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First results on beauty production using HERA II data

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Abstract

The production of beauty quarks has been measured with the ZEUS detector at HERA using an integrated luminosity of 31 pb^{-1} collected in 2003 and 2004. The process $ep \rightarrow e'b\bar{b}X \rightarrow ejj\mu + X$ is investigated to study semi-leptonic decays of beauty quarks into muons in the photoproduction regime. The determination of the beauty fraction is carried out using the distribution of the transverse momentum of the muon relative to the closest jet. The newly installed micro-vertex detector (MVD) is also used to study the beauty content from measurements of the impact parameter of the muon. These methods are compared and show the potential of future beauty quark measurements using the MVD.

1 Introduction

The production of beauty quarks in ep collisions at HERA is a stringent test of perturbative Quantum Chromo-Dynamics (pQCD) since the large b-quark mass provides a hard scale that should ensure reliable predictions. ZEUS has measured beauty photoproduction in dijet events [1,2] and beauty electroproduction [3] in HERA-I data corresponding to a luminosity of about 110 pb^{-1}. The measured cross sections were found to be in reasonable agreement with Next-to-Leading Order pQCD calculations.

HERA has been upgraded (HERA-II) to provide higher luminosity, and is now routinely achieving luminosities of $3 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$. The ZEUS detector has been upgraded as well, with the installation of a silicon Micro-Vertex-Detector (MVD) [4], a new forward tracker (STT) [5], a new tracking trigger (GTT) [6–9] and a further muon trigger based on the backing calorimeter (BAC) [10, 11]. These detector upgrades, in conjunction with higher luminosities, are expected to significantly improve the potential for b physics.

This paper presents the first results on b photoproduction from HERA-II data. A sample of photoproduction events with two jets and a muon, $ep \to e'b\bar{b}X \to ejj\mu + X$, for $Q^2 < 4$ GeV^2 was selected. The beauty content of the sample was investigated by exploiting the distribution of the transverse momentum of the muon with respect to the associated jet (p_T^{rel}) and the impact parameter (δ) of the muon utilizing the MVD.

2 Experimental setup

The data used in this analysis were collected from October 2003 to July 2004, when HERA operated with protons of energy $E_p = 920$ GeV and positrons of energy $E_{e^+} = 27.5$ GeV and is based on an integrated luminosity of 31 pb^{-1}. A detailed description of the ZEUS detector can be found elsewhere [12]. A brief outline of the components that are most relevant for this analysis is given below.

The high-resolution uranium–scintillator calorimeter (CAL) [13] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part is subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons (E in GeV).

Charged particles are tracked in the central tracking detector (CTD) [14] and the MVD, which operate in a magnetic field of 1.43 T provided by a thin superconducting coil. The CTD consists of 72 cylindrical drift chamber layers, organized in 9 superlayers covering the polar-angle[1] region $15^\circ < \theta < 164^\circ$. The MVD is organized into a barrel section with 3 cylindrical layers and a forward section with four planar discs (wheels) perpendicular to the HERA beams. The barrel and the forward sections contain 600 and 112 single-sided silicon strip sensors with 512 and 480 120 μm wide strips respectively. Currently the hit resolution is 40 μm in the RZ and 65 μm in the $R\phi$ plane. The resulting vertex resolution is around 100 μm in both the transverse and longitudinal planes.

The sampling Backing Calorimeter [10] consists of 5200 aluminum proportional drift chambers which are typically 5 m long and have a wire spacing of 1 cm. The chambers are inserted into the iron yoke of the ZEUS detector (barrel and two endcaps) covering the CAL. It is equipped with analog (for energy measurement) and digital (for muon tracking) readouts. The former is based on 2000 towers ($50 \times 50\, cm^2$) providing an energy resolution of $\sim 100\%/\sqrt{E}$. The digital information on hit wires allows the reconstruction of muon trajectories in two dimensions (XY in barrel, YZ in endcaps) with an accuracy of a few mm.

The muon system consists of barrel, rear (BRMUON) [15] and forward (FMUON) [12] tracking detectors. The BRMUON consists of limited-streamer (LS) tube chambers placed behind the BCAL (RCAL), inside and outside the magnetized iron yoke surrounding the CAL. The barrel and rear muon chambers cover polar angles from 34° to 135° and from 135° to 171°, respectively. The FMUON consists of six trigger planes of LS tubes and four planes of drift chambers covering the angular region from 5° to 32°. The muon system exploits the magnetic field of the iron yoke and, in the forward direction, of two iron toroids magnetized to ~ 1.6 T to provide an independent measurement of the muon momentum.

3 Dijet and μ selection

A sample of photoproduction events with two jets and a muon was selected to extract the beauty content. The events were preselected by the ZEUS online trigger system to contain two high E_T jets and a muon. Events preselected by inclusive dijet and muon triggers were included as well. Standard cuts and requirements where applied to reject the contribution from deep inelastic scattering (DIS) events following the selection from [1], corresponding to an effective cut on the photon virtuality $Q^2 < 4\,\mathrm{GeV}^2$ and $0.2 < y < 0.8$, where y is the event inelasticity.

[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 center of HERA. The interaction point is shifted to $x = 1.75$ cm relative to the coordinate origin.

Jets were reconstructed from energy flow objects (EFOs) combining charged tracks reconstructed in the CTD and energy clusters reconstructed in the CAL [16] using the Kt cluster algorithm in the longitudinal-boost invariant mode in the E recombination scheme [17]. At least two jets with $|\eta^{\rm jet}| < 2.5$ and $p_T^{\rm jet1(2)} > 7(6)$ GeV were required in the event. One of the jets in the event was required to contain an identified muon to determine the transverse momentum of the muon with respect to the jet.

In order to increase the statistics, the muon selection was loosened with respect to the one used in [1]. Several muon reconstruction algorithms were combined to exploit the redundancy of the various detector components. A muon was tagged by this algorithm if a well-measured CTD track was matched with a segment in the inner or outer barrel or rear muon chambers (BRMUON) or a track in the forward muon spectrometer (FMUON) or a muon candidate in the backing calorimeter (BAC). A minimal p_T^μ cut of 0.75 GeV was applied. In the barrel region, the muon rangeout in the calorimeter provides an implicit threshold of $p_T^\mu \simeq 1.5$ GeV. The measurement of a corresponding minimum ionizing energy deposit in the calorimeter was used to improve the signal to background ratio.

This selection gave 8010 muon candidates associated to a jet.

4 Beauty fraction determination

The fraction of b quarks in the selected dijet+muon sample can be obtained by exploiting the large B hadron mass. Muons from B hadron decays tend to be produced at large transverse momenta with respect to the initial hadron direction. The $p_T^{\rm rel}$ variable, defined as the transverse momentum of the muon with respect to the direction of the rest of the associated jet, can therefore be used to separate muons originating from beauty from the background, which is composed of muons from charm decays and fake muons from light flavours.

Figure 1 shows the $p_T^{\rm rel}$ distribution from the described dijet and muon selection. This distribution was fitted with a beauty and a background component from charm and light flavours obtained from Monte Carlo (MC) simulations using Pythia 6.2 [18]. The shape of the b component was taken directly from the MC, while the $p_T^{\rm rel}$ shape of the background components from Pythia was corrected to reproduce the $p_T^{\rm rel}$ distribution of an inclusive track sample without muon requirements, as described in [1]. The size of the MC samples used is similar to that of the data.

A b fraction of 16.1 ± 2.7 % (statistical error only) was obtained from a 2-component fit. As expected from simulations, this fraction is lower than the fraction from [1] due to the looser muon requirements and correspondingly higher background. Using the muon selection from [1] would yield a beauty fraction of 19.6 ± 7.2 % (statistical error only), compatible with the results in [1], but with larger statistical error.

Distributions in η and p_T of the muons and of the jets associated to the muons are compared to the prediction from the MC (see figure 2), where the b and background components have been reweighted according to the b fraction obtained from the $p_T^{\rm rel}$ fit. In all distributions, the data are in good agreement with the MC.

5 Impact parameter

The b content of the sample can be also obtained by exploiting the long B hadron lifetime of $c\tau = 502$ μm for $B^{\pm}$ and $c\tau = 462$ μm for B^0 [19]. This can be done by the measurement of the impact parameter (δ) of the muons in the preselected sample with respect to the beam spot.

The expected transverse width of the HERA beams at the interaction point is $\sigma_X = 112$ μm and $\sigma_Y = 32$ μm and therefore the beam position, obtained from a run average of reconstructed event vertices, provides a good determination of the event vertex. After a global alignment of the MVD with respect to the CTD and internal alignment of the MVD layers, the observed widths of the reconstructed event vertex distributions are $\sigma_X \approx 150\ \mu m$ and $\sigma_Y \approx 140\ \mu m$. For triggered ep events, taking the expected transverse widths of the HERA beam spot as given above, these numbers give a measured vertex resolution of $\sigma_X \approx 100\ \mu m$ and $\sigma_Y \approx 140\ \mu m$. These numbers are compatible with those obtained from a cosmic muon sample. In the future, improvements are expected from the inclusion of ep data into the alignment, from corrections of the beam position with time within each run and from the usage of the impact parameter significance instead of the impact parameter.

For this analysis, an impact parameter (δ) was defined as the distance of closest approach of the muon with respect to the beam position in the transverse plane. If this muon track intercepts the axis of the jet associated with the muon downstream of the primary vertex, a positive sign was given to δ, negative otherwise (see figure 3). The impact parameters in the light flavour contribution reflect the detector resolution and should be symmetrically distributed around 0. An excess of events with large positive values is expected for beauty events, and to a lesser extent also for charm events due to the smaller $c\tau$ of charmed hadrons.

The data sample ($20\ pb^{-1}$) was smaller than that used for the $p_T^{\rm rel}$ analysis, since events for which either the MVD or the run averaged beam spot information was not yet available have been removed. In order to use only candidate tracks of good quality, cuts on the number of superlayers in the CTD $n_{superlayers} \geq 3$ and on the number of MVD hits used in the track reconstruction $n_{MVD\ Hits} \geq 4$ were applied. Figure 4 shows the distribution of δ for the selected muons. A clear enhancement at higher positive values is observed in the data with respect to the mirrored negative part.

Figure 5 shows the difference of positive and negative impact parameters, compared to beauty and charm MC, with the beauty normalization taken from the p_T^{rel}-fit (see figure 1) and the charm normalization adjusted to the charm/light flavour ratio predicted by the MC. The excess of data with positive δ is compatible with beauty and charm predictions and the beauty fraction in the data sample found with the p_T^{rel}-fit.

Fig. 6 shows a candidate event from the dijet+muon selection with two muons associated to 2 different jets. The muons have opposite sign, and both have a high p_T^{rel} with respect to their associated jet. Both muons have an impact parameter relative to the beam spot larger than 250 μm. These muons are compatible with the hypothesis that they come from different b quarks.

6 Conclusion

First results on beauty in photoproduction from the HERA II data, taken between October 2003 and June 2004, have been presented. A direct comparison to the HERA I analysis [1] yields compatible results. In order to increase the statistics, a new muon selection with looser p_T cuts and higher efficiency has been made, using additional detector components. A beauty fraction of 16.1 ± 2.7 % is extracted from a p_T^{rel}-fit from this sample.

The new Micro-Vertex-Detector was used in addition to study the beauty content by the determination of the impact parameter of the selected muons. The measured enhancement in the positive impact parameter distribution at higher values is found to be compatible with coming from beauty and charm quarks and the beauty fraction determined by the p_T^{rel}-fit.

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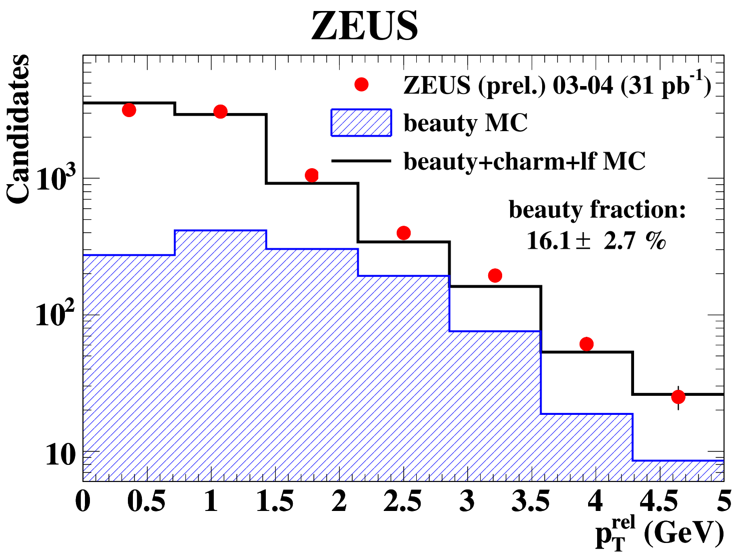

Figure 1: *p_T^{rel} distribution for a HERA II data sample of 31 pb^{-1}. The data are compared to a mixture of beauty and charm+light flavour MC given by the fit. The hatched histogram shows the beauty contribution.*

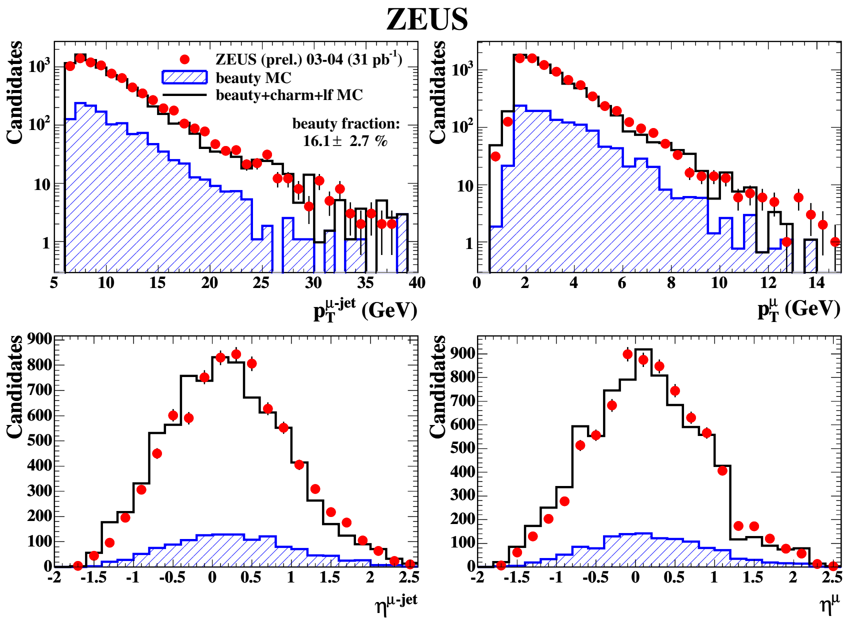

Figure 2: *Distribution of p_T and η of the muon and the jet associated to the muon from a HERA II data sample of 31 pb^{-1}. The data are compared to a mixture of beauty and charm+light flavour MC given by the p_T^{rel} fit from figure 1. The hatched histograms show the beauty contribution.*

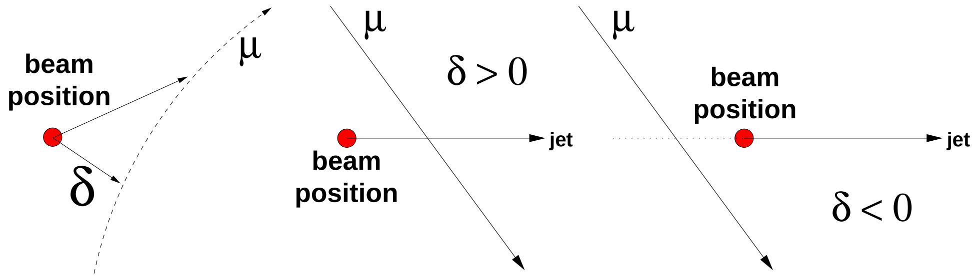

Figure 3: *The impact parameter (δ) is defined as the distance of closest approach of the muon with respect to the beam position in the transverse plane. If this muon track intercepts the axis of the jet associated to the muon downstream of the beam position, a positive sign is given to δ, negative otherwise.*

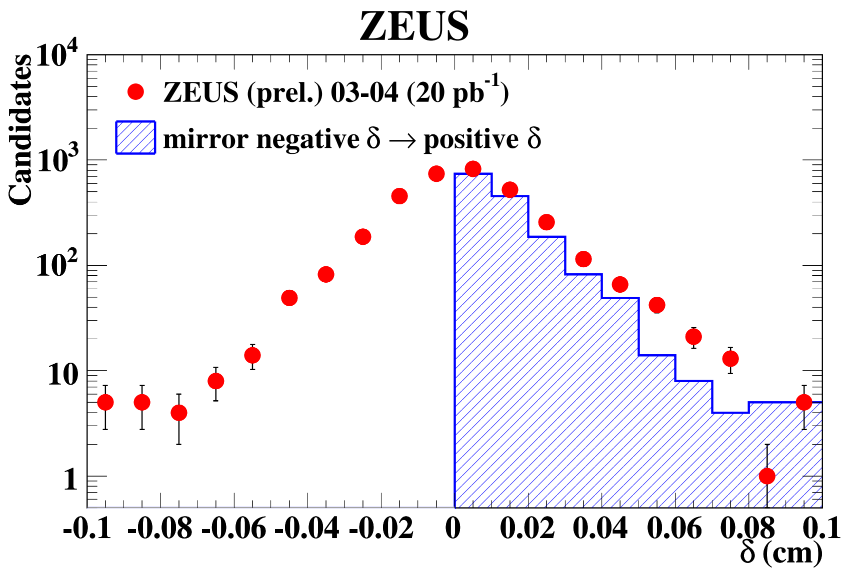

Figure 4: *Impact parameter distribution from a HERA II data sample of 20 pb^{-1}. The negative contribution was mirrored to the positive side (hatched histogram) to show the observed asymmetry.*

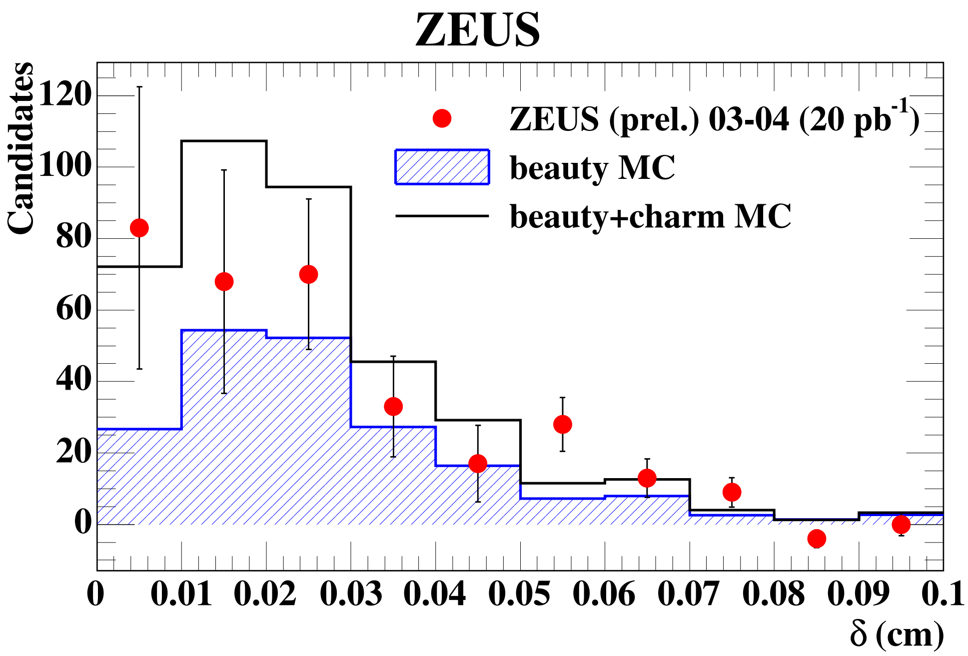

Figure 5: *Impact parameter distribution resulting from the subtraction of the negative from the positive part of the measured impact parameter distribution from a HERA II sample of 20 pb^{-1}. The data are compared to the similar subtracted MC distributions from beauty and charm, scaled by the beauty fraction determined by the $p_T^{\rm rel}$ fit in figure 1 and by the charm fraction predicted by the MC respectively.*

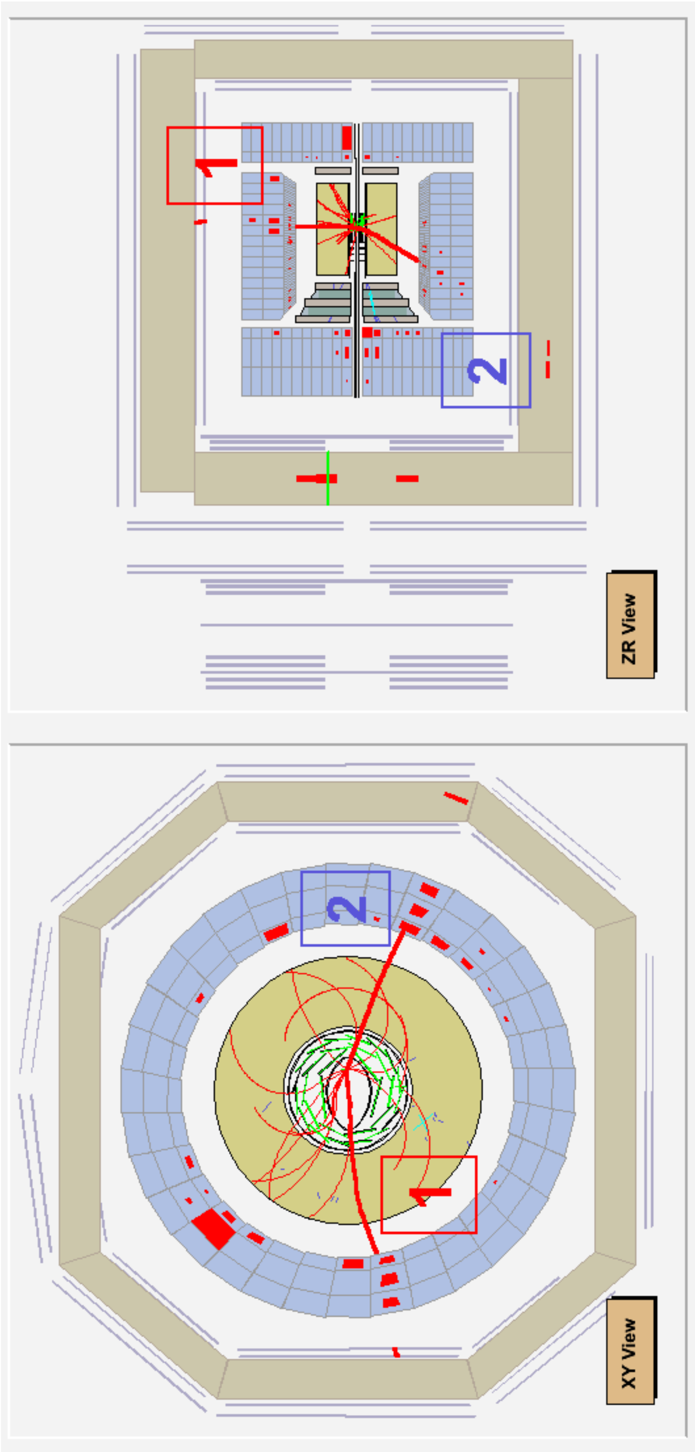

Figure 6: *ZEUS beauty candidate event with 2 jets and 2 associated muons. The muons have impact parameters relative to the beam spot of 250 and 330 μm as well as high $p_T^{\rm rel}$ with respect to the jets of 1.24 and 2.05 GeV. The dimuon pair has an invariant mass of 5.5 GeV.*