Hadronic Beauty Production at HERA

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Abstract. Recent results on beauty production in electron proton collisions at 300-318 GeV center-of-mass energy are presented. The cross sections measured by the H1 and ZEUS experiments at HERA are compared with perturbative QCD calculations.

INTRODUCTION

The measurement of heavy flavour processes at the HERA ep-collider is a powerful means of exploring the dynamics of the strong interactions described by QCD. Perturbative QCD (pQCD) has been seen to successfully describe inclusive production cross sections wherever Q^2, the negative 4-momentum transfer squared, and/or the transverse momenta of the final state are sufficiently large to provide an energy scale for perturbative expansions in orders of the strong coupling constant α_S. In heavy flavour production the largeness of the heavy quark mass provides an alternative energy scale for perturbative calculations, and it has been shown that pQCD provides a reasonable description of charm production. In contrast, the first measurements of beauty production at HERA [1, 2, 3] revealed significant excesses of data over pQCD predictions by factors of ~ 3, in line with similar findings in $p\bar{p}$ and $\gamma\gamma$ collisions at the Tevatron [4] and at LEP [5]. In this paper recent HERA beauty measurements are presented, based on the H1 and ZEUS data recorded between 1995 and 2000.

THEORY

In the Standard Model the dominant mechanism for beauty production in ep-collisions at HERA is the direct boson gluon fusion process as shown in fig. 1a). Further contributions are expected from resolved photon processes as illustrated in fig. 1b). All these processes are directly sensitive to the gluon density in the proton. The kinematics at HERA spans a large range in the photon virtuality Q^2 from photoproduction, where $Q^2 < 1$ GeV^2 to deep inelastic scattering (DIS), where Q^2 can reach values much higher than the squared b-quark mass. It is expected that resolved photon processes are suppressed towards larger Q^2.

The large mass of the beauty quark provides a hard scale, which renders a small coupling constant α_s in the hard subprocess. This facilitates the calculation of cross sections by means of pQCD. One distinguishes the following two approaches:

- In the so-called massive or fixed order scheme[8], u, d and s are the only active flavours in the proton, and charm and beauty are dynamically produced in the hard scattering. This approach should work well for the kinematic region $p_T \leq m_b$, where p_T is the transverse momentum of the outgoing b-quark. Calculation tools up to next-to-leading order (α_s^2) (NLO) are available in the form of Monte Carlo integration programs [9, 10].
- At higher transverse momenta the so called massless or resummed approach [11] should be applicable, where charm and beauty are regarded as active flavours (massless partons) in the proton and in the photon and fragmented only after the hard process into massive quarks. This ansatz incorporates excitation processes, such as the two right most diagrams shown in fig. 1b).

EXPERIMENTAL TECHNIQUE

The total beauty production cross-section at HERA is two orders of magnitude smaller than that of charm. High p_T muons from semileptonic b-decays are used to identify the beauty events. In the single track tag analyses, the selected muon is required to be associated with a jet. To separate beauty events from charm and light quark background, two observables are used which exploit the large mass and the long lifetime of the b-quark, respectively:

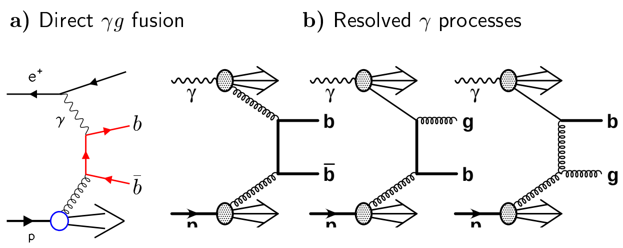

FIGURE 1. Beauty production processes in leading order pQCD.

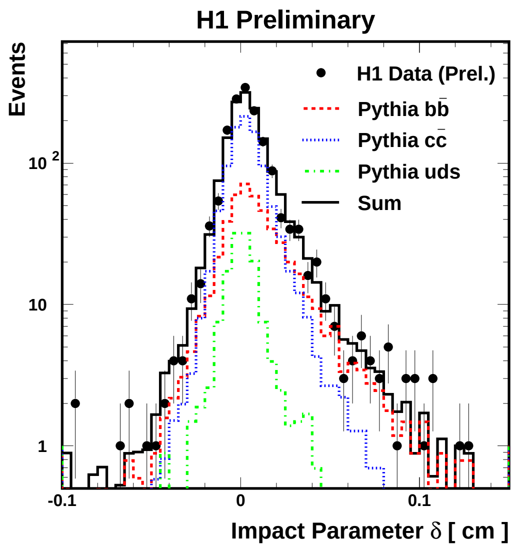

FIGURE 2. Impact parameter distribution as measured by H1 [6]. The lines show the decomposition obtained from a fit of the data into contributions from b (dashed), c (dotted) and light-quark (dashed-dotted) events which simulated using the PYTHIA MC generator [14].

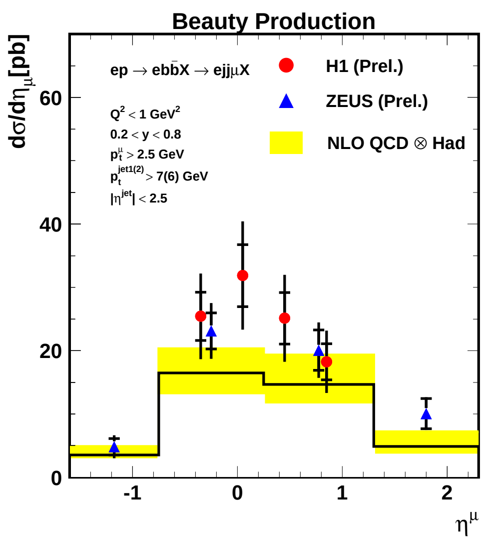

FIGURE 3. Differential beauty cross sections as a function of pseudorapidity of the muon.

1. The transverse momentum p_t^{rel} of the muon with respect to the axis of the associated jet: for muons from b-decays this exhibits a much harder spectrum than for the other sources.
2. The impact parameter δ of the muon track with respect to the primary event vertex: For muons from b-decays this takes larger values as compared to the other sources. This variable is only used by the H1 experiment, where a central silicon vertex detector provides the necessary track resolution (fig. 2).

The relative contributions of beauty and background in the data are determined from likelihood fits to the above observables.

In the double track tag measurements a D^{*+}-meson is required in addition to the muon. It is reconstructed in the decay channel $D^{*+} \to D^0 \pi_s^+ \to K^- \pi^+ \pi_s^+$. The angular and charge correlation between the muon and the D^{*+}-meson are exploited to identify charm and beauty contributions.

RESULTS

New preliminary H1 results [6] are available for beauty production in photoproduction, exploiting a three times larger data sample than for the first results [1]. The measurements are based on the muon single track tag technique described in the previous section. Figure 3 shows the single differential cross-sections for $ep \to eb\bar{b}X \to e\,\mathrm{jet}\,\mathrm{jet}\,\mu$ as a function of the muon pseudorapidity. The H1 data are in agreement with the ZEUS data presented last year [12]. The data points are also compared to

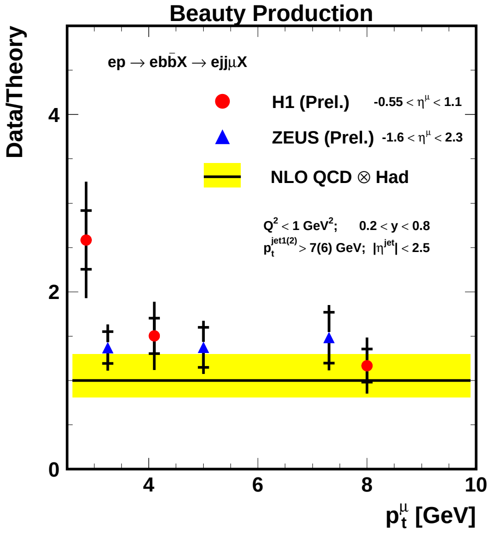

FIGURE 4. Ratio of data and NLO calculation as a function of transverse momentum of the muon.

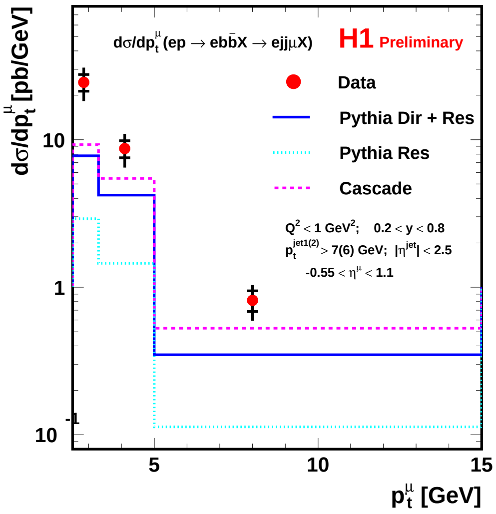

FIGURE 5. Differential beauty cross-sections as a function of transverse momentum of the muon.

an NLO calculation in the massive scheme based on FMNR [9]. For the calculation, fragmentation is performed using the Peterson function [13]. The errors of the theory prediction are dominated by the uncertainties of the renormalisation scale and the b-quark mass. *All* the data points in fig. 3 lie above the theory calculation. However, data and calculation agree at the two sigma level. Figure 4 shows the ratio of the measured cross sections and the NLO calculation as a function of the muon transverse momentum. At the lowest momenta, the theory undershoots the data by a factor of two. The other data points are also above the theory but at a level of $\leq 50\%$. Figure 5 depicts the measured H1 cross-sections in bins of the muon transverse momentum compared to predictions from the leading order Monte Carlo programs PYTHIA [14] and CASCADE [15]. PYTHIA is run in the massless mode and simulates direct and resolved photon processes. Higher orders are approximated in PYTHIA and CASCADE by gluon showers generated using the DGLAP and CCFM evolution prescriptions, respectively. With the settings used, CASCADE and PYTHIA clearly fall below the data.

The contribution from resolved photon processes is investigated by the observable $x_\gamma = \sum_{j1,j2}(E_T^j e^{-\eta^j})/(2yE_e)$. x_γ can be interpreted in the proton rest frame as the fractional photon momentum of the parton (gluon or b-quark) that undergoes the hard scattering process. Figure 6 shows the ZEUS data. Resolved processes, reconstructed at $x_\gamma \leq 0.75$, have a significant contribution to the total cross section of about 30%. The NLO calculation describes the shape of the data, but falls low in normalisation.

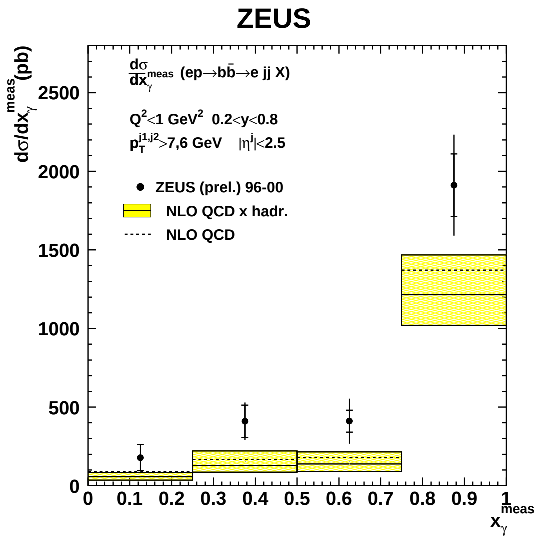

FIGURE 6. Differential beauty cross-section data from ZEUS [12] as a function of x_γ (see text) in comparison with a NLO calculation (band) [9].

ZEUS presented last year the first differential cross-section measurements [16] in the deep inelastic scattering regime. Figure 7 shows the cross sections in bins of the photon virtuality Q^2, compared with a NLO calculation in the massive scheme based on [10]. In contrast to the photoproduction case discussed above, data and theory agree well.

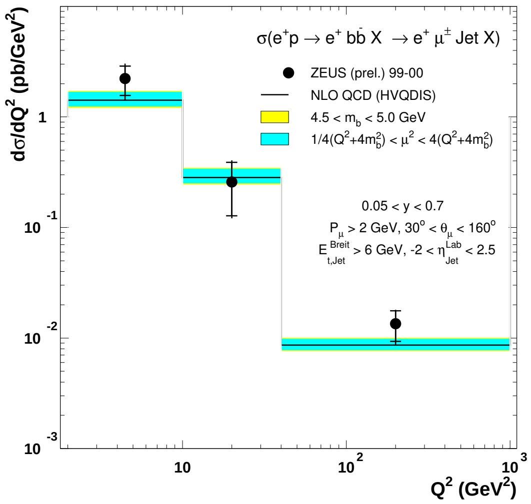

FIGURE 7. Differential beauty cross sections in deep in elastic scattering as a function of the photon virtuality Q^2.

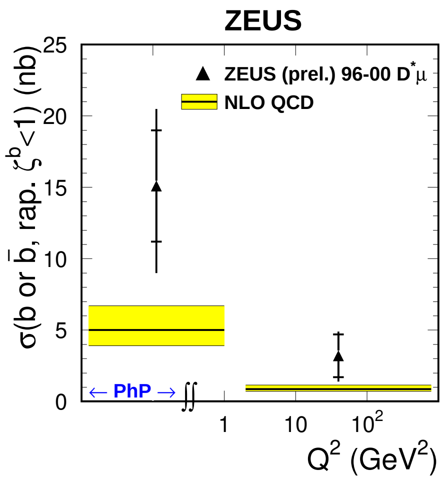

FIGURE 8. $D^{*+}\mu$ cross-sections in photoproduction (left) and DIS (right).

ZEUS has presented at this conference a first double track measurement in the deep inelastic scattering regime using D^{*+}-mesons and muons [7]. The measured cross-section is shown in fig. 8. It lies above the NLO calculation in the massive scheme based on HVQDIS [10]. Also shown in fig. 8 is the corresponding ZEUS result in photoproduction [17] which is also above an NLO calculation based on FMNR [9]. The ZEUS $D^*\mu$ photoproduction results agree with those of the H1 experiment [18].

CONCLUSIONS AND OUTLOOK

Recent measurements of beauty production in *ep*-collisions have been presented. Almost all measured cross-sections are above the QCD calculations which are performed here in the massive scheme in NLO. However, in contrast to some of the earlier measurements, the excesses have now decreased to a level, at which the data are compatible with the theory predictions within errors. In the new H1 photoproduction measurement [6] it is recognised that a large part of the significant excess observed in the corresponding older measurements [1, 2] was due to the fact that the data cross-sections were extrapolated outside their visible range using a leading order Monte Carlo simulation.

The upgraded HERA II collider with a factor of 5 larger luminosity and the improved H1 and ZEUS detectors will allow beauty measurements in *ep*-collisions to be made with much higher precision and in an extended kinematic phase-space, further testing our understanding of the physics of heavy flavour production.

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