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Heavy flavour production at HERA

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The production of charm and beauty quarks in *ep*-collisions at HERA has been studied by the H1 and ZEUS collaborations. Charm and beauty production is reasonably well described by next-to-leading order perturbative Quantum Chromodynamics in a wide kinematic range involving different experimental hard scales. This allows the charm and beauty contribution to the F_2 proton structure function, $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$, to be extracted.

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1. Introduction

The various measurements of charm and beauty production at the electron-proton collider HERA, based on different experimental techniques and covering a wide phase space range, are important to both test the accuracy of perturbative Quantum Chromodynamics (pQCD) and to constrain the gluon density in the proton. In leading order (LO) QCD, the dominant contribution for heavy flavour production in ep-collisions, $ep \rightarrow ec\bar{c}X$, $eb\bar{b}X$, is the photon-gluon fusion (PGF) process, in which a photon emitted from the electron fuses with a gluon from the proton to a charm- or beauty-quark pair (see figure 1). Predictions derived in the framework of pQCD are expected to be reliable whenever an experimental hard scale, μ, is available, with μ being much larger than Λ_{QCD}. Since the charm- and beauty-quark masses are larger than Λ_{QCD}, they each provide such a hard scale. Depending on the measurement, two additional experimental hard scales may be available: the square root of the photon virtuality, Q, and the transverse energy or momentum of the heavy-quark jet.

2. Theoretical aspects

Perturbative calculations of heavy-quark production at HERA are available up to next-to-leading order (NLO) in α_s. A number of theoretical approaches exist to describe heavy flavour quark production in ep-collisions. The different theoretical approximations of heavy flavour quark production are formulated in different theoretical schemes, treating the heavy quark either as massive and produced dynamically (massive scheme), or as massless and as an active constituent of the proton at large scales (massless scheme). The massive scheme is expected to describe the data better at experimental scales which are of the same order as the heavy quark mass, whereas the massless scheme is expected to be valid in regions of the phase space involving larger experimental scales. The general mass variable flavour number scheme (GM VFNS) for heavy quarks interpolates from the massive approach at low scales to the massless approach at high scales. For precise details of the different schemes, consult for instance the references given in [1].

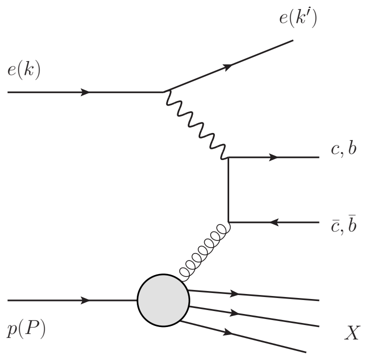

Figure 1: Feynman diagram for the dominant charm- and beauty-quark production process in electron-proton collisions at HERA.

3. Experimental aspects

3.1 ZEUS and H1 Detectors at HERA

The ring collider HERA accelerated electrons and protons to energies of $E_e \simeq 27.6\,\mathrm{GeV}$ and $E_p \simeq 920\,\mathrm{GeV}$. Inside the two experiments H1 and ZEUS the two beams were brought to collision, resulting at a centre of mass energy of $\sqrt{s} \simeq 320\,\mathrm{GeV}$. After a first data taking period from 1992-2000 (HERA I) the HERA accelerator was shut down and underwent a luminosity upgrade program, leading to its second period of operation from 2004-2007 (HERA II). H1 and ZEUS both collected a data set corresponding to an integrated luminosity of $L \simeq 0.5\,\mathrm{fb}^{-1}$.
H1 and ZEUS were classical, asymmetric multi-purpose detectors designed for the measurement of electron-proton interactions: tracks of charged decay products were measured in silicon vertex detectors enclosing the interaction point to identify decay vertices from long-lived particles, and drift chambers. The tracking detectors were surrounded by calorimeters measuring the energy of electrons, photons and hadrons, followed by a muon system. A detailed description of H1 can be found in [2] and of ZEUS in [3].

3.2 Experimental heavy flavour tagging methods at HERA

Charm and beauty production at HERA is suppressed with respect to the production of light flavoured quarks (u, d, s). The corresponding cross sections and consequently event rates very roughly behave like: $\sigma_{uds} : \sigma_c : \sigma_b \approx 2000 : 50 : 1$. For charm a full reconstruction of the D-mesons is possible. This is preferably done with so-called D^*-tags, where the D^*-meson decays to $D^0\pi$ and the reconstruction of subsequent D^0 decays to $K\pi$ are exploited. For beauty, however, no suitable decay channel exists having enough statistics to be fully reconstructed. Other experimental strategies are applied, which are based on either the large quark masses, the long lifetime, or the large lepton-decay branching ratio, $b \to \ell + X$, of B-hadrons.

4. Recent measurements

H1 and ZEUS have recently released several analyses measuring heavy flavour production in photoproduction, where the exchanged photon is almost real ($Q^2 \approx 0\,\mathrm{GeV}^2$), and in deep inelastic scattering (DIS), where the photon virtuality Q^2 is large compared to Λ_{QCD} and can be utilized as a hard scale.

4.1 Charm and beauty in photoprodution

In [4] charm quarks are identified by a D^*-tag and by requiring two low p_T jets. Of particular interest in this analysis is x_γ, which in leading order corresponds to the fraction of the photon's momentum that enters the interaction, and the azimuthal correlation between the two jets $\Delta\phi_{jj}$. Using x_γ, interactions with a pointlike photon (direct processes) can be discriminated against processes where the photon has a resolved hadronic structure. In LO QCD a back-to-back topology is expected ($\Delta\phi_{jj} = \pi$), while radiation of additional gluons leads to smaller opening angles. Differential cross sections as function of $\Delta\phi_{jj}$ are therefore a good test for NLO calculations. The data are compared with a prediction from MC@NLO [5], which is able to describe $\Delta\phi_{jj}$ for the direct

contribution reasonably well. However, it undershoots the measurement in the resolved regime at low azimuthal angles.
The ZEUS collaboration recently released a simultaneous measurement of charm and beauty jets in photoproduction [6]. The heavy flavour contribution to the data set is extracted from displaced tracks and from secondary vertex masses. This measurement benefits in terms of statistics from the inclusive selection and in terms of the comparison to the NLO pQCD prediction from the two hard scales given by the heavy-quark masses and the transverse momentum of the jets: the differential cross sections in the jet transverse momentum and the pseudo-rapidity of the jet are found to agree well with the prediction derived from the FMNR program [7].
A new H1 measurement [8] of beauty photoproduction extends the previously experimentally accessible phase space down to low transverse momenta of the beauty-quark, close to the beauty production threshold, i.e. a region of the phase space with the only available hard scale being the beauty quark mass. This is achieved by exploiting the decay channel $b\bar{b} \to eeX$ and by mastering the experimental challenge of low p_T electron identification. The unfolded differential cross section as function of the mean transverse momentum of the beauty-quark pair is compared to the massive NLO-QCD prediction from FMNR.
In Figure 2 the differential cross sections of beauty photoproduction of the discussed measurements are compared to all currently available beauty photoproduction measurements at HERA and the massive NLO pQCD prediction. It can be seen that the prediction agrees in general rather well with the data, which confirm each other over a wide range in p_T^b. Note that for this plot the central value of the pQCD prediction is derived for the choice $\mu_{r,f} = \mu_0 = 1/2\sqrt{m_b^2 + p_T^2}$ for the renormalization and factorization scales, while previous predictions usually used twice this value.

4.2 Charm and beauty in deep-inelastic-scattering

The H1 collaboration studied D^*-meson production in DIS [9]. This analysis profits from the large HERA II data set and presents a wealth of differential cross sections, which are compared to predictions derived in the massive and massless schemes of pQCD. The agreement between the data and the predictions is in general good, with tensions for the massless calculation at low inelasticity values, y.
In [1] and [10] performed by the H1 and ZEUS collaborations charm and beauty jets in DIS are measured, based on inclusive selections and the exploitation of lifetime information. Another measurement [11], utilizes the semileptonic decay channel $b \to eX$ in DIS. For all these measurements differential cross sections are derived as function of various quantities, but in particular as function of Q^2 and the Bjorken scaling variable, x. In addition they are confronted with massive NLO pQCD predictions, based on HVQDIS [12], which in the observed different kinematic regions of the phase space agree well with the data.
The good agreement of the data and the NLO pQCD calculations in the visible phase space (given by the heavy flavour quark tagging) allows the differential cross sections $\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2}$ and $\frac{d^2\sigma^{b\bar{b}}}{dx\,dQ^2}$ to be extrapolated to the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$, which describe the charm and beauty contribution to the F_2 proton structure function.
The left plot of figure 3 summarizes several $F_2^{b\bar{b}}$ extractions from the ZEUS and the H1 collaborations [13, 14]. The different measurements are based on completely different analysis techniques

and are well compatible within errors. Also shown are different predictions, which are all consistent and describe the data within the uncertainties.
In the right plot of figure 3 $F_2^{c\bar{c}}$ is shown, which is based on the combination of several charm data sets from D-meson measurements, results from displaced tracks and semi-leptonic decay analyses [15]. The averaged $F_2^{c\bar{c}}$ achieves highest experimental precision and is compared to different pQCD approaches. At low Q^2 values those have a large spread; here the data can be used to distinguish between them.

5. Conclusion

Heavy flavour production at HERA is intensively studied in many analyses with various heavy flavour tagging methods, achieving high experimental precision and confirming each other over a large kinematic phase space. The heavy flavour production measurements are able to test pQCD at different scales. In general the pQCD calculations describe the data reasonably well in shape and normalization.

References

[1] F. D. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **71** (2011) 1509 [arXiv:1008.1731 [hep-ex]].

[2] I. Abt *et al.* [H1 Collaboration], Nucl. Instrum. Meth. A **386** (1997) 310;
I. Abt *et al.* [H1 Collaboration], Nucl. Instrum. Meth. A **386** (1997) 348.

[3] ZEUS Coll., U. Holm *et al.*, The ZEUS Detector. Status Report (unpublished), DESY (1993), available on http://www-zeus.desy.de/bluebook/bluebook.html

[4] H1prelim-10-072, available on http://www-h1.desy.de/publications/H1preliminary.short_list.html

[5] T. Toll, "MC@NLO for Heavy Flavour Photoproduction at HERA", DESY-THESIS-2010-004, available on http://www-h1.desy.de/publications/theses_list.html

[6] H. Abramowicz et al. [ZEUS Collaboration] to be published in EPJ C

[7] S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, Phys. Lett., **B348** 633-645, 1995.

[8] H1prelim-11-071, available on http://www-h1.desy.de/publications/H1preliminary.short_list.html

[9] H1prelim-10-172, available on http://www-h1.desy.de/publications/H1preliminary.short_list.html

[10] ZEUSprel-10-010, available on http://www-zeus.desy.de/public_results/publicsearch.html

[11] H. Abramowicz et al. [ZEUS Collaboration] to be published in EPJ C [arXiv:1101.3692v1 [hep-ex]]

[12] B. W. Harris and J. Smith, Phys. Rev. D **57** (1998) 2806 [hep-ph/9706334];
B. W. Harris and J. Smith, Nucl. Phys. B **452** (1995) 109;
B. W. Harris and J. Smith, Phys. Lett. B **353** (1995) 535.

[13] ZEUSprel-10-010, available on http://www-zeus.desy.de/public_results/publicsearch.html

[14] F. D. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **65** (2010) 89 [arXiv:0907.2643 [hep-ex]].

[15] H1prelim-10-045, available on http://www-h1.desy.de/publications/H1preliminary.short_list.html and ZEUS-prel-10-009, available on http://www-zeus.desy.de/public_results/publicsearch.html

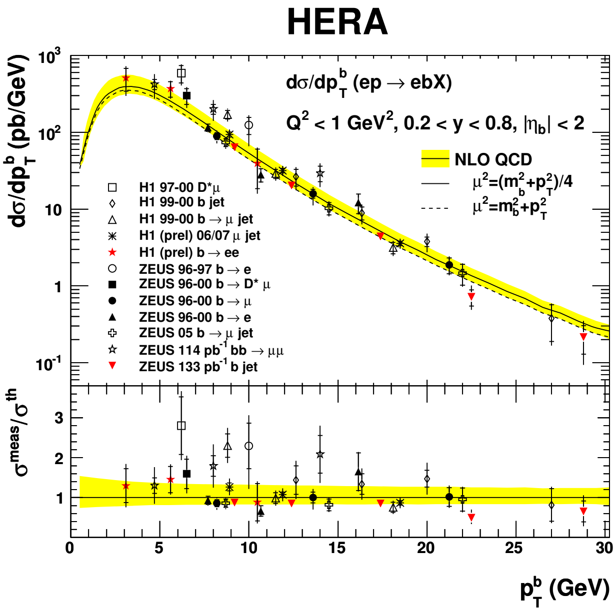

Figure 2: Upper plot: Compilation of beauty photoproduction cross section measurements as function of the mean transverse momentum of the beauty-quark, compared to a massive NLO pQCD calculation [7]. The discussed measurements [6, 8] are shown in red. Lower plot: Ratio of the measured cross sections and the calculated NLO pQCD prediction.

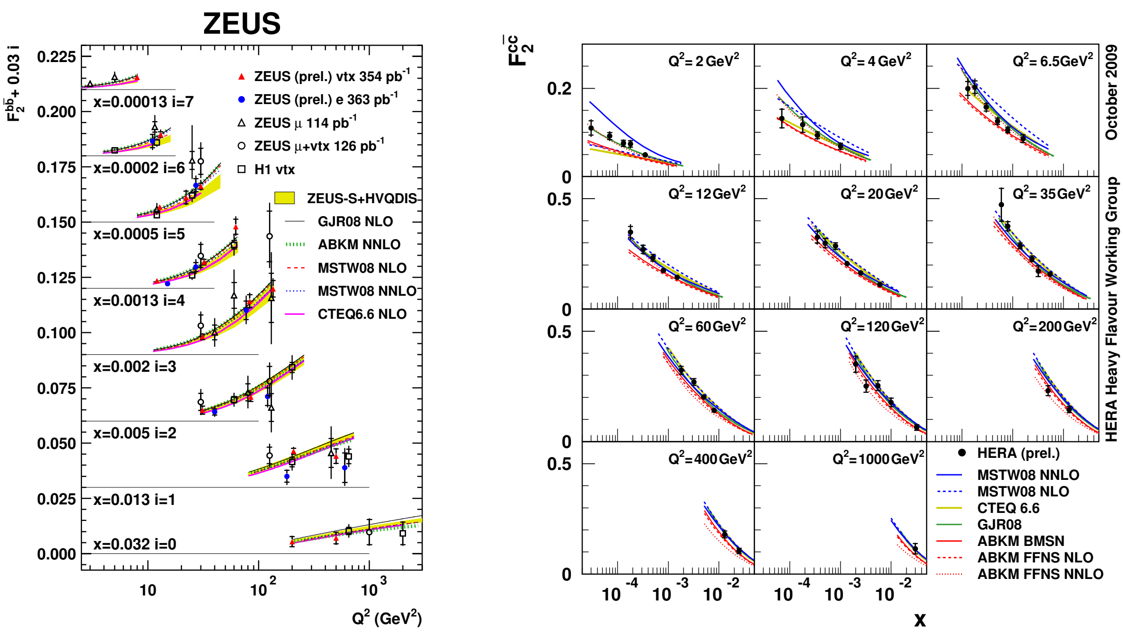

Figure 3: Left plot: Several measurements by H1 and ZEUS of the $F_2^{b\bar{b}}$ structure function as function of Q^2 and x are shown and compared to different pQCD predictions [13, 14]. Right plot: HERA averaged $F_2^{c\bar{c}}$ structure function as function of Q^2 and x compared to recent pQCD predictions [15].