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Nataša Raičević

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New Results on Proton Structure from HERA

Nataša Raičević on behalf of the H1 and ZEUS collaborations[1,a)]

[1]Faculty of Science, University of Montenegro, Cetinjska 2, 81000 Podgorica, Montenegro

[a)]raicevic@mail.desy.de

Abstract. In this paper we show the new set of parton distribution functions (PDFs) determined using new combined H1 and ZEUS data on neutral and charged current inclusive cross sections from all running periods (1994-2007). The combined data are used as the sole input to NLO and NNLO QCD analyses. The new set of PDFs is termed as HERAPDF2.0. Also we show an extended QCD analysis at NLO including the combined data on jet and charm production which enables the simultaneous determination of PDFs (HERAPDF2.0Jets) and the strong coupling constant from HERA data alone.

INTRODUCTION

The reduced cross section of neutral current (NC) $e^{\pm}p$ deep inelastic scattering (DIS), mediated by γ and Z exchange, $e^{\pm} + p \rightarrow e^{\pm} + X$, can be written as,

$$\sigma^r_{NC}(e^{\pm}p) = \frac{d^2\sigma^{e^{\pm}p}_{NC}}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2 \mp \frac{1-(1-y)^2}{1+(1-y)^2} xF_3 - \frac{y^2}{1+(1-y)^2} F_L,$$

with y being the inelasticity which represents the energy transfer between the lepton and the hadron system in the proton rest frame and F_2, xF_3 and F_L are the structure functions of the proton. In the framework of the perturbative QCD inspired quark parton model, the structure functions can be directly related to the parton density functions (PDFs) which are probability densities of partons existing inside the proton. At low Q^2, the contribution of Z exchange is negligible and $xF_3 = 0$ while F_2 is the dominant contribution to the cross section which is an electric-charge squared weighted sum of the quark and anti-quark PDFs of all flavours. In the low x region, F_2 is dominated by sea-quark PDFs, and the DGLAP evolution of QCD ascribes the Q^2 dependence of F_2 ("scaling violation") due to gluons splitting into quark anti-quark pairs. At large values of Q^2, xF_3 becomes significant, and gives information about the valence quark distributions, $u_v = u - \overline{u}$, and $d_v = d - \overline{d}$. The longitudinal structure function, F_L, is zero in the quark-parton model, i.e. without QCD, but in leading order QCD, a finite value of F_L is expected in the small x region by being directly related to the gluon PDF. The contribution of the term containing the longitudinal structure function is only significant for high y.

The reduced cross section of the charged current (CC) DIS interaction, mediated by W exchange , $e^+(e^-) + p \rightarrow \overline{\nu}(\nu) + X$, are also expressed via quark and anti-quark distribution functions,

$$\sigma^r_{CC}(e^+p) \sim x\overline{U} + (1-y)^2 xD = (x\overline{u} + x\overline{c}) + (1-y)^2(xd + xs),$$

$$\sigma^r_{CC}(e^-p) \sim xU + (1-y)^2 x\overline{D} = (xu + xc) + (1-y)^2(x\overline{d} + x\overline{s}).$$

During a period of 15 years of data taking, the H1 and ZEUS collaborations at HERA successfully operated their general purpose detectors. The data taken until the year 2000, with electron/positron beam energy 27.6 GeV and proton beam energies 820, 920 GeV (HERA-I period), have provided accurate neutral current and charged current DIS cross section measurements from about 100 pb^{-1} of e$^+$p and about 15 pb^{-1} of e$^-$p scattering data per experiment. In 2001, HERA and the detectors were upgraded to reach higher luminosities (HERA-II period). Until March 2007, HERA provided about 500 pb^{-1} of e$^{\pm}$p collisions to each of the experiments. From March to June 2007, HERA performed a series of dedicated runs with reduced proton beam energies of 460 and 575 GeV, as compared to the nominal 920 GeV, for a direct measurement of the longitudinal proton structure function.

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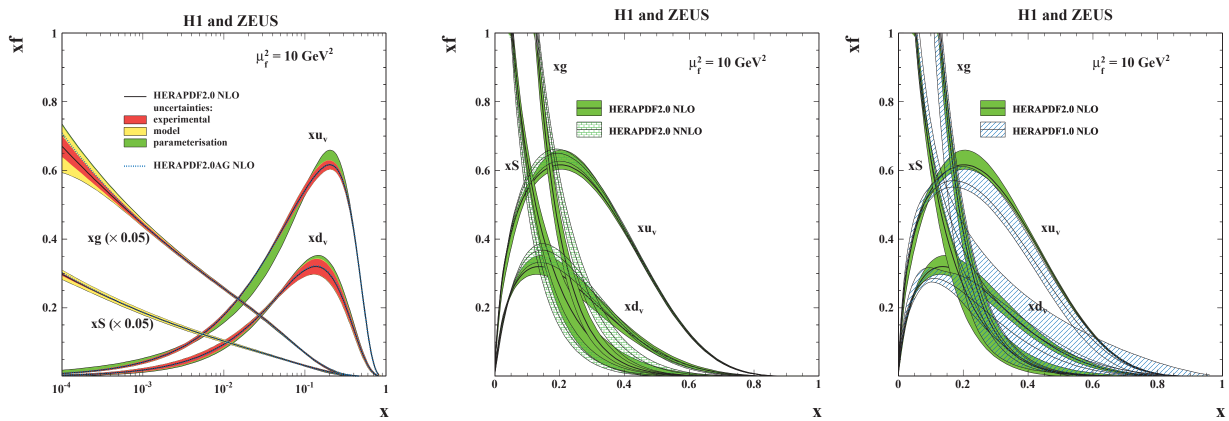

FIGURE 1. x dependence of the parton density functions from HERAPDF2.0 with errors including the experimental, model and the PDF parameterisation uncertainties for: xu_v, xd_v, $xS = x(\overline{U} + \overline{D})$ and xg (leftmost) and comparison of HERAPDF2.0 NLO to HERAPDF2.0 NNLO (middle) and to HERAPDF1.0 NLO (rightmost) with the bands representing the total uncertainties. All plots are at $\mu_f^2 = Q^2 = 10$ GeV^2.

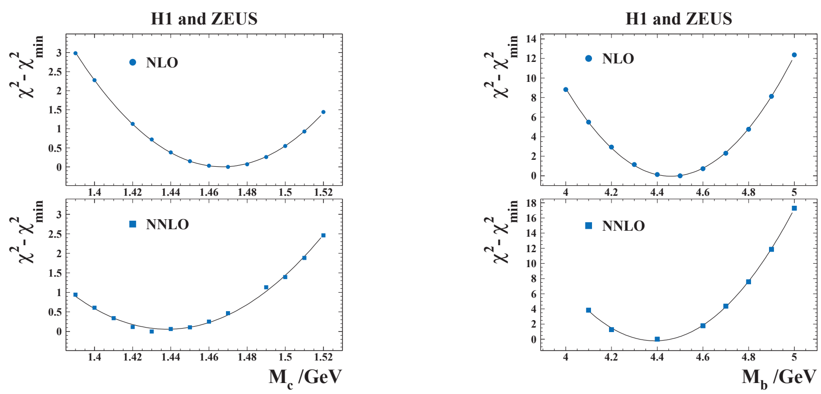

FIGURE 2. The $\chi^2 - \chi^2_{min}$ of the HERAPDF2.0 fit at NLO and NNLO as a function of the charm mass parameter (left) and the beauty mass parameter (right).

H1 and ZEUS combined their results based on the data corresponding to an integrated luminosity of about 1 fb^{-1} and span six orders of magnitude in negative four-momentum-transfer squared, Q^2, and Bjorken x and performed common QCD analysis in order to provide data and proton PDFs with the highest possible accuracy. All parton distributions can be determined from HERA data alone

In this paper we shortly present a new set of parton distribution functions, called HERAPDF2.0 [1] which are based on the combined data from the two collaborations providing a legacy of HERA results.

HERAPDF2.0

The general approach to determine the PDFs from experimental DIS cross section measurements consists of several steps. First, the PDFs are parameterised at a low starting scale $\mu_{f0}^2 = Q_0^2$ by smooth analytical functions with few free parameters. After this, these functions are evolved using the DGLAP equations to higher Q^2 values and calculations of the structure functions and the cross sections are performed. The calculations are compared to experimental data and minimisation of the χ^2 is performed adjusting the free parameters. Several constraints can be applied, like momentum sum rules, requiring the known quark flavour numbers of the proton etc.

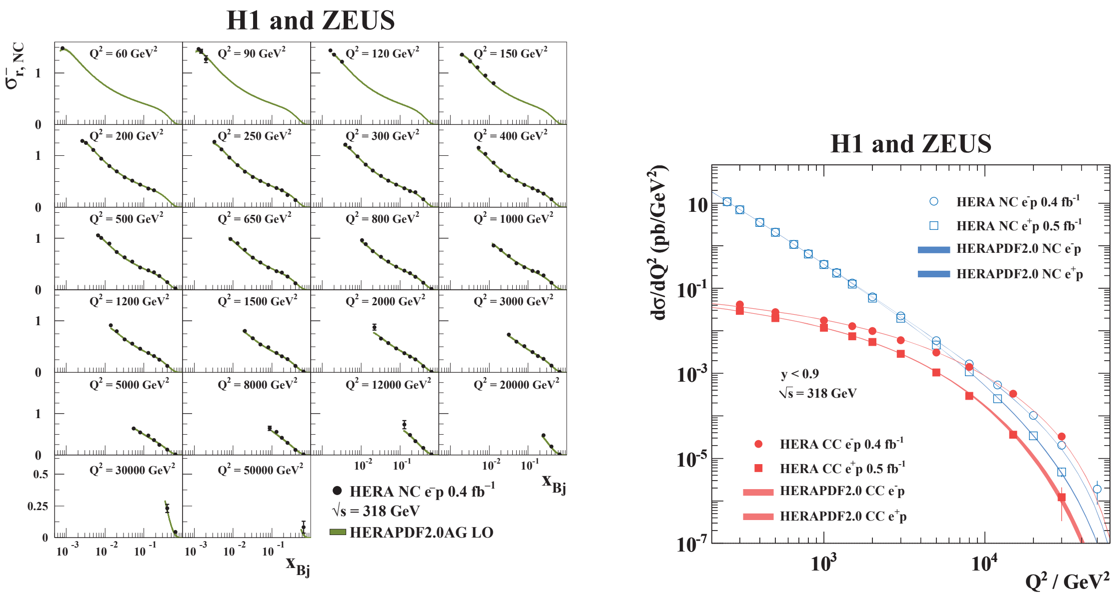

FIGURE 3. Comparison of low Q^2 NC data with HERAPDF2.0 NLO (left) and of high Q^2 NC and CC data with HERAPDF2.0 NLO (right). The bands represent the total uncertainties of the predictions.

The predictions from perturbative QCD are fitted to the combined data and obtained by solving the DGLAP evolution equations at LO, NLO and NNLO. This was done using the programme QCDNUM [2] within the HERAFitter framework [3] and an independent programme, which was already used to analyse the combined HERA I data [4]. The x dependence of PDFs for $Q^2 = 10$ GeV^2 from HERAPDF2.0 at NLO are shown in the leftmost plot of Figure 1. This is a summary plot for the valence distributions for up and down quarks as well as the gluon and sea quark distributions which are scaled down by a factor of 20. The errors including the experimental, model and the PDF parameterisation uncertainties are also shown. The χ^2 per degree of freedom of the HERAPDF2.0 fit is 1357 /1131. The middle plot of Figure 1 shows the comparison of HERAPDF2.0 at NLO and NNLO with total uncertainties. The main difference is the different shapes of the gluon distributions as expected from the different evolution at NLO and NNLO. The rightmost plot of Figure 1 shows the comparison of HERAPDF2.0 at NLO and HERAPDF1.0 at NLO with total uncertainties. From this plot one sees a large reduction of the uncertainties on all PDFs. The shape of the valence distributions have become a little harder. This was caused by the additional data with high x from HERA-II data. The HERAPDF2.0 distribution at high x is also slightly harder than HERAPDF1.0 while the sea distribution of HERAPDF2.0 at high x is considerably softer.

The combined charm and beauty data can help to reduce the uncertainty on PDFs coming from the choice of heavy quark scheme and the value of the charm and beauty mass parameters input to these schemes. Figure 2 shows the $\chi^2 - \chi^2_{min}$ as a function of the charm and beauty mass parameters, for a fit which includes charm and beauty data. For the both mass parameters the dependence shows a clear minimum. The standard choice of heavy-flavour scheme for HERAPDF2.0 is the variable-flavour-number scheme RTOPT [5].

Figure 3 shows comparison of low Q^2 NC and high Q^2 NC and CC data with the new fit with the total uncertainty. As can be seen from the figure the description is very good. The electroweak effects are clearly pronounced and described by the fit.

INCLUSION OF JET DATA - HERAPDF2.0JETS

HERAPDF2.0JETS is based on the combination of all inclusive data from the H1 and ZEUS collaborations and selected data on charm and jet production. The inclusion of jet-production cross sections made a simultaneous determi-

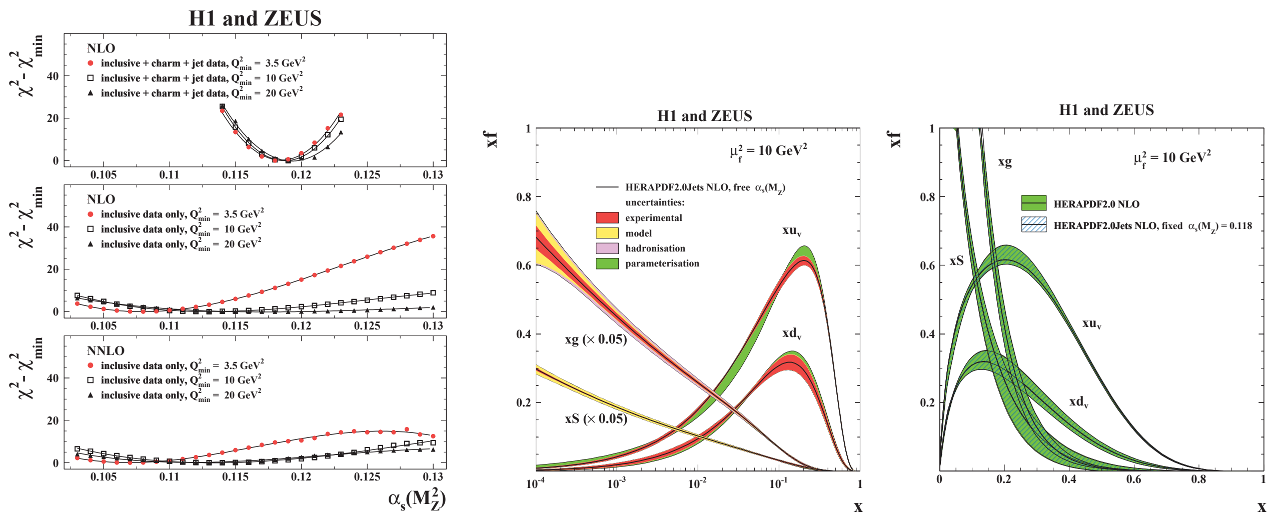

FIGURE 4. The $\chi^2 - \chi^2_{min}$ of the QCD fit at NLO and NNLO as a function of the α_s for three values of Q^2_{min} (leftmost). The PDFs from the HERAPDF2.0Jets fit at NLO with free value of $\alpha_s(M_Z)$ (middle). Comparison of HERAPDF2.0 NLO to HERAPDF2.0Jets NLO with free value of $\alpha_s(M_Z)$ (rightmost).

nation of these parton distributions and the strong coupling constant possible as shown in the leftmost plot of Figure 4. A clear minimum is observed at $\alpha_s(M_Z) = 0.118$ not dependent on Q^2_{min}. This confirms the choice of $\alpha_s(M_Z) = 0.118$ used for HERAPDF2.0 fit of inclusive data. The inclusive data alone can not constrain $\alpha_s(M_Z)$ well as can be seen from the middle and bottom panels of this plot. The middle plot of Figure 4 shows the results of HERAPDF2.0Jets fit at NLO with free values of $\alpha_s(M_Z)$. Here, a full uncertainty analysis was performed as for HERAPDF2.0 with addition of hadronisation uncertainties on the jet data. Since the jet data determine the value of $\alpha_s(M_Z)$ very well, the uncertainty on the gluon PDF, reflected in the hadronisation unceratinty mainly, is not significantly worse with respect to the fit with fixed value. The PDFs from the HERAPDF2.0Jets fit with fixed value of $\alpha_s(M_Z) = 0.118$ are also very similar to the standard HERAPDF2.0 as can be seen from the rightmost plot of Figure 4.
The obtained value of $\alpha_s(M_Z)$ with the uncertainties is,

$$\alpha_s(M_Z) = 0.1183 \pm 0.0009(\mathrm{exp}) \pm 0.0005(\mathrm{model/parameterisation}) \pm 0.0012(\mathrm{hadronisation})^{+0.0037}_{-0.0030}(\mathrm{scale}),$$

which is in excellent agreement with the value of the world average $\alpha_s(M_Z) = 0.1185$.

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