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Beauty Production in Deep Inelastic ep Scattering

H1 Collaboration

Abstract

We report the first observation of beauty production in deep inelastic ep scattering (DIS). Hadrons with b flavour are observed with the H1 detector at HERA through their semi-leptonic decay. The cross section is extracted using the distributions of the impact parameter and of the transverse momentum of muons relative to jets in the kinematic range $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$, for muon polar angles and transverse momenta $35^\circ < \theta < 130^\circ$ and $p_T > 2$ GeV. The result, $\sigma = [39 \pm 8\,(stat.) \pm 10\,(syst.)]\,\mathrm{pb}$ is found to be significantly above NLO QCD predictions.

Beauty production has not yet been observed in deep inelastic scattering (DIS). The process is considered to be reliably calculable in perturbative QCD since the b quark mass sets a hard scale. Particular interest in confronting the theory with experiment in a yet unexplored production environment stems from the fact that b cross sections are found in excess of QCD expectations in $\bar{p}p$ [1], γp [2, 3, 4] and, recently, $\gamma\gamma$ [5] interactions, where the calculations follow the same principles. Moreover, since charm accounts for about a quarter of the inclusive DIS rate in the HERA domain [6], the proton structure analysis of inclusive DIS data [7] relies heavily on the understanding of heavy quark production, for which b production constitutes a new testing ground.

In electron proton collisions, b quarks are predominantly produced, in QCD, via the interaction of a photon coupling to the incoming electron with a gluon in the proton by forming a quark-anti-quark pair. The case of small photon virtuality, $Q^2 < 1$ GeV^2 corresponds to photoproduction (γp). The DIS case of larger Q^2 is complementary, because resolved contributions involving the partonic structure of the photon are expected to be suppressed [8]. Thus theoretical uncertainties due to imperfect knowledge of hadronic structures are smaller in DIS than in the other reactions.

The result presented here is an extension of our measurement of the beauty production cross section [3], from the photoproduction regime to DIS. The analysis starts with a sample of DIS events collected in 1997. The same reconstruction and selection procedures as in [3] are used to obtain a dijet event sample with a muon identified in the instrumented iron and well measured in the central silicon tracker (CST) [9].

Here the electron is scattered into the main detector. Its signature is used in the trigger which requires electromagnetic energy deposition signals from the backward calorimeter SpaCal in coincidence with tracking information from proportional and drift chambers. The integrated luminosity corresponds to $\mathcal{L} = 10.5$ pb^{-1}.

The selection of DIS events follows the methods described in [10]. The scattered electron candidate reconstructed in the SpaCal must be detected with a polar angle $\theta_{e'} < 177^o$ relative to the incoming proton momentum vector and is required to have an energy $E_{e'} > 9$ GeV. The DIS kinematic variables Q^2 and y are reconstructed from the scattered electron. The cross section is determined for the visible kinematic range $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$, $p_T(\mu) > 2$ GeV and $35^\circ < \theta(\mu) < 130^\circ$. $p_T(\mu)$ and $\theta(\mu)$ denote the transverse momentum and the polar angle of the muon with respect to the beam axis. 168 events are selected which contain $N_\mu = 171$ muon candidates.

The composition of the sample, in terms of muons from $b\bar{b}$ events, $c\bar{c}$ events, or background from misidentified hadrons ("fake muons") is analyzed using AROMA Monte Carlo [11] event samples as in [3]. The hadron sample used to model the fake muon background is selected using the same requirements as for the signal, except for the muon identification, and using the same trigger for DIS events.

In the photoproduction case, it has been shown that the impact parameter δ and the transverse momentum p_T^{rel} relative to the jet axis provide independent and consistent signatures for b production. The analysis of the smaller DIS sample relies on the combination of the two observables, which also provided the most precise photoproduction result.

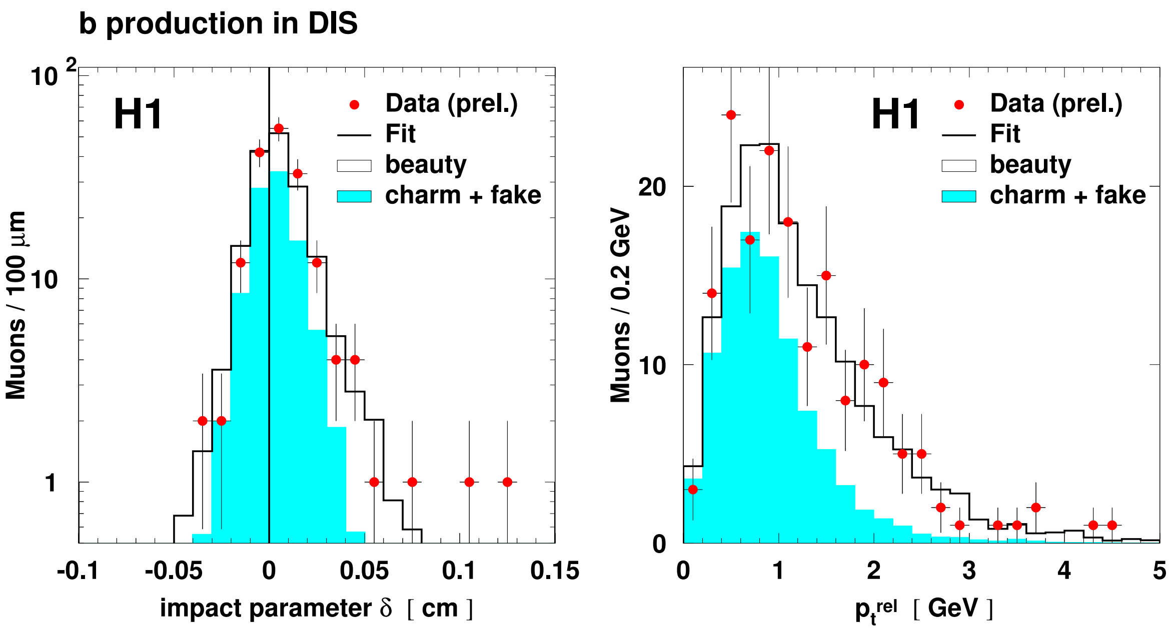

Figure 1: Distributions of the muon impact parameter (left) and transverse momentum relative to the jet axis (right), with decomposition from the likelihood fit.

A likelihood fit of $b\bar{b}$, $c\bar{c}$ and fake muon reference spectra to the two-dimensional distribution in δ and p_T^{rel} adjusts the relative weights of all three components in the data. It yields a $b\bar{b}$ fraction of $f_b = (43 \pm 8)\,\%$.

The projections of this distribution are shown in Fig. 1 together with the decomposition from the fit. The distributions of both variables are well described. The need for a $b\bar{b}$ component is evident from the lifetime based signature as well as from the p_T^{rel} spectrum. The charm and fake muon fractions are varied independently in the fit, but have large, correlated errors. The fit yields $f_{fake} = (11 \pm 22)\,\%$. Within the large error this is consistent with the expectation using fake probabilities determined in Monte Carlo simulations to reweight the hadron track sample, $f_{fake} = 43\,\%$. Fixing the fake muon fraction to this value in the fit changes the result for f_b by less than half the statistical error. The fits to the one-dimensional distributions were performed as cross checks, as in [3] and yield consistent results.

The sources of systematic uncertainty are the same as in the photoproduction case, except for a small contribution ascribed to the electron reconstruction. The dominant contribution is due to the Monte Carlo Model used to extrapolate the cross section. The biggest experimental errors, arising from the stability with respect to variations of the impact parameter analysis and the change of the jet energy scale, were checked separately for the DIS sample and confirmed.

The cross section for the production of muons from b decays is defined as in [2] as

$$\sigma_{ep}^{vis}(ep \to bX \to \mu X) = f_b N_\mu / (2\epsilon\mathcal{L})\,,$$

where ϵ denotes the efficiency for a $b\bar{b}$ event with a primary or secondary muon in the visible range to fulfill the selection and trigger requirements. The factor of 2 accounts for the fact that

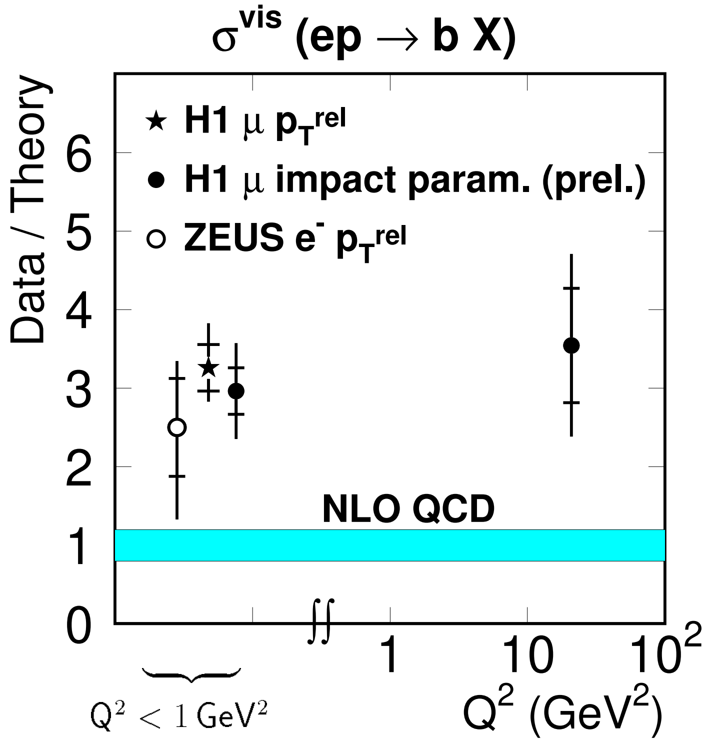

Figure 2: Ratio of measured b production cross sections at HERA over theoretical expectation, as a function of Q^2. The inner (outer) error bars represent the statistical (total experimental) error, the shaded band the theoretical uncertainty.

the experiment measures muons from b and $\bar{b}$ decays. We find

$$\sigma_{ep}^{vis} = [\ 39\ \pm\ 8\ (stat.)\ \pm 10\ (syst.)\ ]\ \mathrm{pb}\ .$$

This measurement can be directly compared to a NLO QCD calculation using the standard HVQDIS program [12] with a Peterson fragmentation function [13] used to scale the quark momenta in order to obtain b hadron momenta. The distributions were then folded with a lepton spectrum extracted from the aroma Monte Carlo generator. The GRV98 parton densities [14] are used, the b quark mass was set to 4.75 GeV, and the renormalization and factorization scales to $\mu = \sqrt{Q^2 + 4m_b^2}$. The Peterson fragmentation parameter to $\epsilon_b = 0.0033$ as obtained from a fit of a fixed order QCD calculation [15] in the same (massive) scheme to the b production spectrum [16] measured in e^+e^- annihilation. The QCD result is (11 ± 2) pb, where the error has been estimated by varying the scale μ by factors of two, ϵ_b between 0.0016 and 0.0069, and m_b between 4.5 and 5 GeV. The b mass has the strongest influence ($\pm 11\,\%$). The AROMA prediction is 9 pb. A LO calculation with the CASCADE program [17] based on the CCFM evolution equation yields 15 pb.

We summarize the HERA results as a function of Q^2 in Fig. 2. Displayed is the ratio of measured visible cross sections over theoretical expectations, which for the photoproduction case have been calculated [2, 4] using the FMNR program [18]. The ratio is consistent with being independent of Q^2; the discrepancy between data and theory is thus not a feature of the photoproduction regime alone.

In conclusion, the b cross section in DIS is measured for the first time and is found to be above QCD expectations. A similar excess as observed in $\bar{p}p$ [1], γp [2, 4] and $\gamma\gamma$ [5] interactions is now also seen in ep scattering.

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