RECENT RESULTS FROM HERA ON THE PROTON STRUCTURE *

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The most recent results on the proton structure obtained from the H1 and ZEUS experiments at HERA are presented. The new preliminary result on parton density functions extracted from the leading-order QCD fit to the preliminary combined H1 and ZEUS data is presented. Electro-weak precision measurements of the double-differential inclusive neutral-current cross section, measured with the ZEUS detector at a centre-of-mass energy of 319 GeV in e^+p and e^-p collisions are shown. They span the kinematic domain of high momentum transfer squared, Q^2, and high Bjorken x, up to $x \simeq 1$. Using the HERA data collected at three different centre-of-mass energies, the H1 Collaboration has updated their measurement of the longitudinal structure function, $F_{\rm L}$, with new results in high Q^2 region.

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1. Introduction

At the HERA collider, a centre-of-mass energy of $\sqrt{s} = 319$ GeV was achieved by colliding electrons or positrons and protons with nominal energies of 27.5 GeV and 920 GeV, respectively. The large energy allowed a value of Q^2, the exchanged boson virtuality, to reach almost 10^5 GeV^2. A value of the Bjorken scaling variable x which represents the momentum fraction carried by the struck quark in the proton's infinite momentum frame, reaches down to almost 10^{-5}.

Until the year 2000 (HERA-I period), the experiments H1 and ZEUS at HERA collected an integrated luminosity of about 120 pb^{-1} each. Afterwords, HERA underwent a major upgrade aiming for higher luminosity

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and until 2007 (HERA-II period) HERA provided in total about 500 pb^{-1} of $e^{\pm}p$ collisions to each of the experiments. In the last three months of the HERA operation, special runs with lower proton beam energies of 460 GeV and of 575 GeV were performed, each experiment collecting approximately 13 pb^{-1} and 7 pb^{-1} of data respectively. The main purpose of these data is the measurement of the longitudinal proton structure function F_{L} which is related to the longitudinally polarised virtual boson exchange in lepton–nucleon collision.

The study of $e^{\pm}p$ deep inelastic scattering (DIS) from HERA has contributed significantly to the precise knowledge of the proton structure which is represented by the parton distribution functions (PDFs).

2. The HERAPDF1.5LO PDF set

To extract PDFs with high precision, the H1 and ZEUS collaborations have performed QCD fits using combined data on neutral current (NC) and charged current (CC) reduced cross sections from the two experiments. The fits were based on the evolution of the PDFs with Q^2 using DGLAP equations in next-to-leading order (NLO) and next-to-next-to-leading order (NNLO). The combined data from HERA-I running period were used for the extraction of the PDF set termed HERAPDF1.0 NLO [1]. By adding the preliminary HERA-II data two PDF sets are provided: HERAPDF1.5 NLO [2] and HERAPDF1.5 NNLO [3] with the considerably improved precision of the PDFs at high x — particularly in the valence quark sector.

The HERA collaborations obtained a new set of PDFs evolved to leading order (LO) in α_{s} [4]. Parton densities at LO are important for the proper simulation of parton showers and underlying event properties in Monte Carlo event generators. Since the increase of energies at the LHC will extend the data to lower values of x, high precision PDFs from HERA low-x region will provide precise prediction of the underlying event properties, minimum bias events and the simulation of the pile-up events. The new fit, HERAPDF1.5 LO, is based on the same data and settings as the HERAPDF1.5 NLO fit. In the new fit α_{s} is chosen to be $\alpha_{\mathrm{s}}(M_Z) = 0.13$ in order to obtain the best value of fit quality. The new fit achieves a reasonable total χ^2 of 762 for 664 degrees of freedom. Figure 1 shows results on NC reduced cross section as a function of Q^2 and x from the new fit compared with the data used in the fit in the low Q^2 region. The fit results are presented together with uncertainty bands reflecting the experimental uncertainties transferred from the data to the PDFs. Good agreement is observed even in the region below the Q^2 cut used in the fit ($Q^2_{\mathrm{cut}} = 3.5$ GeV^2).

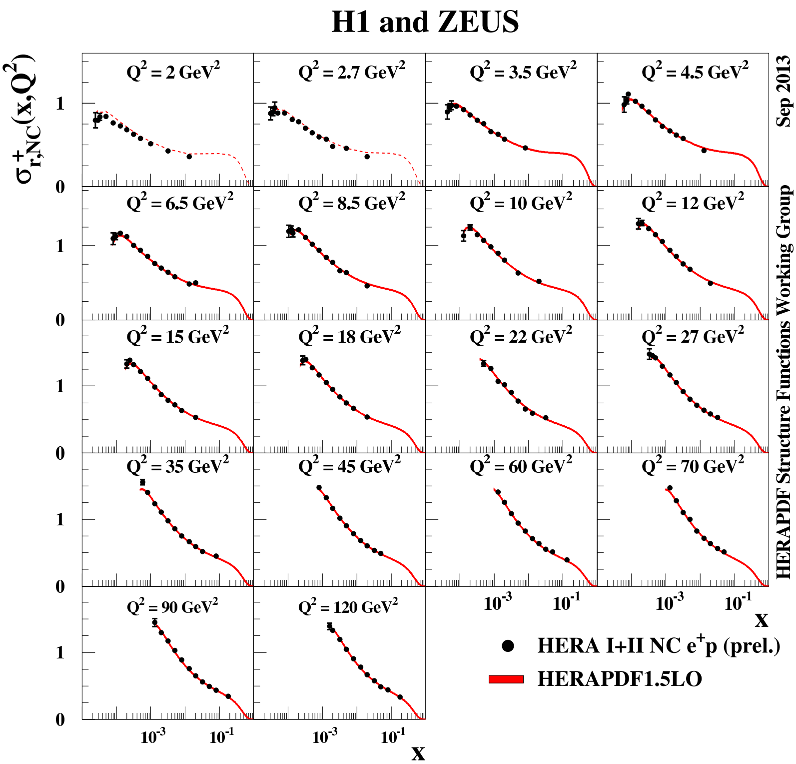

Fig. 1. Neutral current e^+p reduced cross section measurements compared to predictions based on HERAPDF1.5 LO with experimental uncertainties. The dashed line represents the predictions for the region not included in the fit.

3. Neutral current $e^{\pm}p$ cross sections at high Bjorken x

Most of the DIS data available at high x ($x \geq 0.7$) have been obtained from fixed-target experiments which cover a Q^2 range where perturbative QCD (pQCD) is not fully applicable. Therefore, the PDFs are poorly determined at high x and there are sizable differences despite the fact that all QCD fitters use the same parameterisation. The HERA experiments can provide measurements at high x in the Q^2 region where pQCD and DGLAP evolution are applicable.

There are new results from the ZEUS Collaboration on the NC cross section up to values of $x \simeq 1$ using novel reconstruction method with the fine binning in x and the excellent control of the systematic uncertainties [5]. The measurements are obtained for $Q^2 \geq 725$ GeV^2 using data with an integrated luminosity of 187 pb^{-1} of e^-p and 142 pb^{-1} of e^+p collisions, and provide an important input for the extraction of the valence quark PDFs in QCD fits in a method-independent way.

The jet associated with the struck quark at high x disappears down the beam-pipe and due to the missing energy the reconstruction of x is limited. In these events, the cross section is integrated from a certain limit in x (x_{edge}) up to $x = 1$. The limit in x, below which the jet is fully reconstructed, increases with Q^2.

Figure 2 shows the ratio of the measured double-differential cross section in x and Q^2 to those expected from HERAPDF1.5. The expectation for the integrated bin is also shown as a hatched box. The ratio is compared with the predictions from several other commonly used sets of PDFs also normalised to HERAPDF1.5. The theoretical calculations are found to agree well with the data.

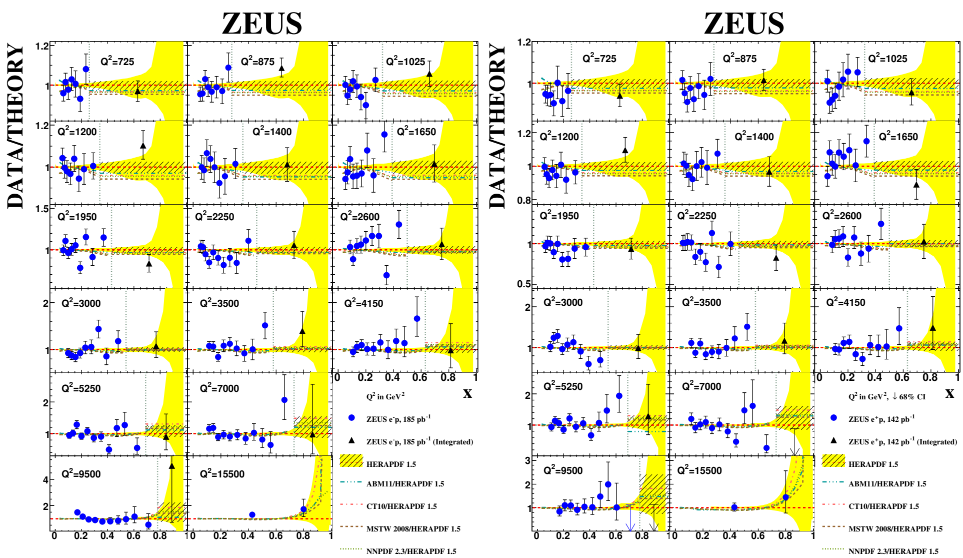

Fig. 2. Ratio of the double-differential cross section in x and Q^2 and the double differential cross section integrated over x for NC e^-p (left) and e^+p (right) collisions to the expectation from HERAPDF1.5 PDFs as a function of x at different Q^2 values. For bins with zero measured events, a 68% probability limit is given. For HERAPDF1.5, the uncertainty is given as a band. The predictions of several other PDF sets normalised to HERAPDF1.5 are also shown.

4. Measurement of the longitudinal proton structure function

At NLO and NNLO QCD analysis, the gluon density is constrained through the measurement of the proton structure function F_2 and the reduced neutral current cross sections through their scaling violations. Also according to pQCD, the gluon density is related to the proton structure function F_L. Therefore, a measurement of the F_L provides a test of parton dynamics and the consistency of QCD by comparison of the gluon density obtained by the two approaches. When the contribution of Z-boson exchange is expected to be small ($Q^2 \leq 1000$ GeV^2), the reduced NC differential cross section for e^+p scattering can be written as

$$\sigma_r = \frac{d^2\sigma}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2\left(x, Q^2\right) - \frac{y^2}{Y_+} F_L\left(x, Q^2\right) , \tag{1}$$

where $Y_+ = 1 + (1-y)^2$. As can be seen from this equation, the longitudinal structure function gives sizable contribution to the DIS cross section only at large values of inelasticity y which is related to the kinematic variables x and Q^2 by $y = Q^2/sx$. Therefore, it is necessary to measure the differential cross sections up to high y, a kinematic region in which the scattered lepton energy is low, lower than the energy of the hadronic jet originating from the struck quark. The main problem of this analysis is the background from photoproduction processes in which a hadron from the hadronic final state may mimic a lepton. The photoproduction contribution increases rapidly with decreasing energy of the lepton candidate and such high background contribution makes high-y DIS measurements very hard and complex.

After realisation of special runs with the reduced proton beam energy in e^+p collisions at HERA ($\sqrt{s} = 225$ and 252 GeV^2), a direct measurement of the F_L became possible. According to the previous equation, F_L can be determined by a linear fit as a function of $y^2/(1+(1-y)^2)$ to the reduced cross section measured at given values of x and Q^2 but at different centre-of-mass energies. The structure functions F_L and F_2 are simultaneously determined from the cross section measurements at different centre-of-mass energies using a χ^2 minimisation technique as employed in the previously published F_L measurement at low and medium Q^2 [6].

The new measurement obtained by the H1 Collaboration improves the experimental precision on F_L in the region $35 \leq Q^2 \leq 110$ GeV^2 and provide the first measurement of this structure function in the region $120 \leq Q^2 \leq 800$ GeV^2. The left plot in Fig. 3 shows the Q^2 dependence of F_L. The data are compared to prediction of different perturbative QCD calculations at NNLO. As can be seen from this plot, in all cases the predictions are in reasonable agreement with the data. The right plot in Fig. 3 shows the gluon density obtained with the two approaches, one obtained from the F_L measurements based on a NLO approximation, and the other one determined in the HERAPDF1.5 NLO QCD fit. From this figure, one can conclude that a gluon density extracted from a NLO approximation using the F_L measurement agrees reasonably with the gluon density determined from scaling violations.

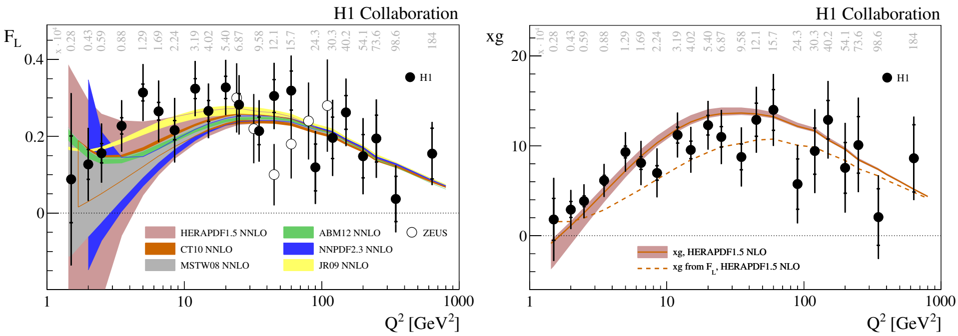

Fig. 3. The proton structure function F_{L} (left) and the gluon density xg (right) averaged over x at different Q^2 (solid points). The average value of x for each Q^2 is given above by each data point. The F_{L} data from ZEUS are also shown (open points). The F_{L} data are compared to NNLO predictions from a selection of PDF sets as indicated and the gluon distribution is compared to the prediction from the HERAPDF1.5 NLO QCD fit. The dashed line in the right plot corresponds to the gluon distribution as obtained by applying prediction of QCD about direct relation of gluon density to the F_{L}.

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