PROTON STRUCTURE FUNCTION MEASUREMENTS AT HERA

V. Chekelian (Shekelyan) [a]
Max Planck Institute for Physics, Foehringer Ring 6, 80805 Munich, Germany
Abstract. Recent results from the electron-proton collider HERA on the structure of the proton and understanding of the data in terms of QCD are presented.

1 Introduction

At the first *ep* collider HERA, electrons of 27.5 GeV collided with protons of 920 GeV (820 GeV until 1997). This corresponds to an *ep* centre of mass energy of 320 GeV. The maximum negative four-momentum-transfer squared from the lepton to the proton, Q^2, accessible with this machine was as high as 100000 GeV^2. The two *ep* interaction regions were instrumented with the multi-purpose detectors of the H1 and ZEUS collider experiments. Over 15 years of data taking from 1992 to 2007, these two experiments together collected a total integrated luminosity of $\approx 1fb^{-1}$, about equally shared between positive and negative polarities and positive and negative longitudinal polarisations of the lepton beam.

This paper concentrates on recent developments related to the central topic of the HERA physics program - the measurements of the inclusive neutral current (NC) and charged current (CC) deep inelastic scattering (DIS) cross sections, determination of the proton structure and understanding of the data in terms of Quantum Chromodynamics (QCD). The ultimate goal for these measurements is to obtain one unique HERA data set, which averages the H1 and ZEUS results produced in different years with emphasis on different features of the apparatus. Recently the combination is performed for HERA I, the first phase of the HERA project from 1992 to 2000, for which both experiments completed and published final results. These combined data are analysed in the QCD framework, and the parton distribution functions (PDFs) in the proton are determined. At the end of the HERA data taking, special runs were performed with reduced energies of the proton beam of 460 and 575 GeV. Using these data the longitudinal structure function was measured in a model independent way.

2 Deep inelastic NC and CC *ep* scattering

The deep inelastic NC $e^{\pm}p$ scattering cross section with unpolarised beams can be expressed in the reduced form as

$$\tilde{\sigma}^{\pm}_{NC}(x,Q^2) = \frac{\mathrm{d}^2\sigma^{\pm}_{NC}}{\mathrm{d}x\mathrm{d}Q^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} = F_2(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2), \quad (1)$$

[a] e-mail: shekeln@mail.desy.de

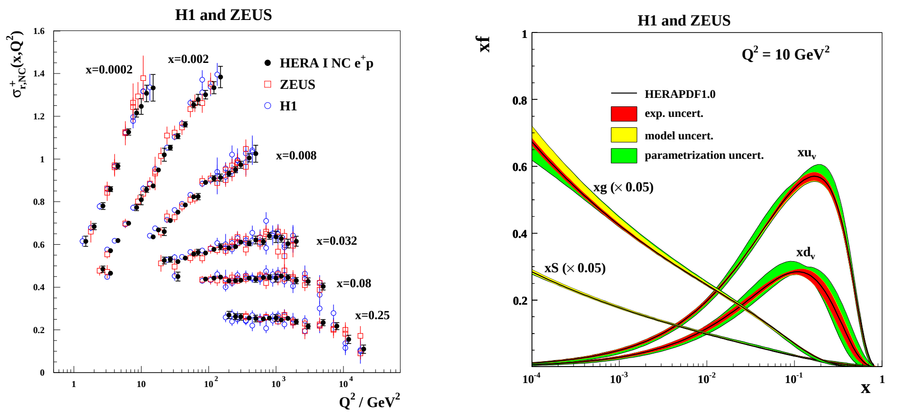


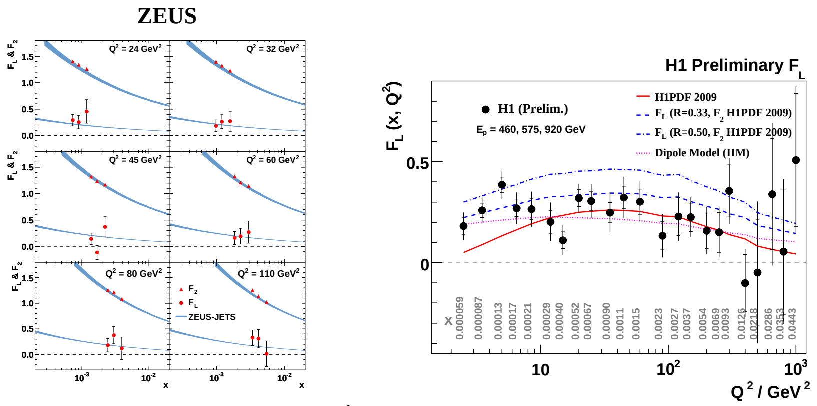
Figure 1: Left: Selection of combined NC e^+p reduced cross sections from HERA I compared to the separate H1 and ZEUS data input to the averaging procedure. Right: The parton distribution functions from HERAPDF1.0, $xu_v, xd_v, xS = 2x(\bar{U} + \bar{D})$ and xg, at $Q^2 = 10\ \text{GeV}^2$. The gluon and sea distributions are scaled down by a factor 20. The experimental, model and parametrisation uncertainties are shown separately.

where α is the fine structure constant, x is the Bjorken scaling variable, y characterises the inelasticity of the interaction and $Y_\pm = 1 \pm (1 - y^2)$. The NC cross section is dominated by the contribution of the proton structure function $F_2(x, Q^2)$. At leading order in QCD, F_2 is related to a linear combination of sums of the quark and anti-quark momentum distributions in the proton, and the structure function $xF_3(x, Q^2)$ is related to a linear combination of their differences. The longitudinal structure function F_L is equal to zero in the quark-parton model due to the spin one half nature of the quarks. Non-zero values of the longitudinal structure function appear in QCD due to gluon radiation.

The deep inelastic CC cross section can be expressed in a similar manner. The $W^\pm$-boson exchange in the charged current process distinguishes between the charges of the constituent quarks. So, for the electron (positron) beam the cross section depends on the $u(d)$ quark content of the proton.

3 Combination of the H1 and ZEUS inclusive data

The published H1 and ZEUS measurements on inclusive NC and CC reactions cover a wide range of x and Q^2. For NC the kinematic range is $6 \cdot 10^{-7} \leq x \leq 0.65$ and $0.045 \leq Q^2 \leq 30000\,\text{GeV}^2$, and for CC it is $1.3 \cdot 10^{-2} \leq x \leq 0.40$ and $300 \leq Q^2 \leq 30000\,\text{GeV}^2$. All published NC and CC cross section measurements from H1 and ZEUS obtained using data collected in the years 1994-2000 are



,

Figure 2: Left: F_2 and F_L as measured by ZEUS as a function of x at fixed values of Q^2. Right: The H1 measurement of $F_L(Q^2)$ averaged over x at fixed values of Q^2. The resulting x values of the averaged F_L are given in the figure for each point in Q^2.

combined [1] in one simultaneous minimisation. The resulting shifts of the correlated systematic uncertainties are propagated to both CC and NC data such that one coherent data set is obtained. This combined data set contains complete information on inclusive DIS cross sections measured by H1 and ZEUS at HERA I.

The data sets considered for the combination were taken with a proton beam energy of 820 and 920 GeV. Therefore, the data are corrected to a common centre of mass energy corresponding to $E_p = 920$ GeV and then averaged. The NC data for $y \geq 0.35$ are kept separate for the two proton beam energies.

The total integrated luminosity of the combined data set corresponds to about 200 pb^{-1} for e^+p and 30 pb^{-1} for e^-p. In total 1402 data points are combined to 741 cross section measurements. The data show good consistency, with $\chi^2/n_{\rm dof} = 636.5/656$. There are in total 110 sources of correlated systematic uncertainty. None of these systematic sources shifts by more than $2\,\sigma$ of the nominal value in the averaging procedure. The total uncertainty of the combined data set reaches 1% for NC scattering in the best measured region, $20 < Q^2 < 100$ GeV^2.

In Figure 1 (left) averaged NC data are compared to the input H1 and ZEUS data. Since H1 and ZEUS have employed different experimental techniques, using different detectors and methods of kinematic reconstruction, the combination leads to a significantly reduced correlated systematic uncertainty. This reduction propagates to all average points, including also those which are based solely on the measurement from one experiment.

4 QCD analysis of the combined data

The combined data set on the NC and CC e^+p and e^-p inclusive cross sections from HERA I is used as the sole input to a next-to-leading order (NLO) QCD PDF fit, called HERAPDF1.0 [1]. The consistency of the present input data justifies the use of the conventional χ^2 tolerance, $\Delta\chi^2 = 1$, when determining the experimental uncertainties of the fit.

The QCD predictions for the structure functions are obtained by solving the DGLAP evolution equations at NLO in the $\overline{\mathrm{MS}}$ scheme with the renormalisation and factorization scales chosen to be Q^2. The DGLAP equations yield the PDFs at all values of Q^2, if they are provided as functions of x at some input scale Q_0^2. This scale is chosen to be $Q_0^2 = 1.9$ GeV^2 such that the starting scale is below the charm mass threshold, $Q_0^2 < m_c^2$. The heavy quark coefficient functions are calculated in the general-mass variable-flavour-number scheme. The heavy quark masses are chosen to be $m_c = 1.4$ GeV and $m_b = 4.75$ GeV. The strong coupling constant is fixed to $\alpha_s = 0.1176$. A minimum Q^2 cut on the data of $Q^2_{min} = 3.5$ GeV^2 is imposed to remain in the kinematic region, where perturbative QCD should be applicable. PDFs are parametrised at the input scale by the generic form

$$xf(x) = Ax^B(1-x)^C(1+\epsilon\sqrt{x}+Dx+Ex^2). \qquad (2)$$

The parametrised PDFs are the gluon distribution xg, the valence quark distributions xu_v, xd_v, and the u-type and d-type anti-quark distributions $x\bar{U}$, $x\bar{D}$.

Figure 1 (right) shows a summary plot of the HERAPDF1.0 distributions at $Q^2 = 10$ GeV^2. The analysis yields small experimental uncertainties and makes an assessment of uncertainties introduced both by model assumptions and by assumptions about the form of the parametrisation. Due to the high precision of the combined data set, the parametrisation HERAPDF1.0 has total uncertainties at the level of a few percent at low x.

5 HERA results for $F_L(x, Q^2)$

A model independent measurement of the longitudinal structure function $F_L(x, Q^2)$ requires several sets of NC cross sections at fixed x and Q^2 but different y. This was achieved at HERA by variation of the proton beam energy. The measurements are performed using e^+p data collected in 2007 with a positron beam energy of 27.5 GeV and with three proton beam energies: the nominal energy of 920 GeV, the smallest energy of 460 GeV and an intermediate energy of 575 GeV.

According to eq. 1, the $F_L(x, Q^2)$ contribution to the reduced cross section is proportional to $f(y) = y^2/[1+(1-y)^2]$. Therefore, the F_L values are determined as the slopes of straight-line fits of the measured $\tilde{\sigma}_{NC}(x, Q^2, y)$ values as a function of the y-dependent factor $f(y)$. The ZEUS result for $F_L(x, Q^2)$ is shown in Figure 2 (left). The result is consistent with the expectation derived from the ZEUS-JETS QCD fit [3] to previous data. The H1 measurements of $F_L(x, Q^2)$ are averaged over x at fixed Q^2, and the resulting $F_L(Q^2)$ is shown in Figure 2 (right). The averaged F_L is compared with calculations based on the H1PDF 2009 fit [5]. For $Q^2 \geq 10\,\mathrm{GeV}^2$, the data are well described by the QCD predictions, whereas at lower Q^2 the QCD calculations underestimate the F_L data. Dipole models are found to describe the measurements. The F_L data are consistent with $R = F_L/(F_2 - F_L) = 0.25$.

6 Summary

Inclusive cross sections of NC and CC $e^{\pm}p$ scattering, measured by H1 and ZEUS at HERA I, are combined providing the most accurate data set with a total uncertainty which reaches 1% for NC in the bulk of the phase space.

A NLO QCD analysis is performed based exclusively on these combined cross section data. A new set of parton distribution functions, HERAPDF1.0, is obtained using a variable-flavour-number scheme. The parametrisation HERAPDF1.0 has total uncertainties at the level of a few percent at low x, which include experimental as well as model and parametrisation uncertainties.

The H1 and ZEUS collaborations measured the longitudinal proton structure function in DIS at low x. The $F_L(x, Q^2)$ values are determined from three sets of cross section measurements at fixed x and Q^2, but different inelasticity y, obtained using three different proton beam energies at HERA. For the $Q^2 \geq 10\,\mathrm{GeV}^2$, the F_L results are consistent with the QCD predictions. At lower Q^2 values the predictions underestimate the F_L measurements.

References

[1] H1 and ZEUS Collab., F.D. Aaron *et al.*, *JHEP01* 109 (2010).

[2] ZEUS Collab., S. Chekanov *et al.*, *Phys. Lett.* **B682** 8 (2009).

[3] ZEUS Collab., S. Chekanov *et al.*, *Eur. Phys. J.* **C42** 1 (2005).

[4] H1 Collab., F.D. Aaron *et al.*, *Phys. Lett.* **B665** 139 (2008);
H1 Collaboration, H1prelim-08-042, H1prelim-09-044,
`http://www-h1.desy.de/publications/H1preliminary.short_list.html`

[5] H1 Collab., C. Adloff *et al.*, *Eur. Phys. J.* **C30** 1 (2003).