PROBING QCD AT HERA*

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The most recent measurements from ep collisions at HERA probing and constraining QCD are presented. Final measurements of inclusive deep inelastic scattering (DIS) by H1 and ZEUS collaborations have been combined for neutral and charged current unpolarised $e^{\pm}p$ cross sections at proton beam energies of 920, 820, 575 and 460 GeV. The combined data correspond to a luminosity of about 1 fb^{-1} and span six orders of magnitude in momentum transfer squared, Q^2, and Bjorken x. It has been used as an input to QCD analyses at LO, NLO and NNLO to determine preliminary versions of new sets of parton distribution functions — HERAPDF2.0 (prel.). The structure of the proton is also constrained through measurements of heavy-quark production which are sensitive to the gluon and heavy-quark content of the proton. The HERA data on charm production in DIS have recently been combined and used differentially as a function of Q^2 to evaluate the charm quark running mass at different scales to one-loop order. The running beauty-quark mass, m_b, at the scale m_b, was determined from a QCD fit at next-to-leading order for the first time at HERA data. High-precision inclusive jet, dijet and trijet differential cross sections have been measured in neutral current DIS and used to determine the value of strong coupling constant and running of the coupling in QCD fit.

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1. Introduction

Measurements of deep inelastic scattering (DIS) of electrons[1] on protons at HERA provide an importand input for determination of proton structure and constraining QCD. HERA collider was operated with electron beam energy of $E_e \simeq 27.5$ GeV and proton beam energies of $E_p \simeq 920$, 820,

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[1] Here and afterwards “electron” refers to both electrons and positrons, if not otherwise stated.

575 and 460 GeV, corresponding to center-of-mass energies $\sqrt{s} = 318$, 300, 251 and 225 GeV. This resulted in data spanning a large phase space in Q^2 and x. In total, approximately 500 pb^{-1} of data were collected per experiment, divided about equally between e^+p and e^-p scattering.

2. The HERAPDF2.0 (prel.) PDF set

A combination of all inclusive DIS cross sections measurements by H1 and ZEUS collaborations have been performed for neutral current (NC) and charged current (CC) unpolarised $e^{\pm}p$ scattering. The combination showed a good consistency of separate data sets [1] with $\chi^2/n_{\mathrm{dof}} = 1685/1620$. All correlations of systematic uncertainties were taken into account, resulting in cross section values with highly improved accuracy. Left part of Fig. 1 shows a comparison of the combined NC reduced cross sections and input data from H1 and ZEUS for e^+p scattering for selected x values.

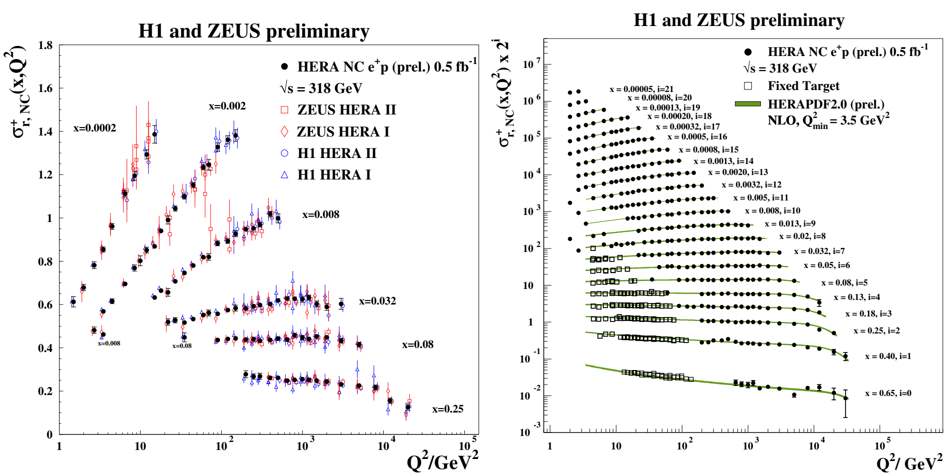

Fig. 1. HERA combined NC e^+p reduced cross section as a function of Q^2 for selected x-bins compared to the separate H1 and ZEUS data (left) and to an NLO QCD fit with $Q^2_{\min} = 3.5$ GeV^2 (right). Error bars on data points include the total uncertainty and the band on QCD fit prediction represent experimental uncertainties.

Combined data have been used as the input for leading order (LO), next-to-leading order (NLO) and next-to-next-to-leading (NNLO) QCD parton distribution functions (PDFs) fits providing a new preliminary PDF set called HERAPDF2.0 (prel.) [2]. The fits were based on the evolution of QCD predictions for structure functions with DGLAP equations in the $\overline{\mathrm{MS}}$ scheme with the renormalisation and factorisation scales chosen to be Q^2. The DGLAP equations provide PDFs at all values of Q^2 if they are set as function of x at some starting scale Q_0^2. For HERAPDF2.0 (prel.), this scale was chosen to be $Q_0^2 = 1.9$ GeV^2. The general-mass variable-flavor-number scheme (GM VFNS) was used for calculations of heavy quark coefficients. Separate PDF sets were estimated for two kinematic cuts $Q^2_{\rm min} = 3.5$ GeV^2 and $Q^2_{\rm min} = 10$ GeV^2. Experimental uncertainties of the fits were evaluated with Hessian method and input assumptions were varied for estimation of model and parametrisation uncertainties. The right part of Fig. 1 shows the comparison of NLO fit for kinematic cut $Q^2_{\rm min} = 3.5$ GeV^2 to NC e^+p HERA data and to fixed target data.

3. Charm and beauty production at HERA

The production of charm and beauty quarks in $e^{\pm}p$ collisions at HERA provides important input for stringent tests of the theory of strong interactions. In the kinematic space with $Q^2 \ll M_Z^2$, charm production is dominated by the boson–gluon-fusion process, $\gamma g \to c\bar{c}$, and thus is sensitive to the gluon distribution in the proton. Three different techniques have been used at HERA for measurements of open charm production in DIS: the full reconstruction of D or D^* mesons, the long lifetime of heavy flavored hadrons and semi-leptonic decays of heavy hadrons. Results of measurements by H1 and ZEUS collaborations using these techniques have been combined into one consistent set taking into account correlated systematic uncertainties and the normalisation [3]. The combined reduced cross sections $\sigma^{c\bar{c}}_{\rm red}$ are compared to the predictions of the ABM group in the fixed-flavour-number-scheme (FFNS) at NLO and NNLO in Fig. 2 (left).

In the $\overline{\rm MS}$ scheme of perturbative quantum chromodynamics, the values of basic QCD parameters depend on the scale at which they are evaluated. The combined HERA charm data shown in Fig. 2 (left) have been used to extract an explicit determination of the running of the charm quark mass for the first time [4]. The calculation is performed on data subdivided into several kinematic intervals in Q^2 and assuming the running of $\alpha_{\rm s}$ and charm mass. For each interval, the value of the charm quark mass $m_c(m_c)$ is extracted from the χ^2 dependence of data to theory comparison on charm mass. Theory predictions on charm cross sections for each charm mass hypothesis were obtained using PDFs from fit on HERA inclusive DIS data. The measured $m_c(m_c)$ are reinterpreted in terms of $m_c(\mu)$ at the scale $\mu = \sqrt{Q^2 + 4m_c^2}$ to minimise the effect of the initial assumption of QCD running on the interpretation of the measurement results. Estimated values of $m_c(\mu)$ and expected running behavior are compared in Fig. 2 (right).

Recently, the ZEUS Collaboration presented an analysis of inclusive jet cross sections in beauty and charm events [5] for the kinematic range of $5 < Q^2 < 1000$ GeV^2 using an integrated luminosity of 354 pb^{-1}. Large masses and the long lifetimes of the weakly decaying b and c hadrons were

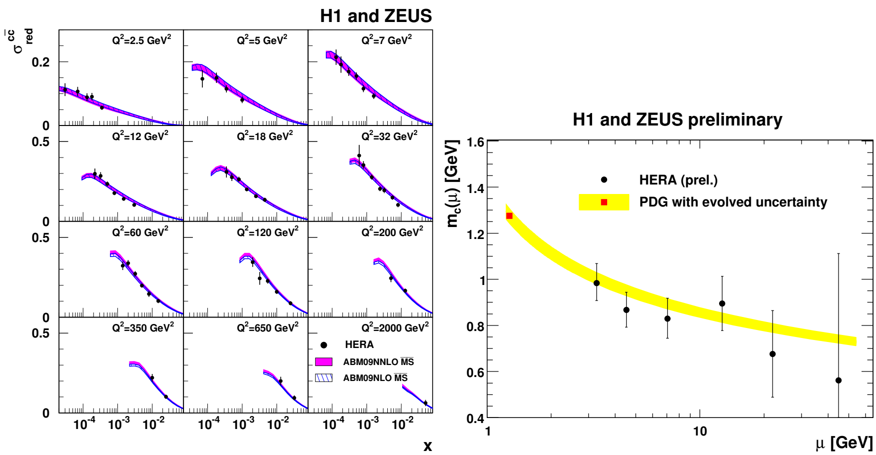

Fig. 2. Combined reduced charm cross sections $\sigma_{\rm red}^{c\bar{c}}$ as a function of x for various values of Q^2 (left) and measured charm mass running $m_c(\mu)$ in the $\overline{\rm MS}$ scheme as a function of the scale μ (right). The error bars represent the total uncertainty. In the right plot, error bars do not include the uncertainties arising from the variation of the QCD renormalisation and factorisation scales, the square point represents PDG world average charm mass and the band is its expected running.

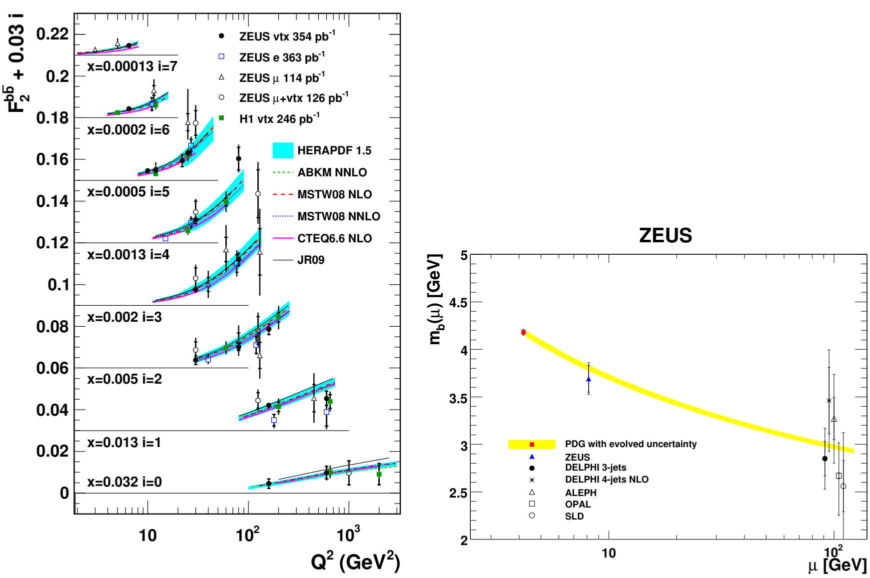

Fig. 3. The structure function $F_2^{b\bar{b}}$ as a function of Q^2 for fixed values of x compared to previous results (left) and measured beauty mass $m_b(\mu)$ (right). The inner error bars are the statistical uncertainty and the outer error bars represent the total uncertainty. The square point in the right plot represents PDG world average beauty mass and the band is its expected running.

exploited for inclusive tagging method and led to substantial increase in statistics with respect to previous ZEUS measurements. The beauty and charm contributions to the proton structure function F_2 and reduced cross sections were extracted as a function of Q^2 and x. The $F_2^{b\bar{b}}$ measurement results are compared to previous ZEUS and H1 measurements at Fig. 3 (left). For the first time at HERA or any other hadron collider, the mass of the beauty quark, m_b, at the scale m_b was measured

$$m_b(m_b) = 4.07 \pm 0.14(\mathrm{fit})^{+0.01}_{-0.07}(\mathrm{mod.})^{+0.05}_{-0.00}(\mathrm{param.})^{+0.08}_{-0.05}(\mathrm{theo.})\ \mathrm{GeV}\,.$$

Values of beauty mass extracted by ZEUS and LEP e^+e^- experiments in terms of $m_b(\mu)$ are shown on Fig. 3 (right) and compared to expected beauty running behavior.

Charm and beauty data from HERA are used together with combined inclusive DIS data for determination of charm and beauty mass parameters M_c^{opt} and M_b^{opt} for HERAPDF2.0 following procedure described in [3].

4. Multijet production

In short distance interactions, quarks and gluons participate as quasi-free particles, but at larger distances, they hadronise into collimated jets of hadrons, which provide momentum information of the underlying partons. Thus, jets measurements can be compared to perturbative QCD predictions corrected for hadronisations effects for testing the theory and extraction of strong coupling $\alpha_{\mathrm{s}}(M_Z)$.

H1 have presented [6] double differential measurements of absolute and normalised inclusive jet, dijet and trijet cross sections in the Breit frame, in which a virtual boson collides head on with a parton from the proton. The cross sections were measured as a function of Q^2 and the average jet transverse momentum $P_{\mathrm{T}}^{\mathrm{jet}}$. Dijet and trijet cross sections were also presented as a function of Q^2 and the proton's longitudinal momentum fraction ξ. Ratios of the number of inclusive jet, dijet and trijet events to the number of inclusive NC DIS events in the respective ranges of Q^2 were also reported and refered as normalised multijet cross sections. In comparison to absolute jet cross sections, they benefit from cancelation of some correlated systematic uncertainties.

Measured jet cross sections were compared to pQCD predictions corrected for hadronisation effects and α_{s} was extracted

$$\alpha_{\mathrm{s}}(M_Z) = 0.1165 \pm 0.0008(\mathrm{exp.}) \pm 0.0038(\mathrm{pdf,theo.})\,.$$

The values of strong coupling as a function of the hard scale of jet production in DIS, $\alpha_s(\mu_r)$ and constant $\alpha_s(M_Z)$ are displayed in Fig. 4, together with results from other recent jet measurements. The prediction for the running of $\alpha_s(\mu_r)$ is also shown, together with its experimental and total uncertainty.

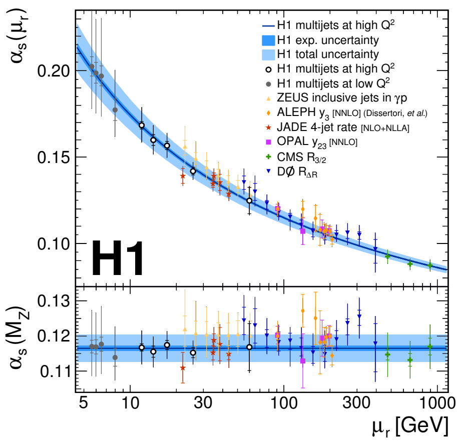

Fig. 4. The upper panel shows values of the strong coupling $\alpha_s(\mu_r)$ from different collaborations and the NLO QCD predictions (solid line) calculated using the renormalisation group equation with $\alpha_s(M_Z) = 0.1165$ as determined from the simultaneous fit to all normalised H1 multijet measurements. The dark shaded band indicates the experimental uncertainty on $\alpha_s(\mu_r)$ and the light shaded band shows the total uncertainty. The lower panel shows the equivalent values of $\alpha_s(M_Z)$.

Measurements of jet cross sections at HERA are included in calculation of HERAPDF2.0Jets set for simultaneous determination of PDFs with reduced uncertainty on the gluon density and the strong coupling constant $\alpha_s(M_Z)$ using the same procedure as for HERAPDF1.6 [7].

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