# BEAUTY PHOTOPRODUCTION*

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Beauty photoproduction in *ep* collisions has been studied with the ZEUS detector at HERA, at a center-of-mass energy of 300 GeV. Beauty quarks are tagged via their semi-leptonic decay into a muon or an electron. Events are selected by requiring the presence of two high-transverse energy jets and one high-$p_{\rm T}$ lepton in the final state. The discrimination between beauty and background events is done by a fit to the $p_{\rm T}^{\rm rel}$ variable, the transverse momentum of the lepton with respect to the jet axis. Total and differential cross sections are presented and compared to leading order Monte Carlo simulations and next-to-leading order QCD predictions.

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## 1. Introduction

The study of heavy quark production in positron–proton scattering provides an important testing ground for QCD, and clarifies the structure of the proton and the photon. At the *ep* collider, HERA, with a center-of-mass energy, $\sqrt{s} = 300$ GeV, heavy quarks are produced predominantly in collisions between a photon, emitted by the incoming positron, and the proton. The main contribution to the cross section comes from the exchange of an almost real photon (*photoproduction*, PHP), *i.e.* when the four-momentum squared, $Q^2$, of the exchanged photon is $\sim 10^{-3}$ GeV$^2$, with an upper limit of 1 GeV$^2$.

Two types of Leading Order (LO) processes can contribute to heavy quarks photoproduction: in *direct* processes, the photon acts as a point-like particle, coupling directly to a parton in the proton, while in *resolved*

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processes the photon fluctuates into a system of quarks and gluons, with one of these partons participating in the hard interaction. Resolved photon processes also include flavour excitation, where a heavy quark is extracted directly from the photon or the proton, and are expected to give a more sizeable contribution in the forward region.

Here, the cross sections measured by the ZEUS Collaboration in beauty photoproduction, tagged via $b$ semi-leptonic decay into a muon or an electron, are reported. The results are compared to LO parton shower Monte Carlo simulations and next-to-leading order QCD predictions. The Monte Carlo models used in the analyses are PYTHIA [1] and HERWIG [2], which both implement direct and resolved photon processes, and CASCADE [3], which uses $k_{\mathrm{T}}$-factorisation and implements CCFM [4] gluon evolution in the proton; only the direct photon–gluon fusion process is implemented. The NLO calculation [5] was performed in a fixed-order approach in which $b$ quarks are not considered to be active partons in the proton and the photon, but are produced dynamically in the hard subprocesses. This approach is valid for $p_{\mathrm{T}} \sim m_Q$, where $p_{\mathrm{T}}$ is the transverse momentum and $m_Q$ the mass of the heavy quark.

## 2. Electron analysis

The ZEUS Collaboration has published [6] the results of an analysis on beauty photoproduction with events tagged by its semi-leptonic decay into electrons, using $\mathcal{L} = 38.5\,\mathrm{pb}^{-1}$ of data collected in 1996–97. The events were selected by requiring: $Q^2 < 1$ GeV$^2$; $0.2 < y < 0.8$ (where $y$ is the fraction of the positron beam energy transferred to the proton in its rest frame); the presence of at least two jets with $E_{\mathrm{T}}^{\mathrm{jet1(2)}} > 7(6)$ GeV and $\eta^{\mathrm{jet1(2)}} < 2.4$ (reconstructed with the $k_{\mathrm{T}}$-algorithm [7]), and at least one electron with $p_{\mathrm{T}}^{e^-} > 1.6$ GeV and $\mid \eta^{e^-} \mid < 1.1$.

An experimental separation of direct and resolved photon processes is obtained from the $x_\gamma^{\mathrm{OBS}}$ variable, defined in terms of the transverse energy $E_{\mathrm{T}}$ and pseudorapidity $\eta$ of the two highest transverse energy jets in the event:

$$x_\gamma^{\mathrm{OBS}} = \sum_{i=1}^{2} \frac{E_{\mathrm{T}}^{\mathrm{Jet}_i} \mathrm{e}^{-\eta^{\mathrm{Jet}_i}}}{2yE_e}\,, \tag{1}$$

where $E_e$ is the incoming positron energy. The variable $x_\gamma^{\mathrm{OBS}}$ is an approximation to the fraction of the $\gamma$ momentum involved in the hard subprocess, so for *direct* photon processes $x_\gamma^{\mathrm{OBS}} \simeq 1$, while *resolved* processes have $x_\gamma^{\mathrm{OBS}} < 1$.

The $x_\gamma^{\mathrm{OBS}}$ distribution for the selected data sample was fitted with direct and resolved HERWIG MC components in order to give an estimation of the direct and resolved photon contributions. From the fit the fraction of resolved processes was $f_{\mathrm{res}} = (28 \pm 5)\%$, to be compared to the HERWIG prediction of 35%.

The beauty cross section was extracted by fitting the $p_{\mathrm{T}}^{\mathrm{rel}}$ distribution of the data to the sum of contributions from beauty and charm. The fraction of beauty was $f_b = (14.7 \pm 3.8)\%$, in good agreement with the predictions by HERWIG (16%) and PYTHIA (19%). By using that value of $f_b$, the cross section for beauty production in the kinematic region previously defined was:

$$\sigma^{b \to e^-}(e^+p \to e^+ \text{ dijet } e^- \ X) = 24.9 \pm 6.4^{+4.2}_{-7.3} \text{ pb} \,. \tag{2}$$

The LO Monte Carlo predictions are 8 pb (HERWIG) and 18 pb (PYTHIA and CASCADE).

This cross section was then extrapolated to the parton level in a restricted range of the transverse momentum and pseudorapidity of the quark using HERWIG and PYTHIA Monte Carlo simulations. The cross section for $p_{\mathrm{T}}^b > p_{\mathrm{T}}^{\mathrm{min}} = 5$ GeV, $|\ \eta^b\ | < 2$, $Q^2 < 1$ GeV$^2$ and $0.2 < y < 0.8$ was:

$$\sigma^{\mathrm{ext}}(ep \to e^+ bX) = 1.6 \pm 0.4(\mathrm{stat.})^{+0.3}_{-0.5}(\mathrm{syst.})^{+0.2}_{-0.4}(\mathrm{ext.}) \text{ nb} \,, \tag{3}$$

where the central value was calculated by using HERWIG to extrapolate and the value obtained with PYTHIA was included in the extrapolation systematic uncertainty. The comparison between the measured cross section and the NLO calculation [5] is shown in figure 1. The NLO prediction of

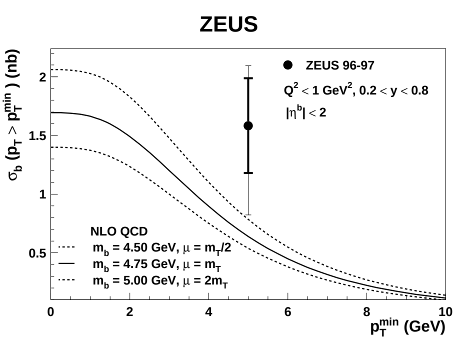


Fig. 1. The extrapolated $b$ cross-section at fixed $p_{\mathrm{T}}^{\mathrm{min}}$ value compared with theoretical predictions plotted as a function of $p_{\mathrm{T}}^{\mathrm{min}}$. The inner error bars represent the statistical error and the outer bars statistical, systematic and extrapolation errors added in quadrature. The curves show the predictions from NLO QCD for varying $b$-quark mass and varying factorisation and renormalisation scale $m_{\mathrm{T}} = \sqrt{m_b^2 + p_{\mathrm{T}}^2}$.

$(0.64^{+0.14}_{-0.10})$ nb is somewhat below the measured value, whereas Cascade prediction of 0.88 nb agrees with the measurement within errors.

## 3. Muon analysis

Preliminary results on beauty photoproduction measured with events tagged by the semi-leptonic decay into muons [8] have been presented. Events were required to have at least two jets reconstructed by the $k_{\mathrm{T}}$-algorithm with one of them containing a muon, associated with it by the jet algorithm.

The kinematic region was $Q^2 < 1$ GeV$^2$, $0.2 < y < 0.8$, $E_{\mathrm{T}}^{\mathrm{jet1(2)}} > 7(6)$ GeV, $\eta^{\mathrm{jet1(2)}} < 2.5$, $p^{\mu} > 3$ GeV and $-1.75 < \eta^{\mu} < 2.3$. The difference between this and the electron analysis is that more forward-going leptons are now included, so that resolved photon processes are expected to give a more sizeable contribution. To quantify the different processes contributing in the two regions, the $x_{\gamma}^{\mathrm{OBS}}$ distribution was analysed. In Fig. 2(left) this distribution is reported for events in the barrel region ($-1.75 < \eta_{\mu} < 1.3$); a peak for high values can be observed, since direct photon dominates. The same distribution is reported for the forward region ($1.3 < \eta_{\mu} < 2.3$) in Fig. 2(right): here the shape is different, with a significant peak at low $x_{\gamma}^{\mathrm{OBS}}$, indicating the dominant contribution from resolved photon processes. The $x_{\gamma}^{\mathrm{OBS}}$ distributions in the two regions were fitted with Pythia direct and resolved components in order to estimate the two contributions. While in the barrel region a significant but not dominant (45%) resolved fraction is needed in order to describe the data shape, this fraction becomes the more important (64%) in the forward region. The measured beauty cross section

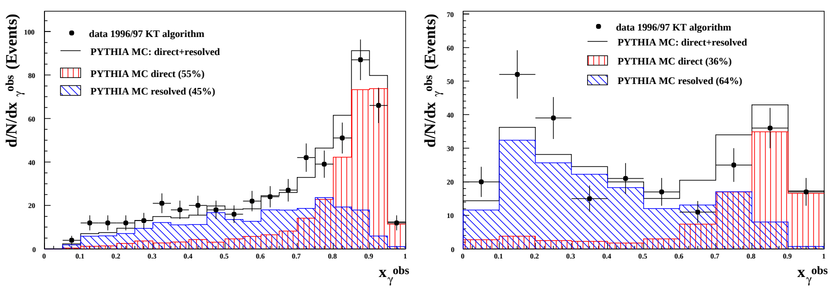


Fig. 2. Distribution of the number of events in $x_{\gamma}^{\mathrm{OBS}}$ in the barrel and rear (left) and forward (right) region. The experimental data is compared to Pythia MC (open histogram) (with a mixture of beauty and charm plus light quarks components according to the percentage given by the fit). The contributions from direct processes (vertically hatched area) and from resolved processes (diagonally hatched area) are shown separately.

was extrapolated to the electron analysis kinematic region and agreed with that measurement. Differential cross sections as functions of the transverse momentum and pseudorapidity of the muon are presented in Fig. 3. The measured values are compared to the predictions of PYTHIA and CASCADE MC simulations. The PYTHIA predictions are in reasonable agreement with the measured cross sections but have a tendency to be too low in the most forward (proton) region. The same behaviour is observed for CASCADE, which slightly underestimates the data in the forward region (high $\eta$ and low $p_{\mathrm{T}}$).

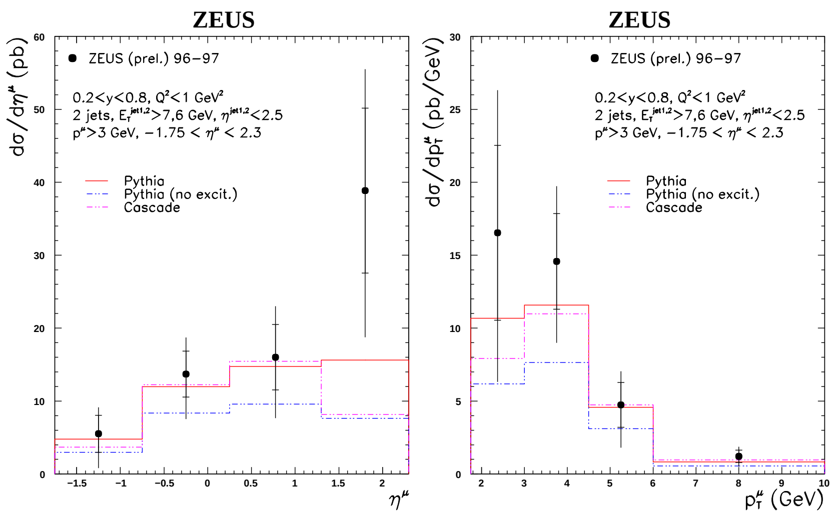


Fig. 3. Differential beauty cross sections as functions of the muon transverse momentum $p_{\mathrm{T}}^{\mu}$ (left) and pseudorapidity $\eta^{\mu}$ (right), for events with two jets and a muon, compared to the absolute predictions from PYTHIA and CASCADE Monte Carlo simulations.

## 4. Conclusion

Beauty photoproduction has been observed at HERA, in the photoproduction regime. In the electron analysis the measured beauty photoproduction cross section lies somewhat above the fixed-order NLO predictions and agrees with CASCADE predictions within errors. The muon analysis has been extended to include a more forward region, where resolved processes are expected to be dominant. Differential cross sections as functions of $p_{\mathrm{T}}^{\mu}$ and $\eta^{\mu}$ were calculated and compared to PYTHIA and CASCADE predictions, and found to be slightly higher than the Monte Carlo, particularly in the most forward region.

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