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# Measurement of beauty photoproduction at HERA II

ZEUS Collaboration

**Abstract**

Beauty photoproduction has been measured with the ZEUS detector using $e^+p$ data collected in 2004 corresponding to a luminosity of 33 pb$^{-1}$. The beauty content of a sample with two jets and a muon was analysed exploiting the muon impact parameter and the transverse momentum of the muon relative to the closest jet. Results were found in agreement with next-to-leading-order QCD predictions and previous measurements.

# 1 Introduction

The production of beauty quarks in $ep$ collisions at HERA is a stringent test of perturbative Quantum Chromodynamics (QCD) since the large $b$-quark mass ($m_b \sim 5\,\text{GeV}$) provides an additional hard scale that should ensure reliable predictions.

The ZEUS collaboration measured beauty production in events with jets and muons [1,2] and found agreement with next-to-leading-order (NLO) QCD calculations. In those analyses, the beauty component was separated from the backgrounds due to charm and light flavours by exploiting the transverse momentum of the muon realtive to the axis of the associated jet, $p_T^{\text{rel}}$. Due to the large $b$ mass, $p_T^{\text{rel}}$ is expected to be larger on average in the case of muons from semileptonic $b$ decays than for muons originating from charm or light flavours.

An alternative method to extract the beauty and charm content of a sample with jets and muons is to use the impact parameter, $\delta$, of the muon that is expected to be large for $B$-hadron decays due to their large lifetime. The H1 collaboration has recently published an analysis based on a combination of $p_T^{\text{rel}}$ and $\delta$ [3] in which good agreement was found with ZEUS results, except for a possible excess at low $p_T$ of the muon. Other hints for a possible excess in beauty production at low $p_T$ are given by double-tag analyses [4–6].

With the HERA luminosity and polarisation upgrade (HERA-II) the ZEUS experiment also underwent a substantial upgrade program. In particular, using the silicon microvertex detector (MVD) [7] beauty and charm production can now be measured using a lifetime tag.

This paper presents the first measurement of $b$ production in HERA-II data. The beauty content of a sample with two jets and a muon was measured using a combination of $p_T^{\text{rel}}$ and $\delta$ providing a measurement of differential cross sections for beauty production.

# 2 Data selection

A sample of photoproduction (i.e. $Q^2 < 1$ GeV$^2$) events with two jets and a muon was selected from $e^+p$ collisions collected in 2004, corresponding to an integrated luminosity of 33 pb$^{-1}$. The energy of the proton and positron beams were 920 GeV and 27.6 GeV respectively for a centre-of-mass energy $\sqrt{s} = 318$ GeV.

The events were preselected by the ZEUS online trigger system to contain two high $p_T$ jets or a muon.

The offline reconstruction of the event kinematics combined information from the calorimeter (CAL) [8], the central tracking detector (CTD) [9], the silicon vertex detector (MVD), barrel and rear[1] muon chambers (BRMUON) [10] and of the forward muon spectrometer (FMUON) [11].

Jets were reconstructed from energy flow objects (EFOs) combining tracking and calorimeter information using the KTCLUS algorithm in the longitudinal-boost invariant mode in the $E$ recombination scheme [12]. At least two jets with $|\eta^{\rm jet}| < 2.5$ and $p_T^{\rm jet1(2)} > 7(6)$ GeV were required in the event. Standard cuts and requirements were applied to reject the contribution from deep inelastic scattering (DIS) events, corresponding to an effective cut of $Q^2 < 1\,{\rm GeV}^2$ and $0.2 < y < 0.8$, where $y$ is the event inelasticity. At least one jet was required to contain a muon candidate.

Muon candidates were obtained by matching a track found by the CTD and the MVD with a segment in the BRMUON or a good track in the FMUON. The requirement on the BRMUON was looser than used previously [1,2] where muons were required to reach the external chambers placed outside the iron yoke. This looser selection gives larger acceptance, in particular at low muon momenta, at the price of a larger contamination of fake muons from punch-through and in-flight decays of $\pi$ and $K$ mesons. Muon candidates were accepted in the pseudorapidity range $-1.6 < \eta^\mu < 2.3$. To reduce the contamination from fake muons, a cut on the muon transverse momentum $p_T^\mu > 2.5$ GeV was applied. Moreover the muon candidates were required to have at least four MVD hits and hits in at least three superlayers of the CTD. The latter requirements, needed for a good determination of the impact parameter, reduce considerably the acceptance in the forward region. After this selection 1806 events were left.

A similar selection was applied to Monte Carlo (MC) samples of beauty ($b$), charm ($c$) and light flavour (LF) events generated with PYTHIA 6.2 [13]. Figure 1 shows the distributions of $p_T$ and $\eta$ for the muon and for the associated jet, compared to a MC mix of $b$, $c$ and LF events, normalized according to the fractions obtained as explained in the next section. A reasonable agreement is found in all the variables.

# 3 Determination of the $b$ content

The heavy flavour content of the selected sample was analyzed by means of $p_T^{\rm rel}$ and $\delta$.

The $p_T^{\rm rel}$ variable was defined [1] subtracting the muon from the jet:

$$p_T^{\rm rel} = \frac{|\boldsymbol{p}^\mu \times (\boldsymbol{p}^j - \boldsymbol{p}^\mu)|}{|\boldsymbol{p}^j - \boldsymbol{p}^\mu|}.$$

[1] The forward (+Z) direction (and therfore positive pseudorapidities $\eta$) is defined as the direction of the incoming proton beam.

The $p_T^{\rm rel}$ distribution of the MC samples of charm and light flavours were corrected in order to reproduce the $p_T^{\rm rel}$ distribution of tracks in an inclusive dijet sample in which the expected beauty contamination is small.

The transverse width of the HERA beams at the interaction point is $\sigma_X \simeq 110\ \mu$m and $\sigma_Y \simeq 30\ \mu$m. Therefore the beam position in $X$ and $Y$, determined run-by-run from an average of reconstructed event vertices, provides a quite precise and unbiased estimate of the event vertex in the transverse plane. In this analysis, a signed impact parameter, $\delta$, was defined as the distance of closest approach of the muon with respect to the beam position in the transverse plane. A positive sign is assigned to $\delta$ if the muon track intercepts the axis of the associated jet downstream of the beam position in the transverse plane; otherwise a negative sign was assigned. In the light flavour component, the muon candidates are expected to originate from the primary vertex and therfore their $\delta$ distribution is expected to be peaked at zero with a symmetric smearing due to impact parameter resolution. An asymmetry towards positive $\delta$ is expected for beauty events and, to a lesser extent, for charm events, since in this case muons are expected to originate from secondary vertices down-stream of the primary vertex. The resolution on $\delta$ in the MC samples was modelled to reproduce the negative part of the $\delta$ distribution of tracks in an inclusive dijet sample in which the expected $b$ component is small.

To extract the fractions of $b$, $c$ and LF in the sample, a binned $\chi^2$ fit of the two-dimensional distribution of the data in the plane $p_T^{\rm rel}$ versus $\delta$ was performed by adjusting the relative normalization of the three MC samples to reproduce the data. Figure 3 shows the constant $\chi^2$ contour containing 68% of the probability in the plane defined by the beauty ($f_b$) and charm ($f_c$) fractions (for a probability density $\propto \exp(-\chi^2/2)$). The fractions obtained from the fit are:

$$f_b = (16.7 \pm 2.6)\%\,,\ \ f_c = (51.8 \pm 9.8)\%$$

for $\chi^2/\mathrm{ndf} = 23.6/22$.

Figure 2 shows the distribution of $p_T^{\rm rel}$ and $\delta$ for the data and the two corresponding projections of the two-dimentional fit. The distribution of $\delta$ has a clear positive asymmetry, well reproduced by the charm and beauty MC samples.

As a cross check, the fractions were extracted using the $p_T^{\rm rel}$ or the $\delta$ distributions alone. The results of these one dimensional fits are compatible with, though less precise, those of the two-dimensional fit. The 68% probability contours from the one-dimensional fits are also shown in Figure 3. The two variables give complementary information since the $p_T^{\rm rel}$-alone fit is able to distinguish the $b$ component from $c$ and LF but not to separate $c$ and LF, while the $\delta$-alone fit gives a good determination of the LF fraction but strongly anti-correlated fractions of $b$ and $c$.

# 4 Results

The differential cross section $d\sigma/dp_T^\mu$ was measured for the process $ep \rightarrow e'b\bar{b}X \rightarrow e'jj\mu X'$ in the kinematic range $Q^2 < 1$ GeV$^2$, $0.2 < y < 0.8$, $p_T^{j_1,j_2} > 7,6$ GeV, $\eta_{j_1,j_2} < 2.5$, and $-1.6 < \eta^\mu < 2.3$. The acceptance, obtained from the beauty signal MC, was corrected for the muon chamber and trigger efficiencies, measured in independent samples. The beauty fraction was determined in each $p_T^\mu$ bin with an independent two-dimensional fit. The result is shown in Fig. 4 compared to ZEUS HERA-I data [1] and to the NLO QCD prediction from the FMNR [14] program (calculated and corrected for jet hadronization effects as explained previously [1]). The main contributions to the systematic uncertainty are the muon chamber efficiency (15%), the resolution on $\delta$ (10%) and the shape of $p_T^{\mathrm{rel}}$ (10%). This measurement is in good agreement with the HERA-I results that were obtained from a luminosity $\sim$ 3 times larger than that of the present measurement, using $p_T^{\mathrm{rel}}$ to separate $b$ from $c$ and LF and fixing the charm-to-LF ratio from external measurements. An external constraint of the charm contribution is not needed in this analysis since $f_c$ is extracted within the same data.

In a similar analysis, the H1 collaboration [3] found a two-standard deviation excess with respect to the NLO calculation for the lowest muon transverse momenta (in the range $2.5 < p_T^\mu < 3$ GeV). The present measurement does not show any excess in this $p_T^\mu$ region.

# 5 Conclusion

The first measurement of beauty photoproduction from HERA II data taken in 2004, has been presented. The muon impact parameter, measured with the new ZEUS silicon microvertex detector, was combined with the $p_T^{\mathrm{rel}}$ variable to improve the determination of the beauty content in a dijet-plus-muon sample. The production cross section was found to be compatible with previous ZEUS measurements and with NLO QCD.

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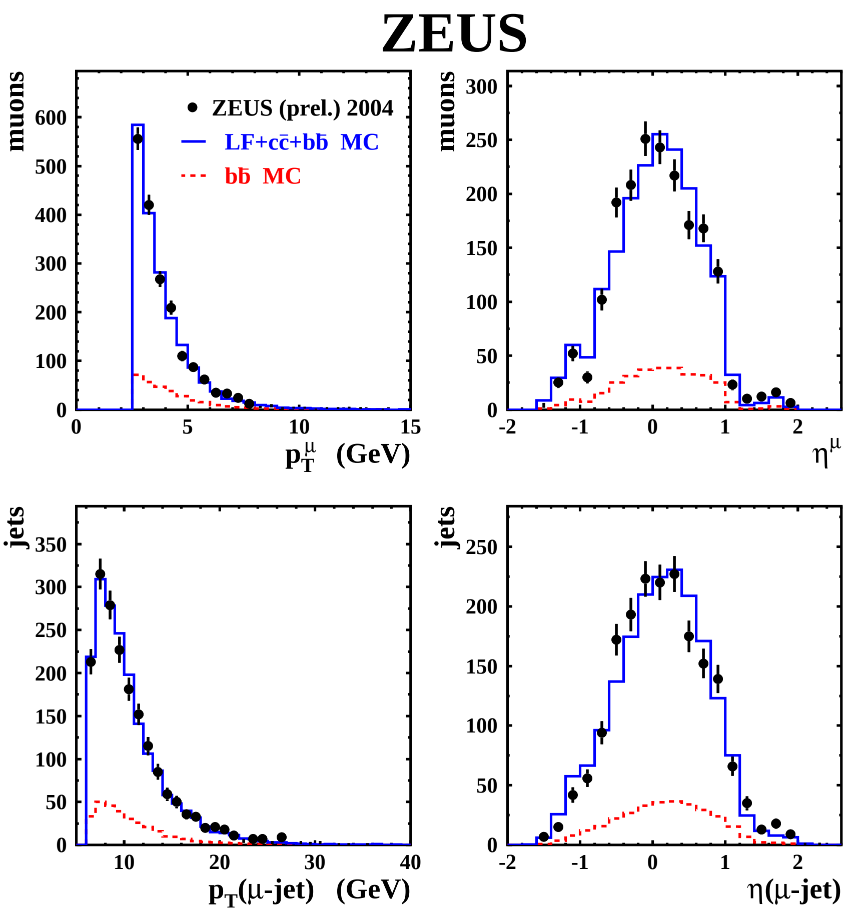


**Figure 1:** *Distribution of $p_T$ (left) and $\eta$ (right) for the muons (top) and for the jet containing the muon (bottom). The data are compared to a mixture of beauty, charm and light flavour MC. The beauty component is also shown.*

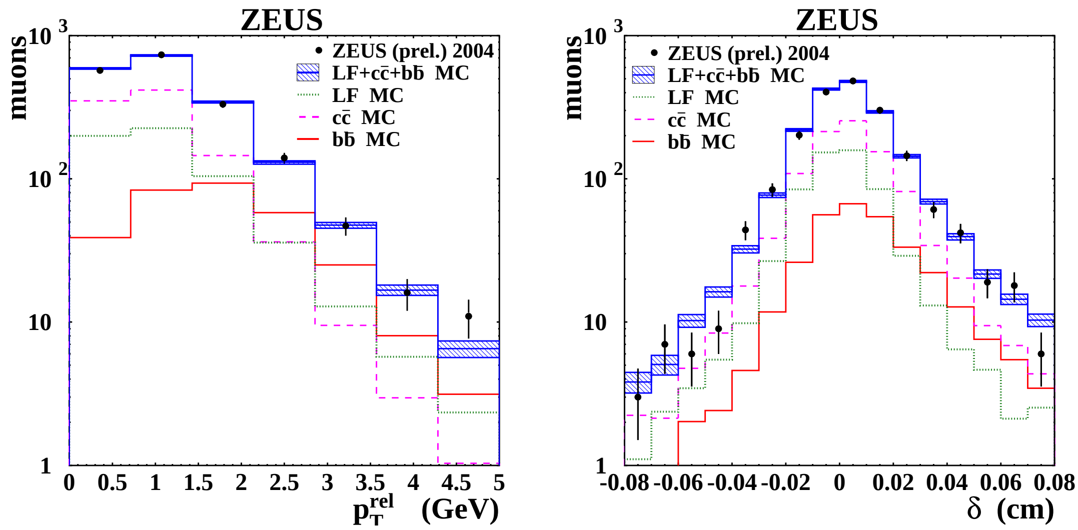


**Figure 2:** *Distribution of (left) $p_T^{\rm rel}$ and (right) $\delta$ for the data and for the MC mixture of beauty, charm and light flavours. The different MC components are also shown independently.*

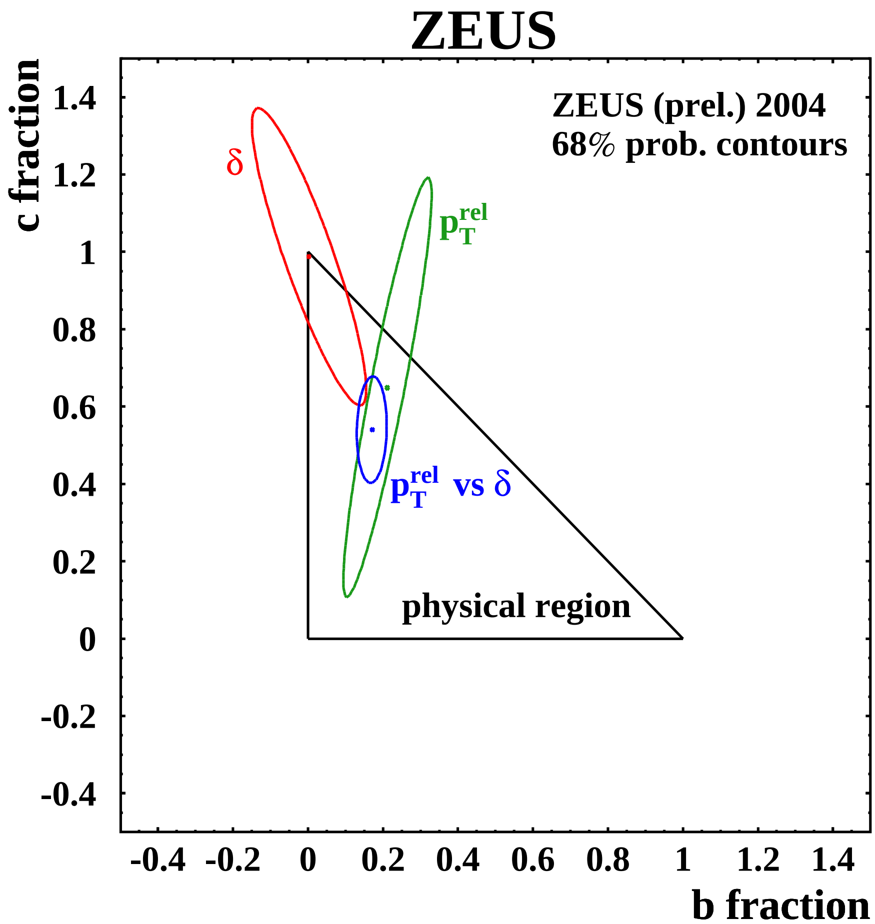


**Figure 3:** *Contours of 68% probability in the plane defined by the beauty and the charm fractions. The result of the $\chi^2$ fit to the two-dimensional $p_T^{\rm rel}$-$\delta$ distribution is shown by the smaller contour. The results for the one dimentional distributions in $p_T^{\rm rel}$ (contour on the right) and $\delta$ (contour on the left) are also shown. The triangle shows the physical region in which $f_b$,$f_c$ and $f_{\rm LF}$ are positive.*

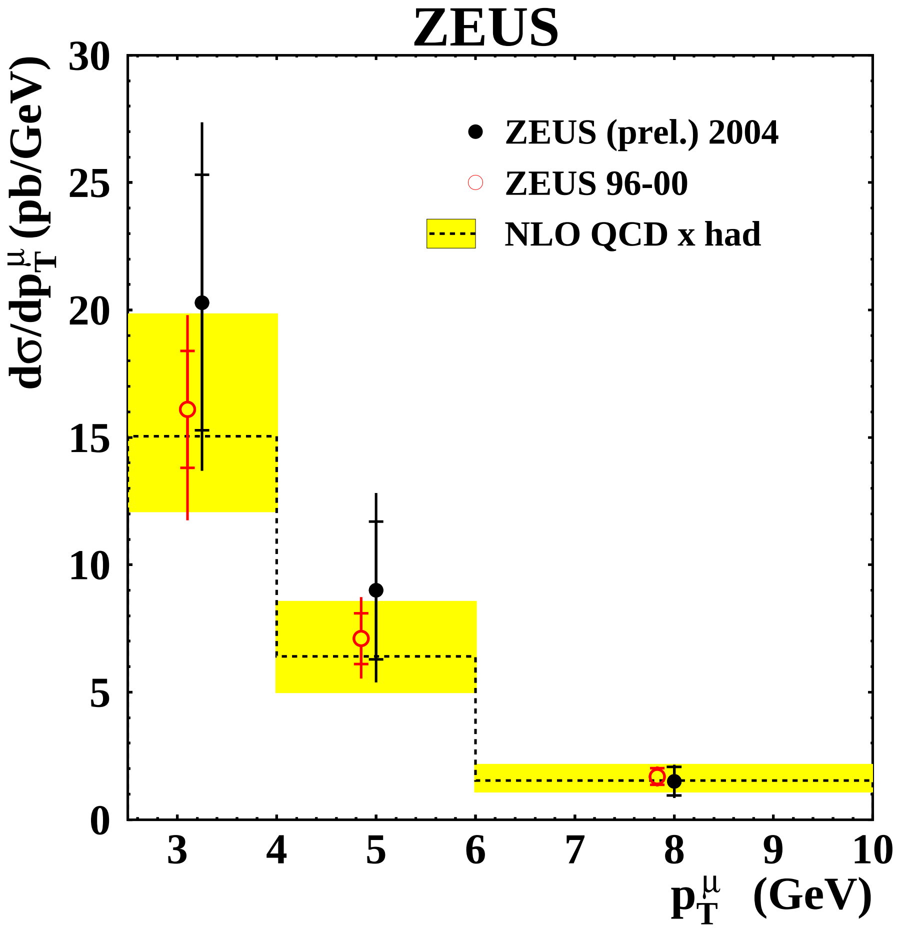


**Figure 4:** *Differential cross section as a function of the muon $p_T$ for $Q^2 < 1$ $GeV^2$, $0.2 < y < 0.8$, $p_T^{j_1,j_2} > 7, 6\,GeV$, $\eta_{j_1,j_2} < 2.5$, and $-1.6 < \eta^\mu < 2.3$. The circles show the results from this analysis and from the previous HERA-I measurement. The inner error bars are statistical uncertainties while the external bars show the statistical and systematical uncertainties summed in quadrature. The band represents the NLO QCD prediction.*