Jets and Heavy Flavors at HERA

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Abstract. Recent results on jet cross sections and heavy-flavor production in photoproduction and neutral current deep inelastic *ep* scattering from the H1 and ZEUS Collaborations are presented. The jet measurements are used to perform stringent tests of perturbative QCD, to extract precise values of the strong coupling and to constrain further the proton and photon parton distribution functions. The measurement of beauty and charm production at HERA is an important testing ground for perturbative QCD and can provide information on the structure of the proton.

Keywords: HERA, Jets, Heavy Flavors

INTRODUCTION

The *ep* collider, HERA, operated from 1992-2007 with protons of energy 920 (820) GeV and electrons or positrons of energy $27.5\,\mathrm{GeV}$. By the end of the running, each of the colliding-beam experiments, H1 and ZEUS, had collected about $0.5\,\mathrm{fb}^{-1}$ of data.

Different kinematic variables are used to describe *ep* interactions: the virtuality of the exchanged boson, Q^2, the Bjorken scaling variable, x, and the inelasticity, y. At HERA, two kinematic regimes are distinguished depending on Q^2: photoproduction (γp), where $Q^2 \approx 0\,\mathrm{GeV}^2$, and deep inelastic scattering (DIS), where $Q^2 \gtrsim 0\,\mathrm{GeV}^2$.

In the following a small selection of recent measurements of jets and heavy quark production in γp and DIS at HERA is presented.

JET PHYSICS AT HERA

At leading order (LO) in α_s, jet production in neutral current (NC) DIS, can be described via the boson-gluon fusion and QCD Compton processes. In γp, two processes are relevant: the direct process, in which the photon interacts as a point-like particle, and the resolved process, in which the photon interacts through its partonic content. Measurements of jet production in γp and NC DIS provide a powerful tool for stringent tests of pQCD calculations.

In recent analyses, jet production was measured at HERA in different kinematic regions. In these analyses jets were defined using the k_T clustering algorithm. For DIS, the jet algorithm was applied in the Breit frame, in which the photon and proton collide head on, and for γp, in the laboratory frame. The measurements from the ZEUS collaboration include the dijet cross section in γp [1] ($Q^2 < 1\,\mathrm{GeV}^2, E_{\mathrm{T}}^{\mathrm{jet,\,1(2)}} > 21(17)\,\mathrm{GeV}$) and inclusive-jet cross sections in γp [2] ($Q^2 < 1\,\mathrm{GeV}^2, E_{\mathrm{T}}^{\mathrm{jet}} > 17\,\mathrm{GeV}$) and high Q^2 DIS [3] ($Q^2 > 125\,\mathrm{GeV}^2, E_{\mathrm{T,B}}^{\mathrm{jet}} > 8\,\mathrm{GeV}$). The H1 measurements include inclusive, 2-jet and 3-jet cross sections as well as the ratio of 2-jet to 3-jet cross sections for low Q^2 [4]

$(5 < Q^2 < 100\,\mathrm{GeV}^2, 5 < p_{\mathrm{T,\,jet}} < 80\,\mathrm{GeV})$ and high Q^2 [5] $(150 < Q^2 < 15000\,\mathrm{GeV}^2, 7 < p_{\mathrm{T,\,jet}} < 50\,\mathrm{GeV})$. For the latter, the jet cross sections were normalized to the inclusive DIS cross section, which significantly reduces the experimental and theoretical errors.

Figure 1 shows the dijet cross section as a function of $\overline{\eta}^{\mathrm{jet}}$ in γp and inclusive-jet cross sections as a function of $E_{\mathrm{T}}^{\mathrm{jet}}$ and P_{T} in DIS. The data are very precise, the dominant experimental error being the energy scale of the jets in the ZEUS measurements and the model dependence of the data correction in the H1 measurement. The measurements are compared to next-to-leading (NLO) QCD predictions which describe the data very well. The theoretical errors are dominated by the renormalization scale uncertainty. The dijet cross sections have the potential of constraining further the proton and photon PDFs and the inclusive-jet cross sections provide direct sensitivity to $\alpha_s(M_Z)$.

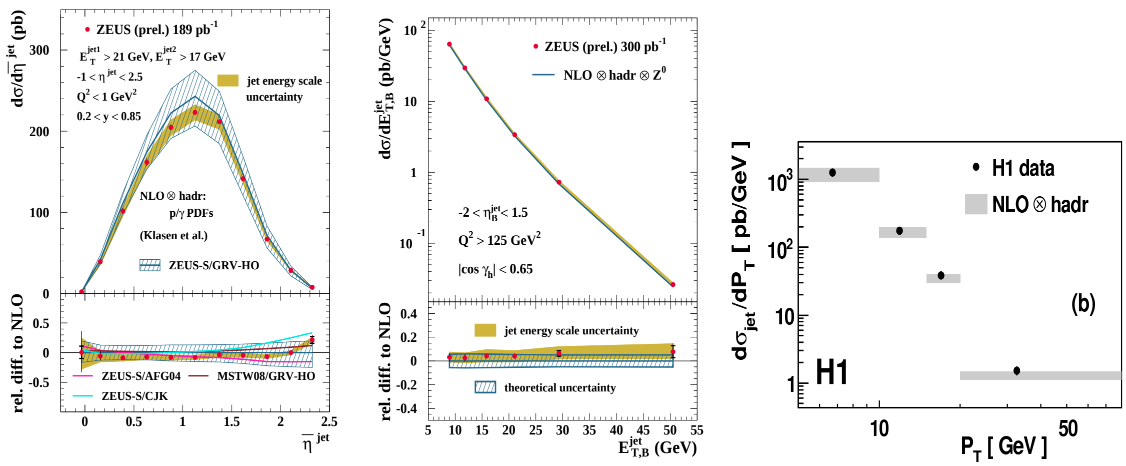


FIGURE 1. Dijet cross section as a function of $\overline{\eta}^{\mathrm{jet}}$ in photoproduction [1] and inclusive-jet cross sections as a function of $E_{\mathrm{T}}^{\mathrm{jet}}$ [3] and P_{T} [4] in DIS.

Extraction of α_s

The jet cross sections described above were used to extract the value of α_s and to test its running. Figure 2 (left) shows a summary of recent $\alpha_s(M_Z)$ measurements from the H1 and ZEUS collaborations together with the HERA averages of 2004 [6] and 2007 [7] and the current world average [8]. All measurements are consistent with each other and with the world average. For many of the measurements the theoretical uncertainties dominate the error. Higher order calculations are expected to improve the results.

The scale dependence of α_s was determined by extracting α_s at different values of the scale. Statistical, systematic and correlated uncertainties were taken into account. Figure 2 (right) shows the running of α_s as a function of the renormalization scale, where the values were extracted from the H1 data at low and high Q^2. The measurements at low Q^2 agree well with the QCD expectations for α_s based on the jet cross section measurements at high Q^2.

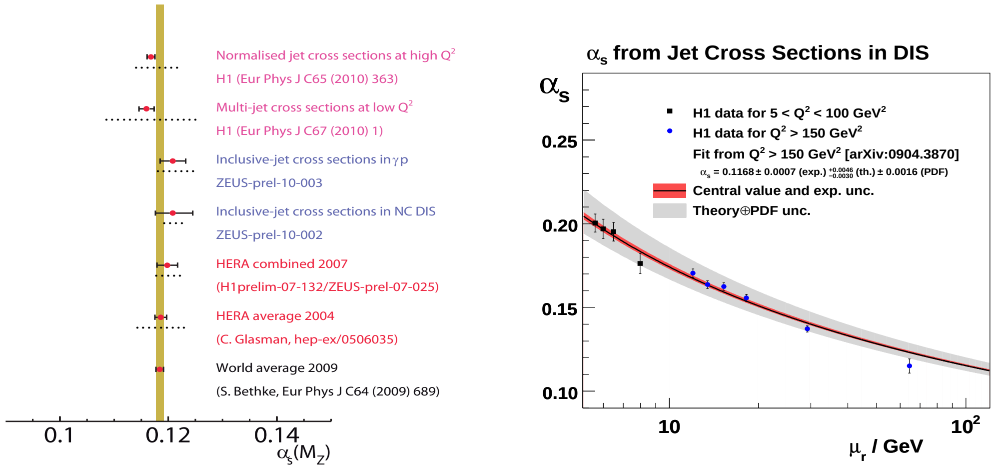


FIGURE 2. Summary of $\alpha_s(M_Z)$ values extracted from the H1 and ZEUS data together with the HERA and world averages (left). Summary of the running α_s values extracted from the H1 jet data in low and high Q^2 (right).

HEAVY FLAVOR PHYSICS AT HERA

In $e^{\pm}p$ collisions, the main production mechanism for heavy flavors is the boson-gluon fusion process. The large mass of the heavy quarks produced in this process and large Q^2 (in case of DIS) or p_T of the heavy quark (in case of γp) provide hard scales, so that pQCD is applicable. Several different experimental techniques are used to tag the heavy quark final state. These methods include identification of a lepton which is produced in the semileptonic decay of heavy quarks (lepton tag), exploiting the lifetime information using the impact parameter or decay length (lifetime tag) and meson identification (e.g. $D^{*\pm}$ tagging). Different tagging methods often cover different kinematic regions and can be combined to enhance the separation between signal and background.

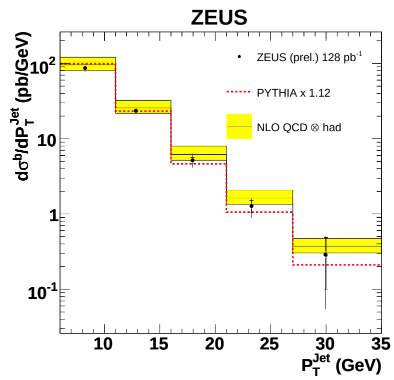
In a recent ZEUS measurement [9], the semileptonic decay of b hadrons into electrons was combined with lifetime information. This analysis was performed in the DIS regime ($Q^2 > 10\,\mathrm{GeV}^2, 0.9 < p_T^e < 8\,\mathrm{GeV}, |\eta^e| < 1.5$). The extraction of the beauty signal was done using a likelihood-ratio test, which allowed information on electron identification to be combined with the semileptonic decay kinematics. The beauty production cross sections were measured in bins of Q^2, x, p_T^e and η^e and the beauty contribution to the proton structure function was calculated. The measured cross sections were found to be in good agreement with the scaled RAPGAP LO MC prediction and NLO QCD predictions calculated from the HVQDIS program.

The H1 collaboration has recently released a new measurement [10] of D^* meson production in DIS ($5 < Q^2 < 100\,\mathrm{GeV}^2, p_T(D^*) > 1.25\,\mathrm{GeV}, |\eta(D^*)| < 1.8$). Single and double differential cross sections were determined and compared to different MC models and NLO QCD predictions. In general all cross sections were found to be reasonably well described by different LO and NLO QCD predictions.

Two preliminary results from the ZEUS collaboration on beauty production in γp [11] ($Q^2 < 1$ GeV$^2, p_T^{\mathrm{jet1(2)}} > 7(6)$ GeV$, -1.6 \leq \eta^{\mathrm{jet1(2)}} < 1.3$) and DIS [12]

$(5 < Q^2 < 1000\,\mathrm{GeV}^2, -1.6 < \eta^{\mathrm{jet}} < 2.2)$, used inclusive secondary vertices associated to jets. The beauty content was determined by a χ^2 fit of the mirrored decay length significance distribution in bins of invariant mass of the secondary vertex. The beauty photoproduction cross section as a function of p_T^{jet} compared to NLO QCD prediction from FMNR and the scaled LO PYTHIA is shown in Figure 3. The measured cross sections are in reasonable agreement with the NLO QCD prediction and their shape is well described by LO MC prediction.

H1 measurements of cross sections for events with charm and beauty jets in DIS [13] $(Q^2 > 6\,\mathrm{GeV}^2, E_T^{\mathrm{jet}} > 6\,\mathrm{GeV}, -1 < \eta^{\mathrm{jet}} < 1.5)$ were also presented. The numbers of charm and beauty jets were determined using variables reconstructed using the H1 vertex detector. The measurements were compared with QCD predictions and with previous measurements. These measurements showed that the production of beauty and charm jets in DIS is reasonably well described by NLO QCD predictions.



3: Differential cross section for beauty production in γp as a function of p_T^{jet}, compared with scaled PYTHIA and NLO QCD predictions [11].

$\mathbf{F_2^{b\bar{b}}}$ and $\mathbf{F_2^{c\bar{c}}}$

The data from beauty production in DIS using the electron decay channel and inclusive secondary vertexing was used to extract the beauty contribution to the proton structure function F_2, denoted as $F_2^{b\bar{b}}$. Figure 4 (left) shows $F_2^{b\bar{b}}$ as a function of Q^2 for fixed values of x. The results from two recent ZEUS measurements has been compared with the previous measurements from H1 and ZEUS. The different measurements are consistent with each other. Also the results are compared to several NLO and NNLO QCD predictions. The data are reasonably well described by the different theory predictions.

The H1 and ZEUS combined $F_2^{c\bar{c}}$ was obtained by combining several different measurements made using different tagging techniques [14]. The correlations of the systematic uncertainties between the different measurements were taken into account. The data covered the kinematic range of $2 < Q^2 < 1000\,\mathrm{GeV}^2$ and $10^{-5} < x < 10^{-1}$. A precision of $5-10\%$ was reached for the combined results. The results were compared with different approaches of pQCD. The comparison with different predictions (see Figure 4 (right)) shows that in most of the x–Q^2 plane the data are more precise than the spread observed in the theoretical predictions. The $F_2^{c\bar{c}}$ data represents therefore valuable constraints on the theory of heavy flavor production in DIS.

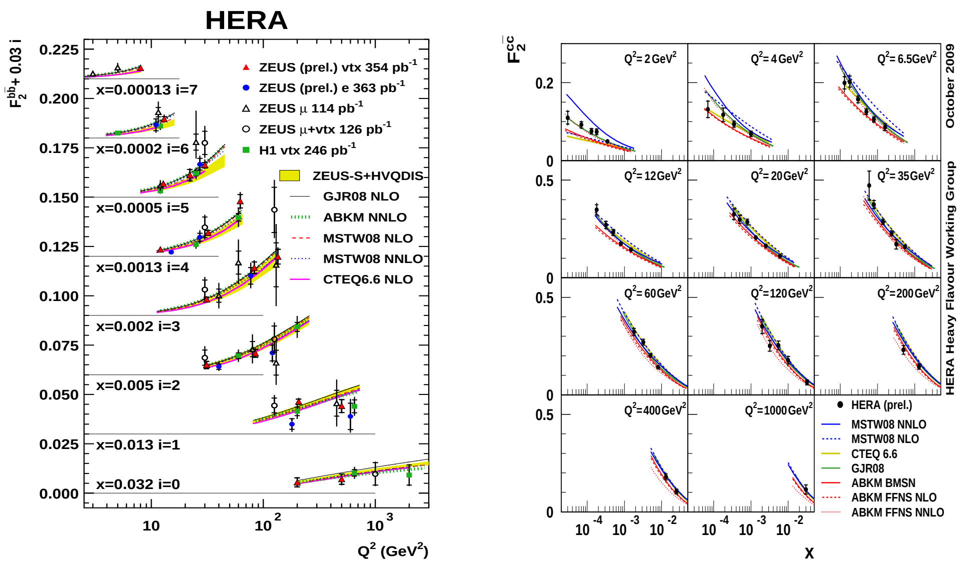


FIGURE 4. $F_2^{b\bar{b}}$ as a function of Q^2 for fixed values of x compared to different theory predictions (left). Combined H1 and ZEUS $F_2^{c\bar{c}}$ (black dots) compared to NLO and NNLO QCD predictions (right).

SUMMARY

A selection of results of recent measurements for jet and heavy flavor production in γp and DIS at HERA was presented. Jet physics at HERA provide high precision QCD measurements. These measurements can help to constrain further the proton and photon PDFs. Precise and consistent α_s extraction in different kinematic regimes has been performed. The running of the coupling is verified over a wide range of the scale.

The measured cross sections for beauty and charm production are in general consistent with the NLO QCD predictions. The different measurements provide a consistent picture of $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$. Combining H1 and ZEUS, $F_2^{c\bar{c}}$ results in precise measurements and provides constraints for theory.

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