RECENT MEASUREMENTS OF THE PROTON STRUCTURE FUNCTIONS AT HERA*

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Recent measurements of the inclusive Deep Inelastic Scattering (DIS) cross section performed by the H1 and ZEUS Collaborations at the HERA collider are presented. The measurements span a wide range in the absolute four momentum transfer squared, $0.2\ \mathrm{GeV}^2 < Q^2 < 30000\ \mathrm{GeV}^2$, from the photoproduction to electroweak domain. A broad coverage in the Bjorken-x variable, $10^{-5} < x < 0.6$, allows to study QCD for different regimes and also to determine the parton distribution functions for the LHC. An extension of the measurement to high inelasticity, $y > 0.6$, gives an access to the proton longitudinal structure function F_{L}. A dedicated run with a reduced proton beam energy taken at the end of the HERA operation will allow to measure F_{L} for the first time at HERA.

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1. Introduction

Deep inelastic lepton–hadron scattering (DIS) plays and important role for the understanding of the structure of the nucleon and of the dynamics of strong interactions. The discovery of Bjorken scaling [1] and its violation [2] have formed the theory of strong interactions, Quantum Chromodynamics (QCD).

An important milestone for the study of the proton structure was the operation of the HERA *ep* collider located at DESY, Hamburg. During its nominal operation, HERA provided 920 GeV protons colliding with 27.5 GeV electrons (and positrons) leading to a large center of mass energy of the collisions $\sqrt{S} \approx 320$ GeV. This large energy provides a wide coverage in the absolute four momentum transfers squared, Q^2, and Bjorken x, thus

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allowing detailed tests of the QCD evolution and of the QCD validity for the high parton density low x regime. In the years 2003–2007 (HERA-II configuration) HERA was operating with longitudinally polarized electron beams allowing for an additional study of the electroweak couplings. At the end of the HERA operation the proton beam energy was reduced to 460 GeV and later set to 575 GeV. The data at different center of mass energies allow measuring of the longitudinal structure function $F_{\rm L}$.

A detailed knowledge of the proton structure is mandatory for the physics program at the future pp collider. For example, a measurement of the Higgs boson production at the LHC, for light Higgs boson masses, is determined by the proton structure at $x \sim 0.01$. For this kinematic range, the Higgs boson is produced predominantly via gluon–gluon fusion making precise measurement of the gluon density an extremely important task. Similarly, quark flavor decomposition is needed for precise estimation of the production of the Z and W bosons as well as other heavy particles, present in theories extending the standard model, with different coupling to different quark flavors.

For low x, the gluon density at HERA is measured using scaling violation of the structure function F_2. Alternatively, the gluon density can be determined using the longitudinal structure function $F_{\rm L}$. $F_{\rm L}$ allows for not only improved precision of the gluon density but also provides an important cross check of the standard QCD picture of low x dynamics.

2. Structure functions

The unpolarized Neutral Current (NC) double differential DIS cross section can be expressed in terms of three structure functions:

$$\frac{d^2\sigma^{\rm NC}_{e^{\mp}p}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_{\rm L}(x,Q^2) \pm \frac{Y_-}{Y_+}xF_3(x,Q^2)\right) , \qquad (1)$$

where $\alpha = 1/137$ is the fine structure constant and y is inelasticity calculated as $y = Q^2/S\,x$ and $Y_\pm = 1 \pm (1-y)^2$.

In the parton model F_2 is proportional to a weighted by electric charge squared singlet quark density, $F_2 = x\sum e_q^2(q(x) + \bar{q}(x))$. The structure function F_2 has a leading contribution to the DIS cross section for the HERA kinematics and thus can be most easily accessed experimentally.

The structure function xF_3 arises from γZ interference. In QCD xF_3 is proportional to a non-singlet quark density, $xF_3 = x\sum 2e_q a_q(q(x) - \bar{q}(x))$, where a_q is an axial coupling of the quarks to Z. The structure function xF_3 is more difficult to measure experimentally compared to F_2. It can be determined by measuring charge asymmetry of the DIS cross section at high Q^2.

The structure function F_{L} vanishes in leading order QCD for spin 1/2 quarks. This property, also known as Callan–Gross relation, played an important role for establishing the nature of the partons. In NLO QCD F_{L} acquires non zero value; for low x F_{L} is determined mostly by the gluon density $xg(x)$. Measuring F_{L} is a challenging experimental task. The structure function has a significant contribution to the cross section only at high inelasticity y which corresponds to a low energy of the scattered electron and thus prone to large background. At least two different center of mass energies are needed to determined the longitudinal structure function. In this case measurements at the same Q^2, x correspond to different values of y and thus the contributions of F_2 and F_{L} can be separated.

At high Q^2, the neutral current structure functions are sensitive to electroweak effects. This sensitivity can be studied at HERA using longitudinally polarized lepton beams. Neglecting the pure Z exchange term, for high Q^2 the structure function F_2 attains a correction from the γZ interference:

$$\Delta F_2 = \kappa(-v_e \mp P a_e) F_2^{\gamma Z} \,, \tag{2}$$

where $\kappa = \frac{1}{4\sin^2\theta_{\mathrm{W}}\cos^2\theta_{\mathrm{W}}}\frac{Q^2}{Q^2+M_Z^2}$, v_e, a_e are vector and axial electron couplings to Z, P is the longitudinal beam polarization, θ_{W} is the Weinberg angle, and M_Z is the Z mass. At a leading order $F_2^{\gamma Z} = x\sum 2e_q v_q(q+\bar{q})$, where v_q is a vector quark coupling to Z. Experimentally, $F_2^{\gamma Z}$ can be measured via polarization asymmetry $A^{\pm}$ where $\pm$ stands for the lepton beam charge

$$A^{\pm} = \frac{2}{P_{\mathrm{R}} - P_{\mathrm{L}}}\frac{\sigma^{\pm}(P_{\mathrm{R}}) - \sigma^{\pm}(P_{\mathrm{L}})}{\sigma^{\pm}(P_{\mathrm{R}}) + \sigma^{\pm}(P_{\mathrm{L}})} \approx \mp\kappa a_e \frac{F_2^{\gamma Z}}{F_2} \,, \tag{3}$$

where P_{R} and P_{L} correspond to the level of polarization for the right and left handed lepton beam, respectively.

The proton parton distribution functions (PDF) are determined from the cross section measurements using dedicated QCD fit programs. To separate different quark flavors, Charged Current (CC) DIS cross section data and data on lepton scattering off the deuteron are used along with NC data for the proton.

3. Measurements at low Q^2

In spring 2007 the H1 collaboration released a new preliminary NC cross section measurement at low Q^2. This measurement is based on data collected in dedicated runs taken during 1999 and 2000 with open trigger conditions. To increase acceptance towards low Q^2, the data in 2000 were taken with the *ep* interaction region shifted by 70 cm away from the calorimeter that was used to measure the scattered electron. The data is reported in terms of reduced cross section, $\sigma_r = d^2\sigma/dxdQ^2 \times xQ^4/2\pi\alpha^2 Y_+$.

The new preliminary data are combined with the published H1 result [4] using special averaging procedure which takes into account correlated systematic uncertainties [5]. The combined data are presented in Fig. 1. The reduced cross section rises as $x \to 0$ for each Q^2 value, the steepness of the rise increases with increasing Q^2. For the lowest x for each Q^2 bin there is a characteristic turn over of the cross section. Since the lowest x for a fixed Q^2 corresponds to the highest inelasticity y, this turn over can be attributed to the influence of the longitudinal structure function F_{L}.

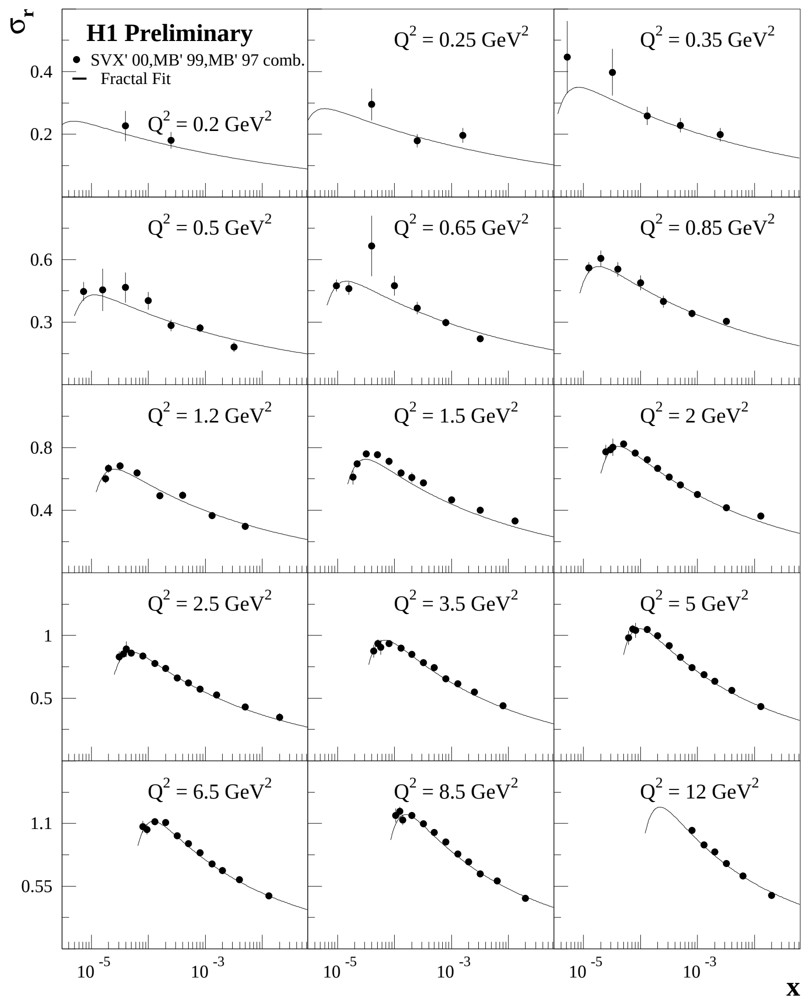

Fig. 1. New preliminary H1 measurement at low Q^2 and low x. The closed circles correspond to the combination of the new measurements and the published result. The line corresponds to a fit with a fractal model [3].

4. Measurements at high Q^2

In summer 2006 preliminary results based on high statistics HERA-II data have become available. A large increase of the e^- sample compared to HERA-I period allows to improve precision for the structure function $xF_3^{\gamma Z}$. These results are shown in Fig. 2(left). Extension of the xF_3 measurement to lower x values probes the valence quark density at low x where its shape is poorly known.

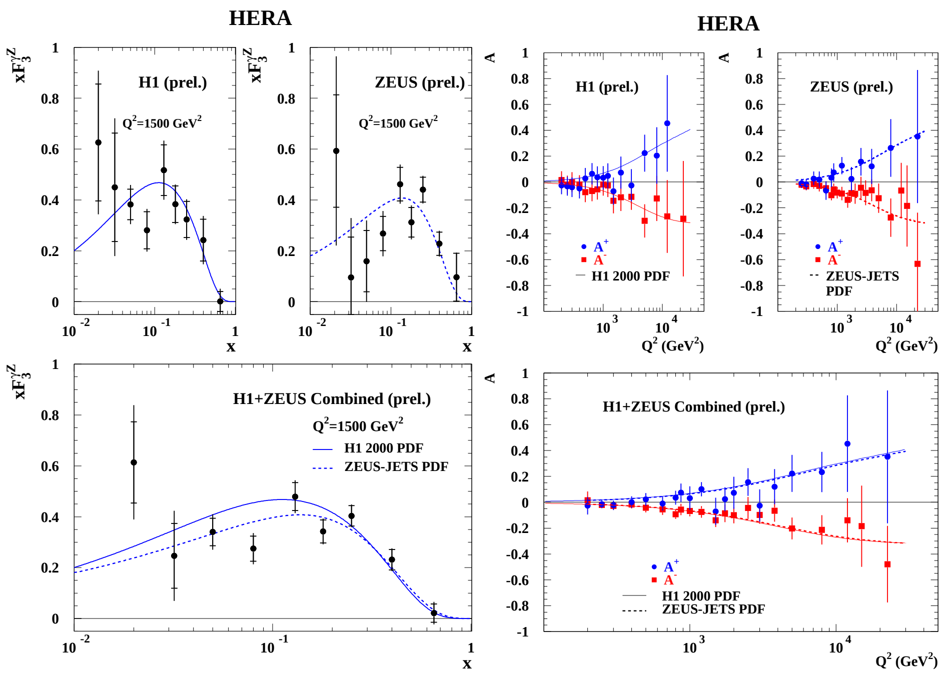

Fig. 2. Left and right: Measurement of the structure function xF_3 and the polarization asymmetry A. The top four panels represent the individual measurements of the of the H1 and ZEUS Collaborations, the bottom panels show them combined in a HERA average.

The H1 and ZEUS Collaborations also released the measurements of the polarization asymmetry A for both e^+p and e^-p samples. The asymmetry is well consistent with the prediction of the standard model. The two collaborations formed a working group to combine the measurements in a HERA average. The combined xF_3 and A presented here are the first results of this activity.

5. Measurements at high y

Recently both H1 and ZEUS Collaborations concentrated their analysis effort on the NC cross section measurement at high inelasticity y. The measurements in this kinematic domain are important, since the data are sensitive to the longitudinal structure function F_{L}, see Eq. (1), but experimentally challenging. For low Q^2, high inelasticity y corresponds to low energies of the scattered electron and thus the signal can be faked by the copious photoproduction background.

The H1 collaboration has reported a new preliminary measurement at high y based on 96 pb^{-1} of the HERA-II data. The new result is shown in Fig. 3. The key feature of this analysis is that the photoproduction background is measured directly from the data using a sample of events in which the track charge of the electron candidate is opposite to the beam charge. About equal luminosities are used in this analysis for e^-p and e^+p data allowing for precise determination of the background for both charges. Fig.3(left) compares the new result with the published data [4], which was taken at a slightly different proton beam energy $E_p = 820$ GeV. The total uncertainties of the new data are reduced by about factor 2.

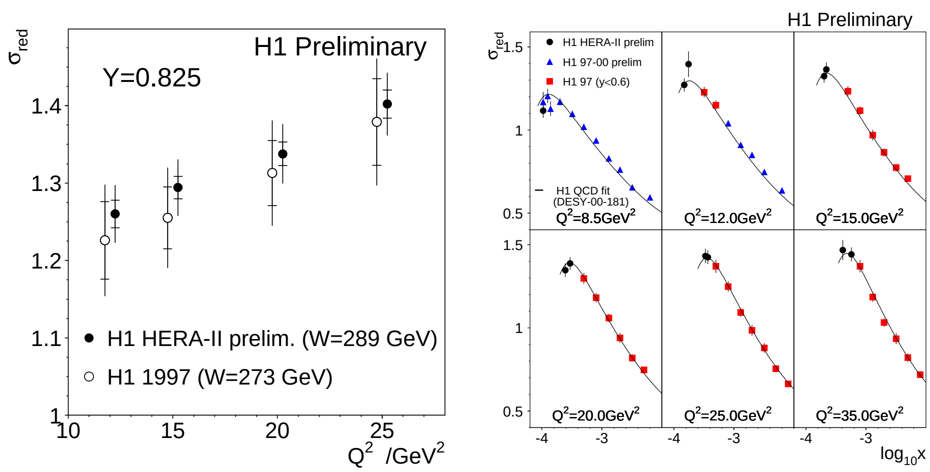

Fig. 3. Left: Measurement of the reduced neutral current cross section at high y. Closed circles represent the new preliminary result based on HERA-II data, open circles correspond to the published HERA-I result. The inner (outer) error bars correspond to statistical (total) errors. Right: Comparison of the new preliminary H1 measurements (closed circles and triangles) to the published results (open circles). The error bars show total uncertainties.

The ZEUS collaboration also reported a preliminary measurement of the NC cross section extending to high y range, see Fig. 4. Compared to the H1 data this measurement corresponds to higher Q^2. The photoproduction background is estimated using a Monte Carlo simulation. The data show good agreement with the expectations of the QCD fits.

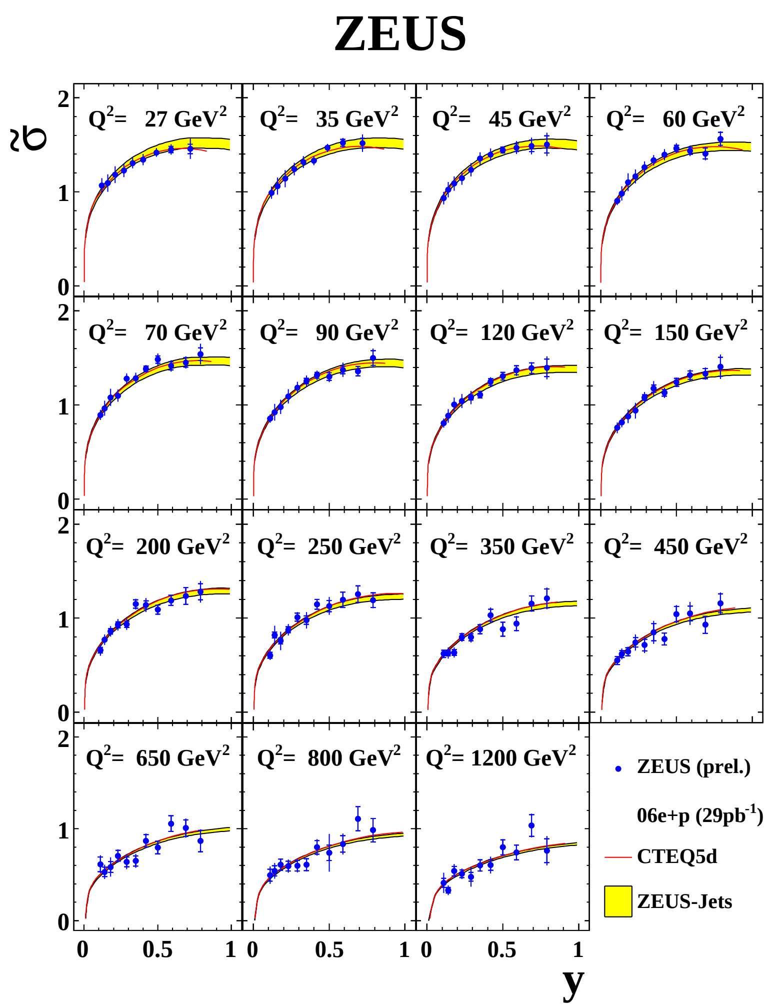

Fig. 4. Preliminary measurement of the NC reduced cross section performed by ZEUS. The inner (outer) error bars correspond to statistical (total) errors. The measurement extends to higher values of y. The data is compared to the CTEQ5D [6] parameterization and ZEUS QCD fit [7].

6. Low energy run

At the end of HERA operation, in March 2007 the proton beam energy has been reduced from the nominal 920 GeV to 460 GeV. After accumulating about 13 pb^{-1} of data, the decision has been taken to collect the data at an intermediate energy point, $E_p = 575$ GeV, and 6.5 pb^{-1} of data were collected using these settings.

These low energy runs allow the measurements of the structure function F_{L} for the first time at HERA. The collected luminosity provides enough data for an accurate measurement at low $Q^2 < 30$ GeV^2. The measurement at $E_p = 575$ GeV allows an additional crosscheck since these data have a different sensitivity to F_{L} and to the photoproduction background.

7. Conclusions and outlook

The years of HERA operation, 1992–2007, were extremely fruitful for understanding of the proton structure at low x. The discovery of the strong rise of the proton structure function F_2 at low x, a successful description of the data for $Q^2 \geq 3.5$ GeV^2 by DGLAP [8] QCD evolution and remarkably precise measurement of the gluon density at low x are among the fundamental achievements. During the last year of the operation, HERA showed that despite her edge she did not loose her flexibility providing more than expected data for special runs with reduced proton beam energy. The end of HERA operation does not stop analysis of the HERA data, a measurement of the longitudinal structure function F_{L} and an ultimate precision analysis of the combined HERA data are among the important results which are expected to come in near future.

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