In 4.1 a selection of differential results of the μ+Jets analyses is presented. In 4.2 summary plots of all recent HERA measurements are shown, as a function of photon virtuality Q^2 and separately for photoproduction as a function of the b quark transverse momentum p_T. In 4.3 the results are concluded with the first measurements of the structure function $F_2^{b\bar{b}}$.

4.1. *μ+Jets analyses:*

Photoproduction: For the H1 and ZEUS photoproduction analyses [8,6] ($Q^2 < 1$ GeV^2) at least two jets are required in the final state with transverse momenta $p_t^{jet_{1(2)}} > 7(6)$ GeV. Figure 2 shows the differential cross sections as a function of the muon pseudorapidity (left) and transverse momentum (right). The H1 and ZEUS measurements agree well in the overlapping region. The data are also compared to a massive scheme NLO calculation, based on the program [1]. The estimated errors of the theory prediction are dominated by the uncertainties of the renormalisation and factorisation scales and of the b quark mass. The data tend to lie slightly above this calculation, however, within the errors the calculation describes all data points. The measured cross sections as a function of the muon transverse momentum are compared in figure 2 (right) to the NLO predictions in the respective kinematic ranges of the H1 and ZEUS measurements. In the lowest bin from 2.5 GeV to 3.3 GeV the H1 measurement exceeds the prediction by a factor of ~ 2.5, while at higher transverse momenta a better agreement is observed. Such an excess is not seen in the ZEUS data. This discrepancy needs to be clarified in the future.

Deep inelastic scattering: For the H1 and ZEUS DIS analyses [8,7] ($Q^2 > 2$ GeV^2) the jet algorithm is applied in the Breit frame and at least one jet

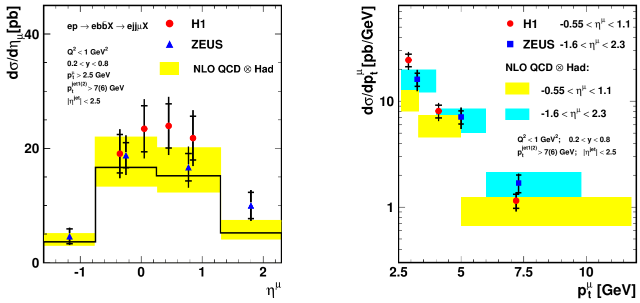


Figure 2. Differential beauty cross sections in photoproduction, for dijet events with a muon associated to one of the jets, as a function of (left) muon pseudorapidity and (right) muon transverse momentum. The H1 and ZEUS data are compared to predictions from a massive scheme NLO calculation.

with transverse momentum $p_{t,jet}^{Breit} > 6$ GeV is required. Figure 3 shows the differential cross sections of the H1 (top) and ZEUS (bottom) measurements as a function of (left) jet transverse momentum in the Breit frame, (middle) muon transverse momentum and (right) muon pseudorapidity. The data are compared to a massive scheme NLO calculation using the program [2]. The H1 and ZEUS measurements are performed in similar kinematic regions and also most of the observations are similar:

(1) An excess of data over NLO prediction by a factor ~ 2 is observed towards smaller muon transverse momenta below 4 GeV.
(2) A rise of the differential cross sections is observed towards more positive muon pseudorapidities, (i.e. more close to the proton direction) which is not reproduced by the NLO calculation.

The excess seen in the H1 data for lower muon transverse momenta is accompanied by an excess for lower jet transverse momenta while for ZEUS an excess is observed for higher jet momenta. More precise measurements are needed to clarify these different findings.

4.2. *Summary of results as a function of Q^2 and p_T*

Figure 4 shows a summary of the data/theory comparison for HERA beauty results as a function of Q^2. For the measurements sensitive to b quarks with $p_T^b \sim m_b$ or lower (black points) there is a trend that the massive NLO QCD predictions [1,2] tend to underestimate the b production rate at very

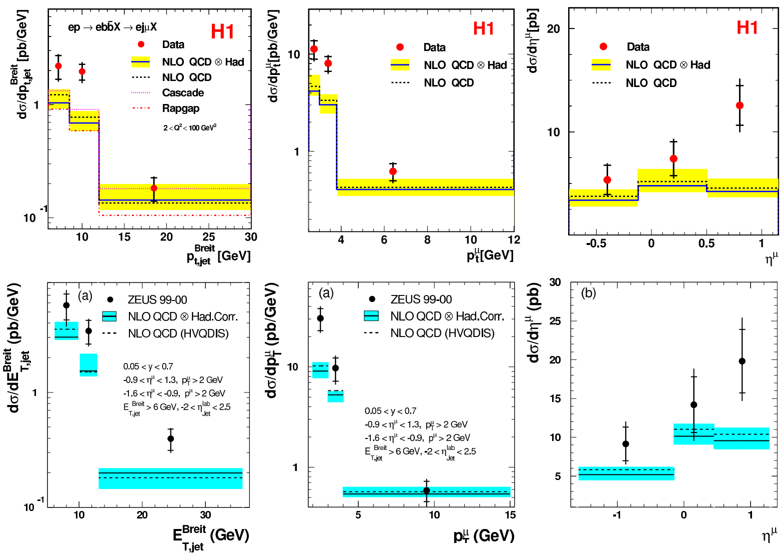
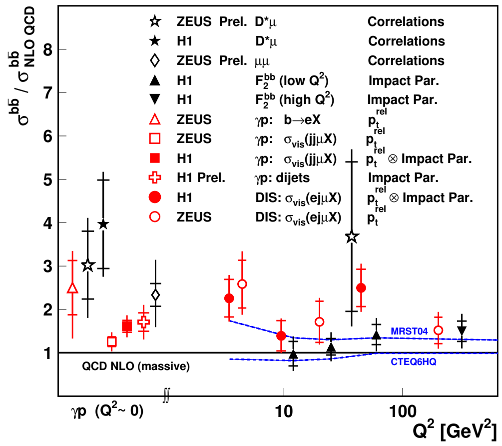


Figure 3. H1 (top) and ZEUS (bottom) measured differential beauty cross sections in DIS, for events with a muon and an associated jet, as a function of (left) jet transverse momentum in the Breit frame, (middle) muon transverse momentum and (right) muon pseudorapidity. The data are compared to predictions from a massive scheme NLO calculation.

low Q^2. For the higher p_T measurements (red/grey points), no clear trend is observed. Note that the estimated theoretical errors, which are typically of order 30%, are not shown. For the DIS data ($Q^2 > 2$ GeV^2) the curves from two mixed scheme NLO calculations are also shown in figure 4. These predictions from CTEQ [4] and MRST [3] are specifically provided for the $F_2^{b\bar{b}}$ inclusive structure function measurements which are shown here as the triangle points and which are discussed in 4.3. While the CTEQ curve is close to the the massive scheme calculation the MRST prediction is up to a factor of two higher. The data are not yet precise enough to separate between the three different predictions.

Figure 5 shows a similar compilation for all HERA measurements in photoproduction ($Q^2 < 1$ GeV^2), now as a function of the b quark p_T. Some measurements agree well with the massive scheme predictions but in general the data tend to be higher than the calculations. There are indications that the data exceed the predictions more significantly towards low p_T. Note, that several measurements appear in both summary figures.



Key	Ref.	Signature	p_T cuts
Photoproduction			
◇	12	$\mu\mu$	low
☆	14	$D^*\mu$	low
★	13	$D^*\mu$	low
△	15	2 jets+e	medium
□	6	2 jets+μ	medium
■	8	2 jets+μ	medium
✚	11	tracks	high
DIS			
☆	14	$D^*\mu$	low
▲	10	tracks	low
▼	9	tracks	low
●	8	1 jet+μ	medium
○	7	1 jet+μ	medium

Figure 4. Ratio of beauty production cross section measurements at HERA to NLO QCD predictions in the massive scheme as a function of the photon virtuality Q^2. The predictions from the mixed scheme NLO calculations by MRST and CTEQ for the DIS kinematic regime $Q^2 > 2$ GeV^2 are also presented (valid for comparison with the measurements shown as triangles). Since theoretical errors are different for each point, they are not included in this plot.

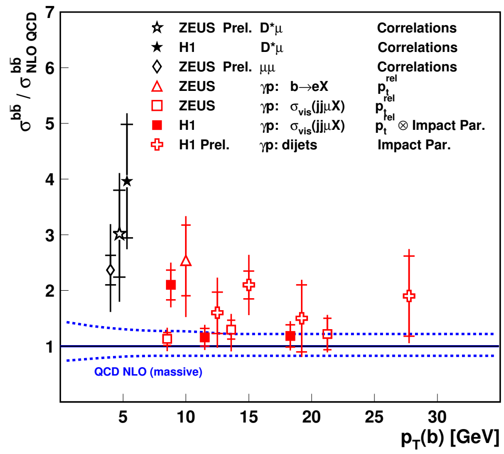


Figure 5. Ratio of beauty production cross section measurements in photoproduction at HERA to NLO QCD predictions in the massive scheme as a function of the transverse momentum of the b quark p_T. The dashed line gives an indication of the size of the estimated theoretical uncertainties.

4.3. *First measurement of structure function $F_2^{b\bar{b}}$*

Recently the first measurements [9,10] of the beauty contributions to the inclusive deep inelastic ep scattering have been made. These analyses are based on inclusive lifetime tagging. Figure 6 shows in the left plot the obtained results for the structure function $F_2^{b\bar{b}}$ as a function of Q^2 for various values of *Bjorken* x. The data exhibit positive scaling violations i.e. rises of $F_2^{b\bar{b}}$ with Q^2 for fixed x. The data are compared to mixed scheme NLO calculations from CTEQ [4] and MRST [3]. The difference between the two calculations, which reaches a factor two at the lowest Q^2 and x, arises mainly from the different treatments of threshold effects by MRST and CTEQ. However, within the current experimental errors, these differences cannot yet be resolved and both calculations describe the data well. The data are also compared to the mixed scheme NNLO predictions from MRST [5], which is somewhat lower than the NLO prediction from the same group, but also agrees with the data. In the right plot of figure 6 the fractional contribution of beauty events to deep inelastic ep scattering is shown as expressed by the ratio $f^{b\bar{b}} = F_2^{b\bar{b}}/F_2$. The beauty contributions rises strongly from a few permille at small $Q^2 = 12$ GeV^2 $< m_b^2$ to about 3% at the largest $Q^2 = 500$ GeV$^2 \gg m_b^2$. This reflects the kinematic threshold behaviour, i.e. at small Q^2 and x the invariant mass of the gluon-photon system exceeds barely the minimal required mass of $2m_b$. For comparison the corresponding fractional charm contribution is also shown, which is in the covered phase space rather flat with values of about 20-30%.

5. Outlook

The currently ongoing HERA II data taking will collect until summer 2007 at least five times more statistics than HERA I. This together with the upgraded H1 and ZEUS detectors will bring a qualitative step for beauty measurements towards precision in the order of 10% for the total cross sections and 20% for differential cross sections. This will allow to clarify the situation concerning possible excesses of the data compared to perturbative QCD calculations. Improved measurements of the structure function $F_2^{b\bar{b}}$ will allow to separate between the existing calculations in massive and mixed pQCD schemes.

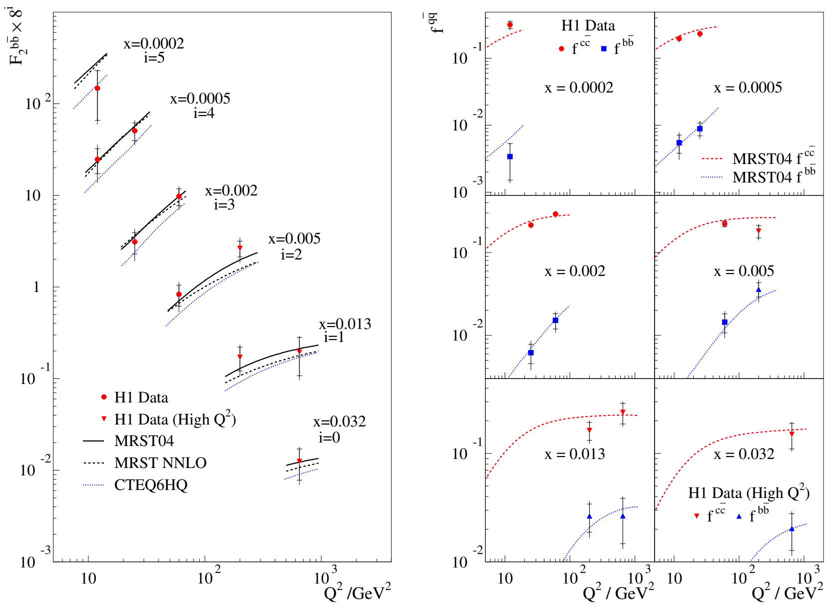


Figure 6. The first results for the beauty contribution $F_2^{b\bar{b}}$ to the inclusive structure function F_2 . The left plot shows $F_2^{b\bar{b}}$ as a function of Q^2 for various x. The right plot shows the observed relative beauty contributions to the total cross section $f^{b\bar{b}} = F_2^{b\bar{b}}\ /F_2$. The results for the relative charm contribution are also shown. The data are compared to different perturbative QCD calculations.

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