Structure Functions at Very High Q^2 From HERA

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Abstract. Measurements of Deep-Inelastic Neutral and Charged current interactions are presented in lepton proton scattering at HERA. The measurements are obtained from taken during 1996 to 1999 and consists of $30\,\mathrm{pb}^{-1}$ of e^+p and $16\,\mathrm{pb}^{-1}$ of e^-p data. The addition of the new high statistics electron data with the positron data allows the first extraction of the parity violating structure function xF_3 and tests of high-Q^2 electroweak effects of the heavy bosons Z^0 and W are observed and found to be consistent with the Standard Model expectation.

INTRODUCTION

Deep–Inelastic scattering (DIS) of leptons off nucleons has played a fundamental role in understanding the structure of matter. HERA the first electron-proton (ep) collider ever built is capable of investigating the two main contributions to DIS, Neutral Current (NC) interactions, $ep \to eX$ and Charged Current (CC) interactions, $ep \to \nu X$. In the Standard Model a photon (γ) or a Z^0 boson is exchanged in a NC interaction, and a $W^\pm$ boson is exchanged in a CC interaction. DIS can be described by the four-momentum transfer squared Q^2, Bjorken-x and inelasticity y defined as:

$$Q^2 = -q^2 \equiv (k - k')^2 \quad (1)$$

$$x = \frac{Q^2}{2p \cdot q} \quad (2)$$

$$y = \frac{p \cdot q}{p \cdot k} \quad (3)$$

with $k(k')$ and p being the four-momentum of the incident (scattered) lepton and proton respectively. The centre-of-mass energy $\sqrt{s}$ of the ep interaction is given by $s \equiv (p + k)^2 = Q^2/xy$.

In this paper measurements are presented of the NC and CC cross-sections at high $Q^2 > 200\,\mathrm{GeV}^2$ for both electron and positron scattering from both the H1 and ZEUS experiments. The integrated luminosity in the e^+p data sample is $35.6\,\mathrm{pb}^{-1}$ ($30\,\mathrm{pb}^{-1}$) and in the e^-p data sample is $16\,\mathrm{pb}^{-1}$ ($16\,\mathrm{pb}^{-1}$) for the H1 (ZEUS) collaborations.

I EXPERIMENTAL SETUP

The H1 and ZEUS detectors are described elsewhere [1], [2]. Both detectors are nearly hermetic multi-purpose apparatus built to investigate ep interactions. The measurements in both experiments rely primarily on the calorimetry, tracking and the luminosity detectors.

In both experiments the Charged Current event selection is based on the observation of large P_T^{miss}, which is assumed to be the transverse momentum carried by the outgoing neutrino. For NC events it is based on the identification of a scattered electron (positron), further fiducial (NC) and kinematic cuts (CC and NC) are then applied. Details of the selection procedure can be found in [2,3].

II CROSS SECTIONS

The electroweak Born-level NC DIS cross section $d^2\sigma^{NC}/dxdQ^2$ for the reaction $e^{\pm}p \rightarrow e^{\pm}X$ can be written as:

$$\frac{d^2\sigma_{Born}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2(x,Q^2) \mp Y_-xF_3(x,Q^2) - y^2F_L(x,Q^2)\right] \tag{4}$$

For unpolarised beams, the structure functions F_2 and xF_3 can be decomposed taking into account Z^0 exchange as:

$$F_2 \equiv F_2^{em} - \upsilon\frac{\kappa_w Q^2}{(Q^2+M_Z^2)}F_2^{\gamma Z} + (\upsilon^2+a^2)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)F_2^Z \tag{5}$$

$$xF_3 \equiv -a\frac{\kappa_w Q^2}{(Q^2+M_Z^2)}xF_3^{\gamma Z} + (2\upsilon a)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z \tag{6}$$

where M_Z is the mass of the Z^0, $\kappa_w = 1/(4\sin^2\theta_w\cos^2\theta_w)$ is a function of the Weinberg angle (θ_w) and υ and a are the vector and axial couplings of the electron to the Z^0. For unpolarised beams, F_2 is the same for electron and positron scattering, while xF_3 changes sign.

The NC "reduced cross-section" $\tilde{\sigma}$ is defined from the measured as:

$$\tilde{\sigma}_{NC}(x,Q^2) \equiv \frac{1}{Y_+}\frac{xQ^4}{2\pi\alpha^2}\frac{d^2\sigma^{NC}}{dxdQ^2} \tag{7}$$

The Born double differential CC cross-section for $e^+p \rightarrow \overline{\nu}X$ can be written in leading order QCD as:

$$\left(\frac{d^2\sigma_{CC}^{e^+p}}{dxdQ^2}\right)_{Born} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 [(\bar{u}+\bar{c})+(1-y)^2(d+s)] \tag{8}$$

for e^-p scattering the coupling is predominantly to the u type quarks for e^+p scattering the electroweak coupling is predominantly to the d type quarks.

$$\left(\frac{d^2\sigma_{CC}^{e^-p}}{dxdQ^2}\right)_{Born} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 [u+c+(1-y)^2(\bar{d}+\bar{s})] \tag{9}$$

The double differential CC "reduced" cross-section $\tilde{\sigma}_{CC}$ is defined as:

$$\tilde{\sigma}_{CC} = \frac{2\pi x}{G_F^2}\left(\frac{M_W^2+Q^2}{M_W^2}\right)^2 \frac{d^2\sigma_{CC}}{dxdQ^2} \tag{10}$$

III RESULTS AND INTERPRETATION

The NC and CC single differential cross-sections and $d\sigma_{NC}/dQ^2$, $d\sigma_{CC}/dQ^2$ are shown in fig 1, also shown are the Standard Model expectations given from NLO QCD fits to the data by both the CTEQ [5] and the H1 [7] collaborations. The Standard Model is seen to give a good description of the data.

The measurement of he NC cross-section spans more than two orders of magnitude in Q^2 and the cross-section falls with Q^2 by about 6 orders of magnitude for both the e^+p and the e^-p cross section. For Q^2 values above $1000\,\mathrm{GeV}^2$ the e^-p cross section can be seen to be significantly above the e^+p cross section. This is consistent with the Standard Model picture in which one expects constructive interference of the photon and Z^0 for e^-p interactions and destructive interference for e^+p interactions.

Due to the propagator mass term and the different coupling the CC cross-section is smaller than the NC cross-section and it falls less steeply, by about 3 orders of magnitude, between $Q^2 = 300$ and $15\,000\,\mathrm{GeV}^2$ for both the e^-p and e^+p cross section. The shape and magnitude of the NC and CC cross-sections are well described by the Standard Model expectation. The e^-p cross section is at relatively low Q^2 to be approximately twice as big as the e^+p cross section, which is consistent with the Standard Model picture in which the u quark density probed is expected to be approximately twice the d quark density.

Shown in fig. 1 is the single differential CC cross section $d\sigma_{CC}/dx$ for $Q^2 > 200\,\mathrm{GeV}^2$ for e^+p scattering from the ZEUS collaboration [10]. The ratio of the measured cross section $d\sigma_{CC}/dx$. At high x the e^+p CC cross-section depends mainly on the d quark density which is less constrained than the u quark density. All data agree well with the Standard Model expectation using PDFs extracted from CTEQ4D and those from the ZEUS NLO fit [11]. The possibility of a larger d/u ratio than previously assumed has been of interest in recent years, for example

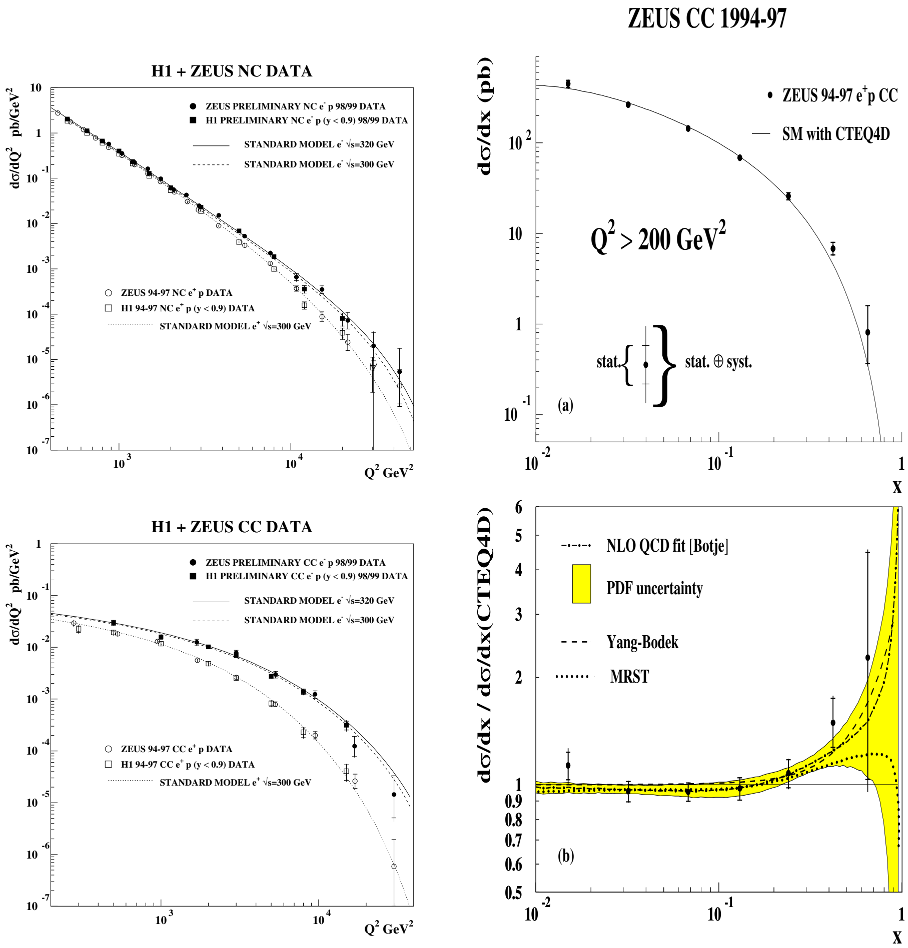

FIGURE 1. a) The high-Q^2 $e^{\pm}$ NC cross section $d\sigma_{e^{\pm}p}/dQ^2$ from the ZEUS and H1 collaborations along with the Standard Model predictions using the CTEQ4D parton momentum distributions. b)The high-Q^2 CC cross section $d\sigma_{e^{\pm}p}/dQ^2$ from the ZEUS and H1 collaborations along with the Standard Model predictions using the CTEQ4D parton momentum distributions. c) The ZEUS CC high-Q^2 structure function $d\sigma/dx$ with the Standard Model prediction using CTEQ4D. d) The ratio of the measured ZEUS CC high-Q^2 structure function $d\sigma/dx$ with the Standard Model prediction using CTEQ4D. Also shown are the predictions from Yang-Bodek and the ZEUS NLO QCD fit.

see [12,13]. Modification [12] of PDFs with an additional term $\delta(d/u)$ yields $d\sigma/dx$ close to the NLO QCD fit.

The NC cross-section $d\sigma_{NC}/dx$ for $Q^2 > 10\,000\,\mathrm{GeV}^2$ is shown in Fig. 2 along with the expectations from the Standard Model with a Z^0 mass of set to the PDG value, which gives a good description of the data. Also shown is the expectation from the Standard Model with Z^0 mass set to infinity, thereby effectively removing the weak interaction so that only photon (γ) exchange is possible. It can be seen the data clearly favours the need for the Z^0 contribution.

IV DOUBLE DIFFERENTIAL NC AND CC CROSS-SECTIONS

The double differential reduced NC cross-section is shown in Fig. 2 for fixed x as a function of Q^2 for both e^+ and e^- data. Also shown are the expectations of the Standard Model which give a good description of the data. For Q^2 values below $1\,000\,\mathrm{GeV}^2$ the e^+ and e^- cross-sections are within errors equal, for higher values of Q^2 the cross sections are seen to deviate, with the e^-p cross-section seen to increase above the e^+p cross section. This difference is consistent with the change in sign of the parity violating structure function xF_3.

The ZEUS collaboration go a step further and combine the e^+ and e^- cross sections, where $30\,\mathrm{pb}^{-1}$ of e^+p data collected at a centre of mass energy of $\sqrt{s} = 300\,\mathrm{GeV}$ were combined with $16\,\mathrm{pb}^{-1}$ of e^+p data collected at a centre of mass energy of $\sqrt{s} = 300\,\mathrm{GeV}$. To reduce statistical fluctuations several bins from the double differential binning [9]. Figure 2 shows xF_3 at fixed values of Q^2 as a function of x. The Standard Model expectation evaluated with either the CTEQ4D or MRST(99) [6] parton density functions are seen to give a good description of the data.

The reduced cross sections as functions of x and Q^2 are displayed in Figs. 2 along with the prediction of the H1 NLO QCD fit [7]. The relative increase in the e^-p cross section over the e^+p cross section is consistent with a larger u quark density relative to that of the d quark.

The absolute magnitude of the CC cross section, described by equation 8 is determined by the Fermi constant G_F and the PDFs, while the Q^2 dependance of the CC cross-section includes the propagator term $[M_W^2/(M_W^2 + Q^2)]$ which produces substantial damping of the cross section. The ZEUS collabiration have fitted the measured differential cross section, $d\sigma/dQ^2$, treating G_F and M_W as free parameters, yields

$$G_F = (1.171 \pm 0.034((\mathrm{stat.})^{+0.026}_{-0.015}(\mathrm{syst.})^{+0.016}_{-0.015}(\mathrm{PDF})) \times 10^{-5}\,\mathrm{GeV}^{-2} \qquad (11)$$

and

$$M_W = 80.8^{+4.9}_{-4.5}(stat.)^{+5.0}_{-4.3}(syst.)^{+1.4}_{-1.3}(PDF)\,\mathrm{GeV} \qquad (12)$$

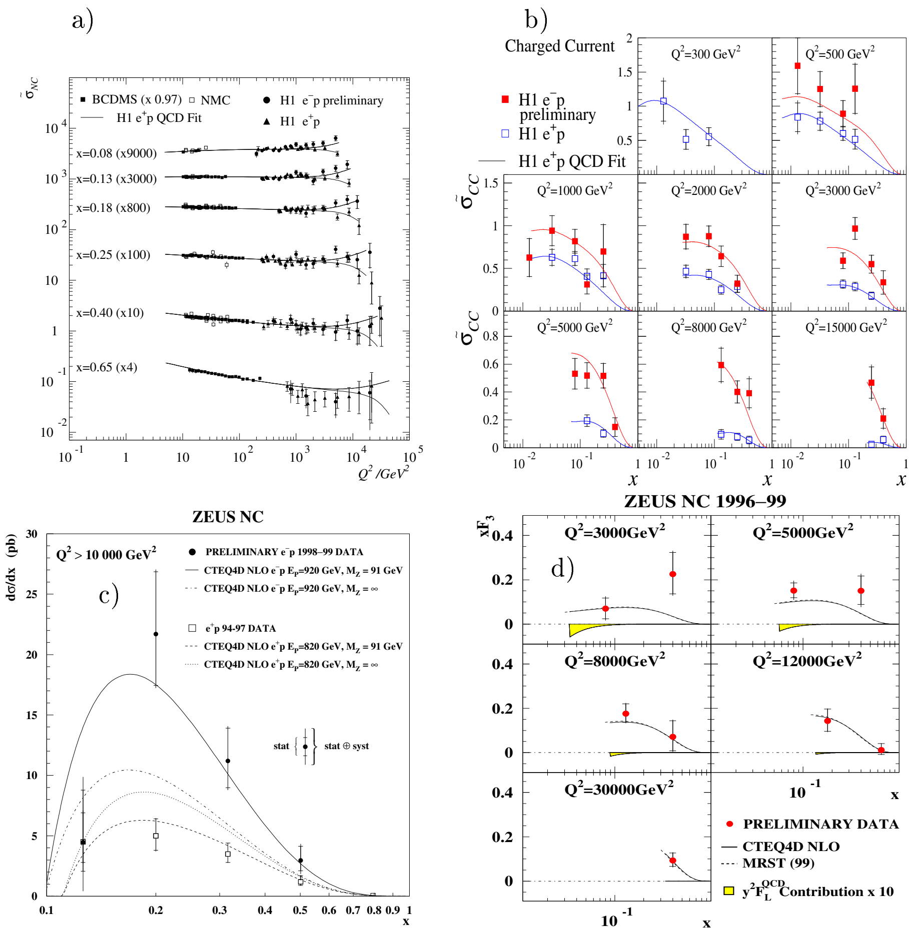

FIGURE 2. a) The high-Q^2 NC e^-p (circles) e^+p (triangles) reduced cross sections $d^2\sigma_{e^\pm p}/dxdQ^2$ from the H1 collaboration along with the Standard Model predictions from the H1 NLO QCD fit. b)The high-Q^2 CC reduced cross section $\tilde{\sigma}_{CC}$ from the ZEUS and H1 collaborations along with the Standard Model predictions using the CTEQ4D parton momentum distributions. c) The high-Q^2 $e^\pm p$ cross section $d\sigma_{e^\pm p}/dx$ and the Standard Model predictions using the CTEQ4D PDFs for $Q^2 > 10\,000\,\mathrm{GeV}^2$. Also shown are the theoretical predictions without the weak interaction were absent ($M_Z = \mathrm{inf}$). d) The Structure function xF_3, extracted by the ZEUS collaboration. the data were obtained from the 1998/99 e^-p data set recorded at $\sqrt{s} = 318\,\mathrm{GeV}$ and the e^+p data set taken $\sqrt{s} = 300\,\mathrm{GeV}$, plotted at fixed Q^2 between $3\,000\,\mathrm{GeV}^2$ and $30\,000\,\mathrm{GeV}^2$ as a function of x together with the Standard Model predictions using the CTEQ4D and MRST(99) PDFs.

The central values are obtained using the CTEQ4D PDFs. Further fits to the data were also performed [10], the 'propagator-mass' fit to the measured differential cross-section, $d\sigma/dQ^2$, with G_F fixed to the value $G_F = 1.16639 \times 10^{-5}\,\mathrm{GeV}^{-2}$ yields the result

$$M_W = 81.4^{+2.7}_{-2.6}(stat.) \pm 2.0(syst.)^{+3.3}_{-3.0}(PDF)\,\mathrm{GeV} \tag{13}$$

Using the Standard Model constraint α, M_Z, and all fermion masses, other than the mass of the top quark, M_t, are set to the PDG values [4]. The central result of the fit was obtained with $M_t = 175\,\mathrm{GeV}$ and the mass of the Higgs boson $M_H = 100\,\mathrm{GeV}$. The χ^2 function is evaluated along the line given by the SM constraint, gives the following result.

$$M_W = 80.50^{+0.24}_{-0.25}(stat.)^{+0.13}_{-0.16}(syst.) \pm 0.31(PDF)^{+0.03}_{-0.06}(\Delta M_t, \Delta M_H, \Delta M_Z)\,\mathrm{GeV} \tag{14}$$

V HERA UPGRADE

From September 2000, the luminosity of the HERA collider will be increased by a factor of five. At the same time longitudinal lepton beam polarisation will be provided for the collider experiments H1 and ZEUS. Over a six year running period it is anticipated that the total luminosity of $1\,000\,\mathrm{pb}^{-1}$ will be delivered. This large data volume will allow F_2^{NC} to be extracted with an accuracy of 3% over the kinematic range $2 \times 10^{-5} < x < 0.7$ and $2 \times 10^{-5} < Q^2 < 5 \times 10^4\,\mathrm{GeV}^2$. With this accuracy it is anticipated that it will be possible to determine α_S from the scaling violations of F_2^{NC} with a precision of < 0.003. The gluon distribution will also be determined from such a fit with a precision of 3% for $x = 10^{-4}$ and $Q^2 = 20\,\mathrm{GeV}^2$.

There will also be a significant benefit to the CC cross-section measurement, with the potential of a clean determination of the u and d quark densities.

With the introduction of polarised beams it will be possible to obtain a measurement of the vector and axial-vector couplings of the u-quark, ν_u and a_u respectively, obtained in a fit in which ν_u and a_u are allowed to vary. With a luminosity of $250\,\mathrm{pb}^{-1}$ per charge, polarisation combination and taking the vector and axial-vector couplings of the u and d-quarks as free parameters gives a precision of 13 %, 6 %, 17 % for ν_u, a_u, ν_d and a_d respectively. By comparing the NC couplings of the c and b-quarks obtained at LEP, it will be possible to test the universality of the NC couplings.

VI SUMMARY AND OUTLOOK

The latest Deep-Inelastic Neutral and Charge current cross-sections have been presented from the H1 and ZEUS experiments. The Standard Model is seen to give a good description of the data in all cases. The high luminosity data at high Q^2 from both experiments has enabled the first tests of electroweak effects in both Neutral and Charged current interactions. In NC interactions the data are seen to be consistent with the effect of γZ° interference and has allowed the first extraction of the parity violating structure function xF_3 at high Q^2.

With the factor of five increase in yearly luminosity expected from the HERA upgrade further high precision tests of the Strong and Weak Interaction will be made. The future CC measurements will allow precision determinations of the u and d quark densities and a determination of the vector and axial-vector couplings of the quarks from the NC interaction, providing important information for future high energy hadron colliders such as the LHC.

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