Heavy flavour and jet production at HERA

Martin Brinkmann for the H1 and ZEUS Collaborations

Deutsches Elektronen-Synchroton (DESY), Notkestrasse 85, 22607 Hamburg, Germany

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The study of heavy flavour and jet production in *ep* collisions at HERA provides an insight into QCD processes and the parton distribution functions of the proton which is of particular importance for the measurements at the LHC. A selection of new measurements of jet and charm and beauty production by the H1 and ZEUS collaborations in photoproduction and deep inelastic scattering is presented. New precise measurements of the running strong coupling α_s are presented. Recent results on the combination of measurements from both experiments namely the charm contribution $F_2^{c\bar{c}}$ to the proton structure function F_2 are shown.

1 Introduction

For the description of heavy flavour and jet production processes the QCD factorisation theorem holds where the production cross section can be written as a convolution of the parton distribution functions (PDFs), the hard scattering matrix element and a hadronisation part. The hard scattering part can be treated within perturbative QCD (pQCD) in the presence of a hard scale which is for heavy flavour production automatically given by the heavy quark mass. Therefore the measurement of heavy quark production processes provides an ideal testing ground for pertubative QCD. The dominant hard processes is the photon gluon fusion (PGF), which provides a direct sensitivity to the gluon density in the proton. For jet production the other dominant process is the QCD comption scattering, where a (light) quark from the proton is scattered off and radiates a gluon. By analysing jet cross sections with different jet multiplicities a precision measurement of the running strong coupling constant is possible.

Measurements of jet and heavy flavour production processes provide constraints on the PDFs, which allow an important cross check of the distributions obtained from inclusive measurements. Further, an description of the hadronisation is necessary to connect the measured cross sections to the hard process of interest. Whereas for jet production the hadronisation can be described by applying a relatively small correction factor, the heavy quark fragmentation into hadrons has to be understood in detail.

Heavy quark and jet production measurements are made in two kinematic regions. In the photoproduction regime (γp) the square of the momentum transfer in the process is small, $Q^2 \approx 0$, whereas deep inelastic scattering (DIS) is characterized by $Q^2 > 4$ GeV^2.

To correct for the detector inefficiency and acceptance, Monte Carlo (MC) simulations based on leading order ($O(\alpha_s)$) matrix element using parton showers to approximate the higher orders are used. The RAPGAP program [1] for DIS and PYTHIA [2] for γp are based on collinear factorisation and DGLAP evolution of parton densities. CASCADE [3] uses a k_T unintegrated gluon density and is based on CCFM evolution.

The data are compared to higher order (NLO, NNLO) QCD calculations. The NLO calculation FMNR [4] for γp and HVQDIS [5] for DIS are used, respectively. In these models the quark structure of the proton contains only 3 flavours, charm and beauty are produced in a hard scattering (Fixed Flavour Number Scheme, FFNS). A NLO calculation in the generalized mass variable flavour number scheme GM-VFNS [6] is also used for comparison to data.

2 Measurement of jet production at HERA

Inclusive jet cross sections have been measured by ZEUS in γp [7] and in DIS [8] with an integrated luminosity of $L_{int} \sim 189\,\mathrm{pb}^{-1}$ and $L_{int} \sim 300\,\mathrm{pb}^{-1}$, respectively, covering a kinematic region of photon virtuality $Q^2 \sim 0 - 20000\,\mathrm{GeV}^2$. The measured cross sections as a function of the transverse energy of the leading jet are shown in Fig. 1. The data which are very precise on a few percent level are compared to results from NLO calculations. The NLO calculations describe the data in both kinematic regions well. ZEUS also provides new dijet measurements in γp with an integrated luminosity of $L_{int} \sim 189\,\mathrm{pb}^{-1}$ [9]. The data are well described by NLO QCD calculations in the whole measured range.

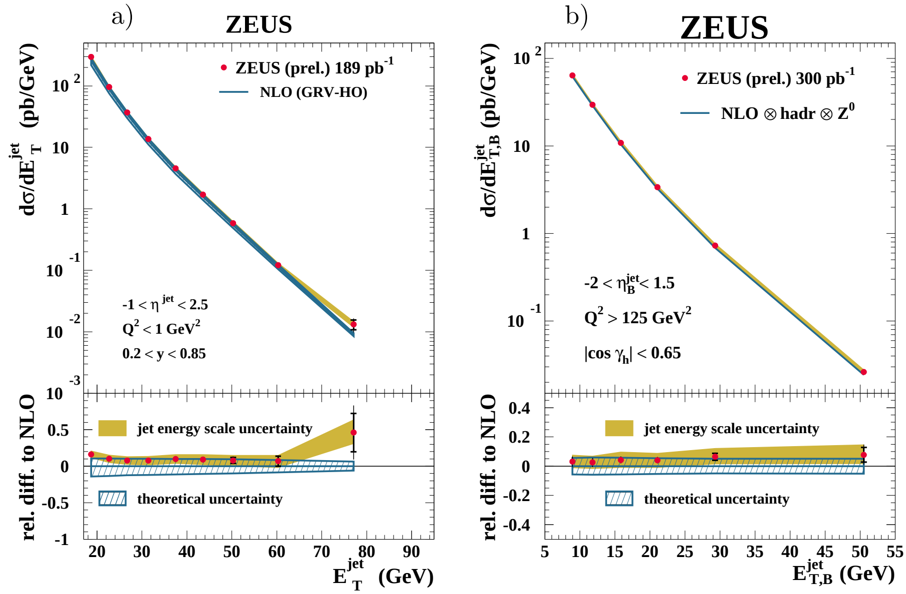

Figure 1: Measured inclusive jet cross sections for γp a) and DIS b) in bins of the transverse energy of the leading jet. In each plot below the relative difference of the data to the NLO calculation is shown.

Recent results on multijet measurements by H1 cover the phase space region $5 < Q^2 < 100\,\mathrm{GeV}^2$ [10] and $150 < Q^2 < 15000\,\mathrm{GeV}^2$ [11] with a lumi of $L_{int} \sim 44\,\mathrm{pb}^{-1}$ and $L_{int} \sim 395\,\mathrm{pb}^{-1}$, respectively. Within these analyses inclusive, dijet and trijet cross sections have been measured as a function of Q^2, the jet transverse momentum and the proton momentum fraction. The measurements are well described by NLO predictions which are used to perform a simultaneous fit of the measurements to extract the running strong coupling α_s.

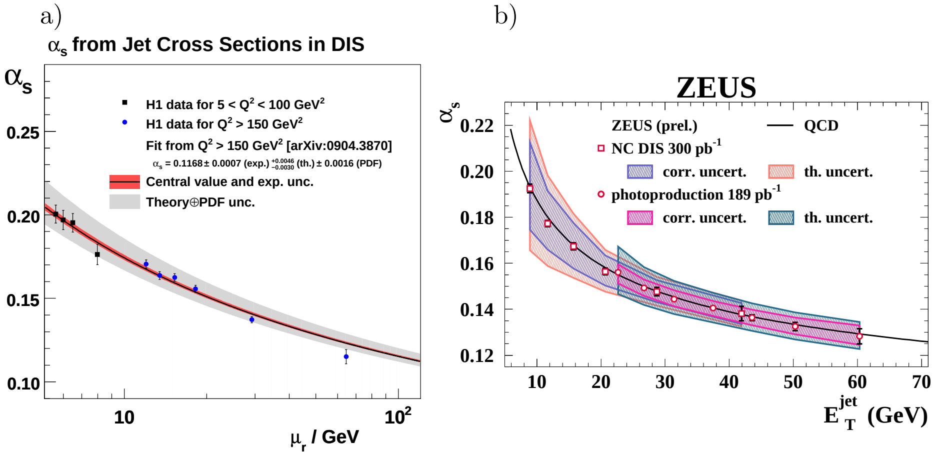

Figure 2: Running α_s as a function of the renormalisation scale μ_r measured by H1 a) and ZEUS b). The bands show the corresponding predictions from the fits with experimental und theoretical uncertainties.

In Fig. 2 a) the extracted running strong coupling α_s in data for the H1 measurements is shown where the renormalisation scale is choosen to be $\mu_r = \sqrt{Q^2 + p_t^2}$. The prediction from the fit of the high Q^2 data is in good agreement with all data points. In Fig. 2 b) the results on α_s based on the ZEUS measurements [7] and [8] are shown ($\mu_r = E_T^{jet}$) together with the expectations from the fits which agree well with the data. Both experiments performed a successful test of the running of α_s over a wide range of scale. The value $\alpha_s(M_Z)$ extracted from the measurements mentioned above is in good agreement with the world average.

3 Measurement of heavy flavour production at HERA

Charm quarks are tagged at H1 and ZEUS via the reconstruction of charmed hadrons ($D^{*\pm}$, D^0, $D^\pm$ - Mesons) or semileptonic decays. Other methods are based on long lifetimes and heavy masses of c- and b-quarks, where the c- and b-tagging is done by using the measurement of the displacement of tracks from the primary vertex or the reconstructed secondary vertex.

ZEUS performed measurements of beauty quarks in γp ($L_{int} \sim 128\,\text{pb}^{-1}$) and DIS ($L_{int} \sim 354\,\text{pb}^{-1}$) using the reconstruction of the secondary vertex for b tagging [12, 13] In addition a jet corresponding to the reconstructed secondary vertex is reconstructed. A recent beauty measurement from H1 in DIS ($L_{int} \sim 189\,\text{pb}^{-1}$) uses the displacement of the tracks for lifetime tagging [14]. In addition two jets are required according to the expected heavy quark pair in BGF. All beauty cross sections measured as a function of jet quantities (p_t^{jet}, η^{jet}) and event kinematics (Q^2,x) are in reasonable agreement with NLO QCD predictions. To compare the results of different beauty measurements in DIS with different phase spaces and tagging techniques, the beauty contribution $F_2^{b\bar{b}}$ to the proton structure function F_2 is extracted from cross sections measured double differentially in Q^2 and x. The results are shown in Fig. 3. The measurements are consistent with each other and with the NLO QCD predictions.

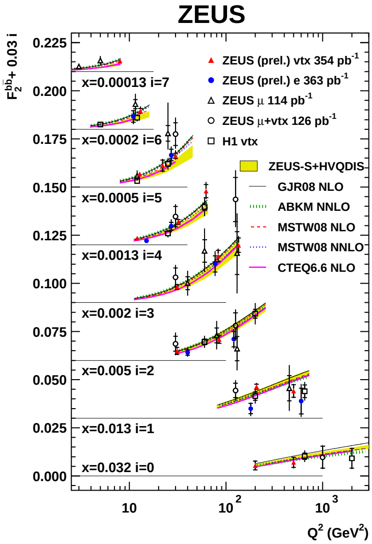

Figure 3: Summary of $F_2^{b\bar{b}}$ measurements compared to NLO and NNLO calculations using different PDF sets)

Within the charm production recent measurements based on D-meson reconstruction exists. In a measurement from ZEUS in DIS ($L_{int} \sim 323\,\text{pb}^{-1}$) charm is tagged by the reconstruction of the ground state charmed hadron $D^{\pm}$ [15]. Further measurements of charm production based on the reconstruction of the D^{*}-Meson has been performed by H1 ([16, 17]) and ZEUS ([18, 19, 20]). In Fig. 4 the $D^{*\pm}$ production cross sections as a function of Q^2 are shown for the measurements by H1 (a) and ZEUS (b). A good description of the data by NLO calculation (HVQDIS) is achieved over four orders of magnitude in Q^2. The NLO calculations describe the data also in the kinematic of the D-Mesons well. Charm has also been reconstructed by H1 within the lifetime tag measurement mentioned above ([14]). The measured charm dijet cross sections are reasonable well described by NLO QCD prediction HVQDIS.

Using the recent measurements on charm production at the H1 and ZEUS experiments, $F_2^{c\bar{c}}$ is extracted. The individual results are combined [21, 22] taking into account the correlations between the systematic uncertainties of the different charm tagging methods. The result is shown in Fig. 5: In (a) the data are compared to NLO and NNLO models in a VFNS as well with the NLO FFNS calculation using different sets of parton density functions. The precision in data of $5-10\,\%$ is good enough to discriminate between the different theory predictions although none of the predictions is absolutely favoured by the data. In Fig. 5 b) the combined $F_2^{c\bar{c}}$ is compared to the prediction from the recent HERAPDF1.0 fit. The data are well described by the prediction except the lowest Q^2 bin.

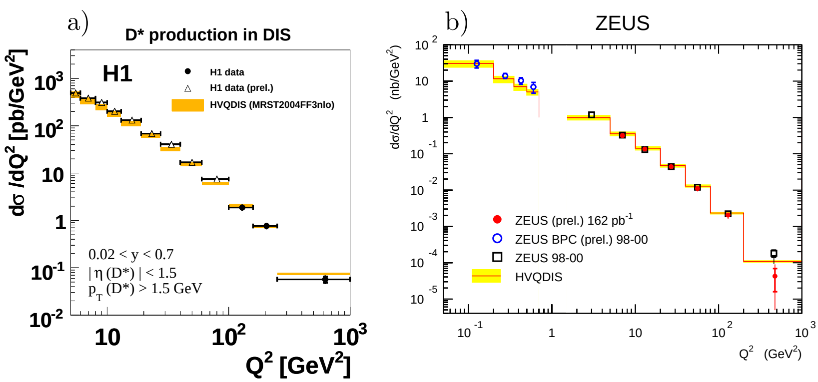

Figure 4: Measured $D^{*\pm}$ cross sections as a function of Q^2 by H1 (a) and ZEUS (b). The band indicate the NLO predictions from HVQDIS.

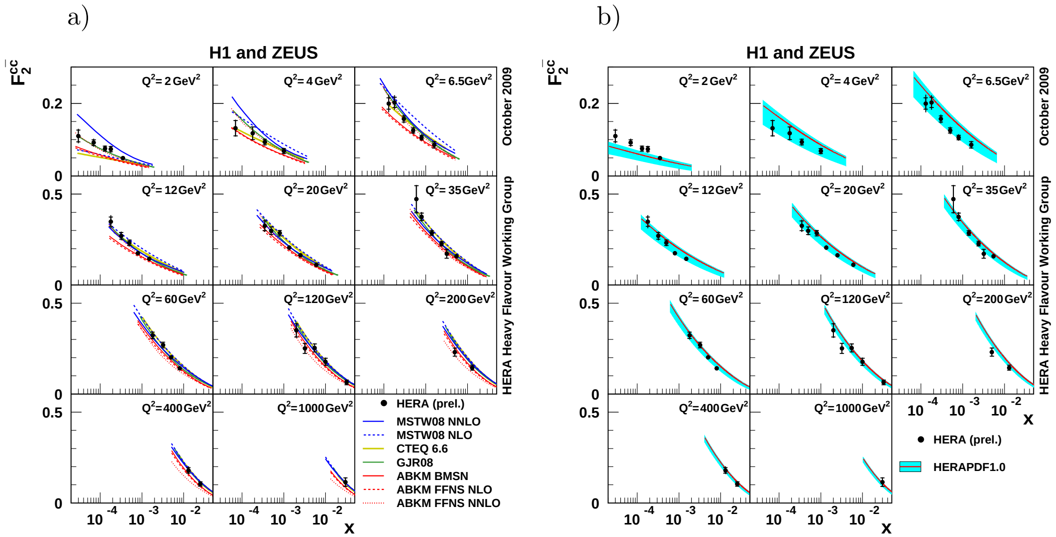

Figure 5: Combined $F_2^{c\bar{c}}$ compared to NLO and NNLO calculations (a) and to HERAPDF1.0 (b)

4 Conclusions

The jet measurements at H1 and ZEUS at HERA provides precise data to test perturbative QCD predictions at NLO. Within each experiment a precise and consistent extraction of the strong coupling constant and its running over a wide range of scale has been performed. The calculation in the NLO pQCD describe the heavy quark measurements by the H1 and ZEUS experiments reasonably well in both photoproduction and DIS within the theory uncertainty, which in many cases is larger than the experimental one. Based on the measured heavy flavour production cross sections the heavy quark contributions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ to the proton structure function F_2 have been extracted. Different beauty measurements provide consistent results of $F_2^{b\bar{b}}$ and predictions of $F_2^{b\bar{b}}$ from NLO QCD calculations describe the measured $F_2^{b\bar{b}}$. Combining H1 and ZEUS $F_2^{c\bar{c}}$ measurements provide a precision of $5 - 10\,\%$ in a wide kinematic range which is less than the spread between different NLO and NNLO pQCD models using different sets of parton density functions.

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