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# NEW HERA RESULTS ON PERTURBATIVE QCD*

Nataša Raičević

for the H1 and ZEUS collaborations

University of Montenegro, Faculty of Science
Džordža Vašingtona BB, 81000 Podgorica, Montenegro

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The H1 and ZEUS collaborations continue to produce final precision measurements of QCD physics. To achieve high-precision measurements, data from both experiments have been combined leading to significantly reduced experimental uncertainties. The two collaborations recently obtained combined results and a QCD analysis of beauty and charm production cross-section measurements in deep inelastic *ep* scattering. New results on the first determination of $\alpha_{\rm s}$ from jet data from deep inelastic scattering at NNLO from the H1 Collaboration and studies of prompt photon production from the ZEUS Collaboration are also presented.

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## 1. Introduction

In this paper, we present first the most recent results obtained from the deep inelastic *ep* scattering (DIS) data from HERA experiments, H1 and ZEUS, in the hard QCD sector. In the second section, the final combination of charm and beauty data from H1 and ZEUS experiments [1] is presented. The third section contains results on first determination of $\alpha_{\rm s}$ from DIS jet data at NNLO obtained by the H1 Collaboration [2] and, in the fourth section, results on isolated photon production with a jet in DIS obtained by the ZEUS Collaboration [3] are presented.

## 2. Production of heavy quarks in DIS

The main source of heavy quarks in DIS is boson–gluon fusion. Concerning inclusive production, up to about 30% is due to charm and up to 1% due to the beauty contribution.

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To improve precision, H1 and ZEUS combine their measurements which are based on different tagging techniques: the reconstruction of particular decays of charmed mesons (eight data sets), the inclusive analysis of tracks exploiting lifetime information (two data sets) and reconstruction of leptons from heavy-flavour semi-leptonic decays (three data sets). The new results are presented in [1]. This is the first combination of beauty cross sections from the two collaborations. The value $\chi^2/\mathrm{n.d.f.} = 149/187$ shows consistency of input data and, as can be seen from the cited paper, there is significant improvement by the data combination.

The combined data are compared with theoretical predictions. NLO and NNLO predictions are calculated with OPENQCDRAD program [4] interfaced within the open-source QCD fit framework for PDF determination xFitter [5]. The comparison is performed using input PDFs in the massive fixed-flavour-number scheme (FFNS) NLO and approximate NNLO QCD, and in the variable flavour-number scheme (VFNS) NLO and approximate NNLO QCD. The dominant uncertainty comes from default renormalisation scale $\mu_{\mathrm{R}}$ and factorisation scale $\mu_{\mathrm{F}}$ which are set to $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \sqrt{Q^2 + 4m_Q^2}$, where $m_Q$ is the appropriate pole of running mass. The combined data together with the inclusive HERA data are used for the new QCD fit termed HERAPDF-HQMASS in which the running heavy-quark masses are fitted simultaneously with the parton density functions (PDFs). The values of running quark masses and their experimental/fit, model and parameterisation uncertainties determined from the fit are:

$$m_c(m_c) \; = \; 1.290^{+0.046}_{-0.041}(\mathrm{exp/fit})^{+0.062}_{-0.014}(\mathrm{model})^{+0.003}_{-0.031}(\mathrm{parameterisation})\ \mathrm{GeV}\,,$$

$$m_b(m_b) \; = \; 4.049^{+0.104}_{-0.109}(\mathrm{exp/fit})^{+0.090}_{-0.032}(\mathrm{model})^{+0.001}_{-0.031}(\mathrm{parameterisation})\ \mathrm{GeV}\,.$$

Heavy-quark production is directly sensitive to the gluon density already at leading order, while from inclusive DIS data, it is determined via scaling violations and higher order corrections. To reduce the influence of the inclusive data in the gluon density determination, a series of fits was performed by requiring a minimum on Björken variable $x_{\mathrm{Bj}}$ for the inclusive data used in the fit. Figure 1 shows the ratios of combined charmed data cross sections and the NLO FFNS predictions based on HERAPDF-HQMASS without and with the $x_{\mathrm{Bj}} > 0.1$ cut to the predictions based on the most recent fit of inclusive HERA data, HERAPDF2.0 FF3A [6]. The new fit without the $x_{\mathrm{Bj}}$ cut agrees well with the HERADF2.0 FF3A and there is reasonable agreement between the combined data and the fits. Although a somewhat steeper dependence on Björken variable $x_{\mathrm{Bj}}$ is visible in data distributions than in the fits, there is agreement within $2.9\sigma$. As expected, the reduced cross section with the $x_{\mathrm{Bj}}$ cut imposed on the inclusive data rise more strongly towards lower values of $x_{\mathrm{Bj}}$ and describe the data better than the other predictions. The quark masses determined from the fit with the cut on $x_{\mathrm{Bj}}$ are consistent with the values given above.

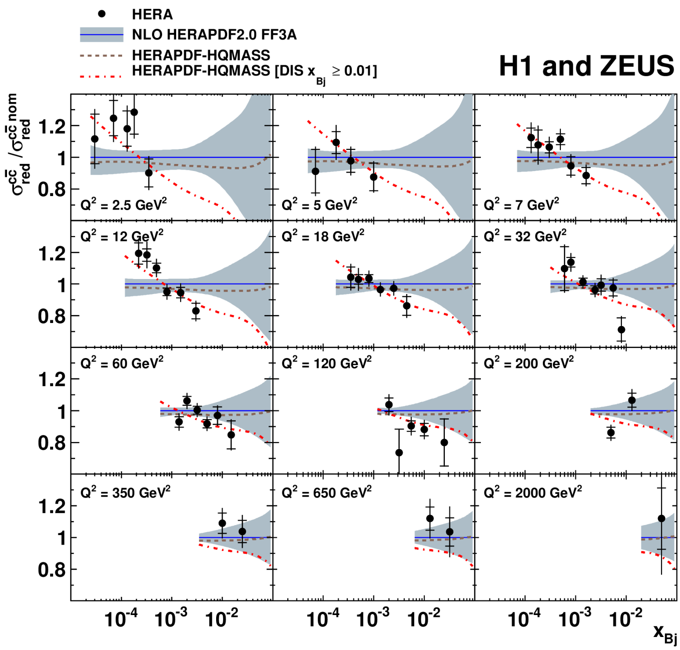


Fig. 1. Dependence on the Björken variable, $x_{\mathrm{Bj}}$, of the ratio of charm cross sections (full circles) and NLO FFNS predictions based on HERAPDF-HQMASS with and without $x_{\mathrm{Bj}}$ cut with respect to the reduced cross section obtained from HERAPDF2.0 FF3A fit.

Although there is better agreement between the combined data and the fit with the $x_{\mathrm{Bj}}$ cut, the inclusive HERA data are not described with this fit as can be seen in [1].

## 3. NNLO $\alpha_{\mathrm{s}}$ fit of DIS jet data

Precise knowledge of strong coupling constant, $\alpha_{\mathrm{s}}$, as one of the least known parameters of the Standard Model (SM) is of great importance for: precision measurements, consistency tests of the SM and searches for physics beyond the SM. Complete predictions at NNLO for jet production in DIS are now available [7] — about 25 years after NLO calculations for jet production cross sections in DIS were first published. For the first time, $\alpha_{\mathrm{s}}(m_Z)$ is determined from inclusive jet and dijet cross sections in NC DIS by the H1 Collaboration using NNLO QCD predictions. The comprehensive analysis and results are presented in [2]. The jet cross-section calculations are performed using the program NNLOJET [8] which is interfaced to fastNLO [9] to provide efficient, repeated calculations with different values of $\alpha_s$, different scale choices, and different PDF sets. There are two approaches used in the analysis. First, the value of $\alpha_s$ is determined in NNLO from inclusive and dijet data using pre-determined PDFs as input with the evolution starting scale $\mu_0 = 20$ GeV. In the other approach, the value of $\alpha_s$ is determined together with the PDFs from inclusive DIS and jet data. After a detailed study of the scale uncertainty, the renormalisation and factorisation scales are chosen to be $\mu_R = \mu_F = \sqrt{Q^2 + p_T^2}$.

The experimental, scale, $\mathrm{PDF}_{\alpha_s}$, quadratic sum of all PDF related uncertainties, and the theory uncertainties of $\alpha_s$ fit were studied as a function of $\bar{\mu}_{\mathrm{cut}}$ which restricts the jet data to high scales selecting $\bar{\mu} > \bar{\mu}_{\mathrm{cut}}$. It was shown that the scale uncertainty dominates at low values of $\bar{\mu}_{\mathrm{cut}}$ and decreases with increasing $\bar{\mu}_{\mathrm{cut}}$, while the experimental uncertainty increases with the scale cut. The compromise is made by using cut of $\bar{\mu} > 28$ GeV. The value of $\alpha_s$ obtained with the cut of $\bar{\mu} > 28$ GeV is

$$\alpha_s(m_Z) = 0.1157(20)_{\mathrm{exp}}(6)_{\mathrm{had}}(3)_{\mathrm{PDF}}(2)_{\mathrm{PDF}_{\alpha_s}}(3)_{\mathrm{PDF_{set}}}(27)_{\mathrm{scale}}\,.$$

This value is the main result of $\alpha_s$ in this analysis.

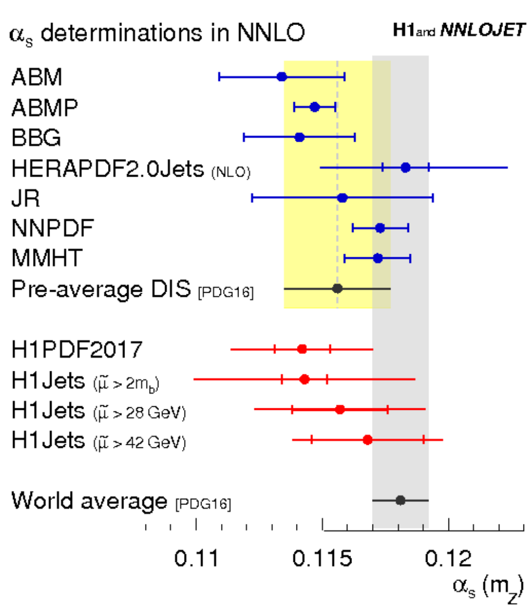


Fig. 2. The new H1 results of $\alpha_s$ determined from NNLO QCD fits compared with other DIS results. The inner error bars indicate the experimental and the outer error bars the total uncertainty.

As mentioned above, $\alpha_s$ was also determined from a calculation at NNLO together with the non-perturbative PDFs using the jet and inclusive data. This fit is termed as H1PDF2017[NNLO] and the determined value of $\alpha_s$ is consistent with the values quoted above. Figure 2 shows the $\alpha_s$ value obtained with the two approaches together with other determinations from DIS data. The so-called pre-average value from DIS data and the world average [10] are also shown. As can be seen, the new results show consistency with the calculations from HERA data at NLO and the other DIS data. The scale uncertainty is reduced by a factor of about two in NNLO, but the theoretical scale uncertainty still dominates.

## 4. Prompt photon production in DIS

High-energy photons can be produced in DIS either by the incoming or outgoing quark ("$QQ$" photons) or by the incoming or outgoing lepton ("$LL$" leptons). $QQ$ photons are classified as "prompt" and $LL$ photons are treated as background to the QCD process. ZEUS have obtained new results [3] from analysis of DIS events with the production of an isolated photon and at least one additional jet.

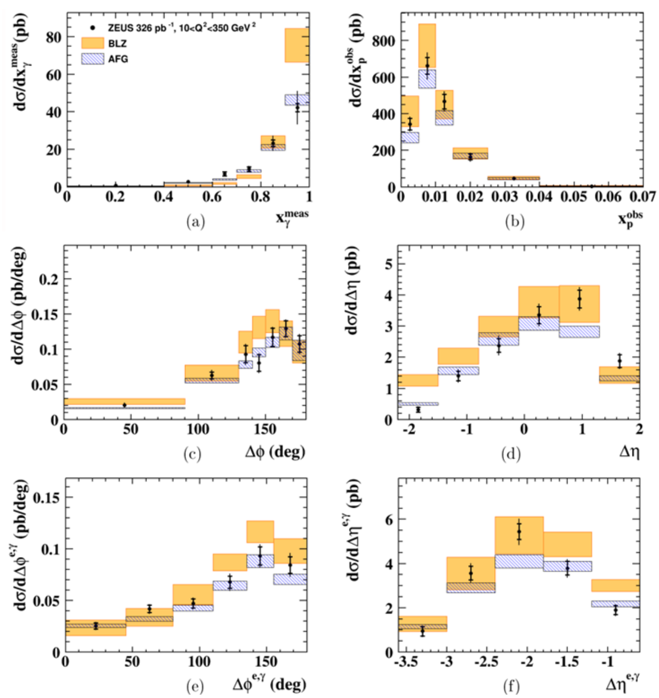


Fig. 3. Differential cross sections in (a) $x_\gamma^{\mathrm{meas}}$, (b) $x_p^{\mathrm{obs}}$, (c) $\Delta\Phi$, (d) $\Delta\eta$, (e) $\Delta\Phi^{e,\gamma}$ and (f) $\Delta\eta^{e,\gamma}$ compared to the BLZ and AFG models.

Differential cross sections are obtained as functions of the fraction of the exchanged photon energy and longitudinal momentum that is given to the photon and the jet, $x_\gamma^{\mathrm{meas}}$, the fraction of the proton energy taken by the parton that interacts with the photon, $x_p^{\mathrm{obs}}$, the azimuthal angle between the prompt photon and the jet, $\Delta\Phi$, the pseudorapidity difference between the prompt photon and the jet, $\Delta\eta$, the azimuthal angle between the prompt photon and the scattered electron, $\Delta\Phi^{e,\gamma}$, and the pseudorapidity difference between the prompt photon and the scattered electron, $\Delta\eta^{e,\gamma}$.

Figure 3 shows the resulting cross sections compared to theory calculations based on the $k_{\mathrm{T}}$-factorisation method used by BLZ (Baranov, Lipatov, Zotov) model [11] and the AFG (Aurenche, Fontannaz, Guillet) model including collinear factorisation in NLO [12]. As can be seen, $x_\gamma^{\mathrm{meas}}$ and $\Delta\eta$ distributions are not well-described by $k_{\mathrm{T}}$-factorization, while the AFG model provides a very good description of the normalisation and shape of the distributions.

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