DEEP INELASTIC SCATTERING AT HIGH Q^2

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Measurements of the cross sections for charged and neutral current deep inelastic scattering at HERA are presented. Comparing data from electron-proton and positron-proton collisions highlights the effect of the exchange of Z^0 and W bosons at high Q^2. The structure function xF_3^{NC} is extracted from the measured neutral current cross sections and found to be in agreement with the Standard Model expectation.

1 Introduction

Deep inelastic scattering (DIS) of leptons off nucleons probes the structure of matter at small distance scales. Two types of DIS interactions are possible at HERA: the neutral current (NC) reactions $e^-p \to e^-X$ and $e^+p \to e^+X$, where a photon or Z^0 boson is exchanged and the charged current (CC) interactions $e^-p \to \nu X$ and $e^+p \to \bar{\nu}X$, where a $W^\pm$ boson is exchanged.

The HERA accelerator collides electrons or positrons with protons. In the years 1994 to 1997 HERA collided positrons of energy 27.5 GeV with protons of energy 820 GeV , giving collisions at a centre of mass energy of 300 GeV. In this period the ZEUS and H1 detectors collected data samples with integrated luminosities of 47.7 pb^{-1} and 35.6 pb^{-1}, respectively. In 1998 and early 1999 HERA collided electrons of energy 27.5 GeV with protons of energy 920 GeV, giving collisions at a centre of mass energy of 320 GeV. In this period the ZEUS and H1 detectors collected data samples with integrated luminosities of 16.4 pb^{-1}. In addition measurements from the H1 collaboration based on 45.9 pb^{-1} of positron-proton collision data collected in 1999 and 2000 are presented.

The kinematics of charged current and neutral current deep inelastic scattering processes are defined by the four-momenta of the incoming lepton (k), the incoming proton (P), the outgoing lepton (k') and the hadronic final state (P'). The four-momentum transfer between the electron and the proton is given by $q = k - k' = P' - P$. The square of the energy in the centre of mass frame is given by $s = (k + P)^2$. The description of DIS is usually given in terms of three Lorentz invariant quantities, which may be defined in terms of the four-momenta k, P and q:

- $Q^2 = -q^2$, the negative square of the four-momentum transfer,
- $x = \frac{Q^2}{2p \cdot q}$, the Bjorken scaling variable,
- $y = \frac{q \cdot P}{k \cdot P}$, the fraction of the energy transferred to the proton in its rest frame.

These variables are related by $Q^2 = xys$, when the masses of the particles can be neglected.

Measurements of the neutral and charged current deep inelastic scattering cross sections are presented as functions of x and Q^2, in the kinematic region $Q^2 > 200\text{GeV}^2$.

2 Experimental setup

The ZEUS and H1 detectors are described in detail elsewhere[1,2]. The measurements presented make use primarily of the calorimeters, tracking detectors and luminosity measurement detectors. Selection of neutral current DIS events is based on the identification of a scattered electron or positron. The primary signature of charged current DIS events is missing transverse momentum from the final-state neutrino, which escapes undetected.

3 Cross sections

The double-differential Born-level cross section for the neutral current deep inelastic scattering processes $e^-p \rightarrow e^-X$ and $e^+p \rightarrow e^+X$, with unpolarised beams, is given by:

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

where $Y_{\pm} = 1 \pm (1-y)^2$, and α is the QED coupling constant. The neutral current structure functions in the quark parton model, where $F_L^{NC}(x,Q^2) = 0$, are given by:

$$F_2^{NC}(x,Q^2) = \frac{1}{2}\sum_q [(V_q^L)^2 + (V_q^R)^2 + (A_q^L)^2 + (A_q^R)^2][xq(x,Q^2) + x\bar{q}(x,Q^2)] \tag{2}$$

$$xF_3^{NC}(x,Q^2) = \sum_q [V_q^L A_q^L - V_q^R A_q^R][xq(x,Q^2) - x\bar{q}(x,Q^2)] \tag{3}$$

where the sums run over all quarks, q, in the proton. The structure function xF_3^{NC} has contributions from the interference between the photon and Z^0 exchange amplitudes, and pure Z^0 exchange, and violates parity. The functions V_q and A_q contain the couplings of the electron to the photon and Z^0. The NC reduced cross section, $\tilde{\sigma}_{NC}$, is defined to be:

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

The double-differential Born-level cross section for the unpolarised charged current deep inelastic scattering processes $e^-p \to \nu X$ and $e^+p \to \bar{\nu}X$ are given by:

$$\frac{d^2\sigma_{Born}^{CC}(e^-p)}{dxdQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2+M_W^2)^2} [(u+c) + (1-y)^2(\bar{d}+\bar{s})] \tag{5}$$

$$\frac{d^2\sigma_{Born}^{CC}(e^+p)}{dxdQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2+M_W^2)^2} [(\bar{u}+\bar{c}) + (1-y)^2(d+s)] \tag{6}$$

where M_W is the mass of the W boson and G_F is the Fermi constant. The CC reduced cross section, $\tilde{\sigma}_{CC}$, is defined to be:

$$\tilde{\sigma}_{CC} = \frac{2\pi}{G_F^2} \left(\frac{Q^2+M_W^2}{M_W^2} \right)^2 \frac{d^2\sigma_{Born}^{CC}}{dxdQ^2} \tag{7}$$

4 Results and interpretation

Figure 1 (left) shows the single-differential cross sections $d\sigma/dQ^2$ for NC and CC DIS in both e^+p and e^-p scattering, measured by the H1 collaboration[10,8,9]. The measurements are well described by the Standard Model evaluated using the NLO QCD fit from the H1 collaboration[10] to their e^+p data only. The NC cross sections fall approximately six orders of magnitude over the Q^2 range 200 GeV^2 to 30000 GeV^2. At the higher end of the Q^2 range it can be seen that the cross section for e^-p scattering is higher than that for e^+p. The Standard Model predicts a higher cross section for

e^-p interactions, due to constructive interference between the photon and Z^0 exchange amplitudes, compared to e^+p interactions where destructive interference is expected. The cross sections for CC DIS are lower than those for NC DIS and fall less steeply due to the propagator mass term. It can be seen that the CC DIS cross section for e^-p scattering is significantly higher than that for e^+p interactions. This is expected from the cross section formulae in which e^-p scattering is dominated by the u quark density and e^+p interactions probe the smaller d quark density and are suppressed by a factor of $(1-y)^2$. Shown in figure 1 (right) are the reduced NC cross sections for e^+p and e^-p scattering, measured by the ZEUS collaboration[6]. The cross sections are plotted at fixed values of x as functions of Q^2, and are well described by the Standard Model evaluated with either CTEQ4D[3] or MRST(99)[4] parton density functions (PDFs). The effects of interference between photon and Z^0 exchange amplitudes can clearly be seen at higher values of Q^2 where the cross section for e^-p scattering is higher than that for e^+p interactions.

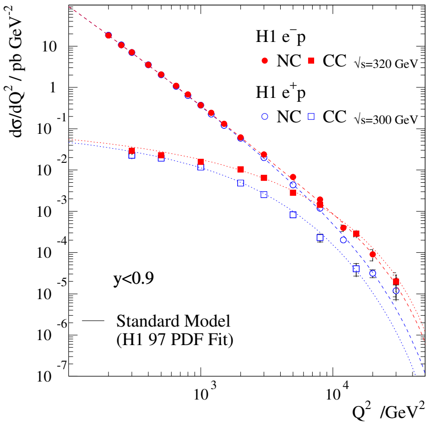
The NC cross sections for e^-p and e^+p scattering can be combined to extract the structure function xF_3^{NC}. Figure 2 shows the structure function xF_3^{NC} extracted by the ZEUS[6] and H1[8] collaborations. Both are shown at fixed values of Q^2 as functions of x, and are found to be well described by the Standard Model prediction.

Figure 3 (left) shows the reduced cross section for charged current e^+p interactions at fixed values of Q^2 as a function of x measured by the ZEUS collaboration[7]. It can be seen that the data are well described by the Standard Model. At low Q^2 and low x it can be seen from the dashed and dotted lines, which show the contributions from the valence and sea quarks, that the measurements are sensitive to the sea quark distribution. Figure 3 (right) shows the extracted values of the u and d valence quark distributions from the H1 collaboration[9], as a function of Q^2 at fixed values of x. The extracted quark densities are compared with the Standard Model prediction evaluated using the CTEQ5M, MRST and H1 NLO QCD fit PDFs.

5 Summary and future prospects

Cross sections for neutral and charged current deep inelastic scattering interactions have been presented by the H1 and ZEUS collaborations. In all cases the Standard Model gives a good description of the data. In the neutral current case the data at high Q^2 are consistent with the effects of interference between processes where a photon is exchanged and a Z^0 is exchanged. The structure function xF_3^{NC} has been extracted for the first time at HERA.

The HERA upgrade programme is scheduled to provide a factor of five



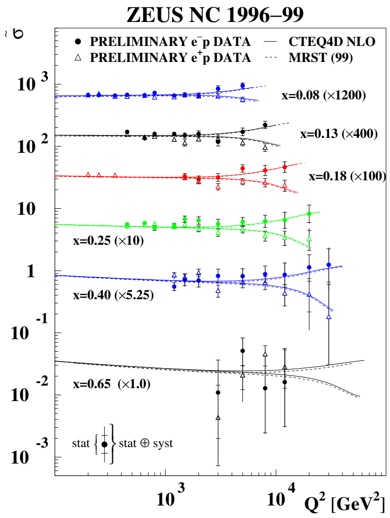


Figure 1. The cross section $d\sigma/dQ^2$ is shown (left) for NC (circles) and CC (squares) DIS interactions for both e^+p (open symbols) and e^-p (filled symbols) scattering from the H1 collaboration. ZEUS collaboration measurements of the NC reduced cross section for e^+p (open triangles) and e^-p (filled circles) are shown (right), at values of fixed x as functions of Q^2. Also shown are the Standard Model predictions evaluated using the CTEQ4D and MRST(99) parameterisations of the parton density functions.

increase in luminosity and longitudinally polarised lepton beams towards the end of 2001. The precision of NC and CC DIS cross section measurements will benefit from the large volume of data. In particular determination of the u and d quark densities at high Q^2 and at high x from the CC DIS cross sections will be possible with much improved accuracy and in the case of NC DIS, fits to determine the gluon density distribution and the value of the strong coupling constant, α_S, will achieve a higher precision than currently possible. The introduction of longitudinally polarised lepton beams for the H1 and ZEUS experiments will allow the investigation of the chiral nature of the Standard Model. Searches for right-handed charged currents and the determination of the vector and axial-vector couplings to the u and d quarks will be among the measurements possible at high Q^2 with high luminosity and longitudinally polarised lepton beams.

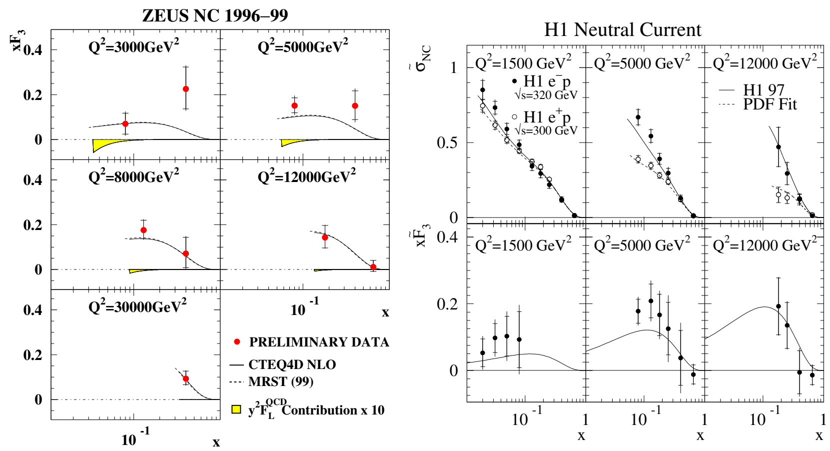


Figure 2. The structure function xF_3^{NC} extracted by the ZEUS collaboration (left), plotted at fixed values of Q^2 between 3000 GeV^2 and 30000 GeV^2 as a function of x. Also shown are the Standard Model predictions evaluated using the CTEQ4D and MRST(99) parameterisations of the parton density functions. The H1 collaboration measurements (right) illustrate the extraction of xF_3^{NC}. The upper half of the diagram shows the reduced NC cross sections for e^+p (open circles) and e^-p (filled circles) at fixed values of Q^2 from 1500 GeV^2 to 12000 GeV^2 as functions of x. The lower half shows the xF_3^{NC} extracted from the cross section measurements. The measurements are compared to the Standard Model predictions evaluated using PDFs from the H1 QCD fit.

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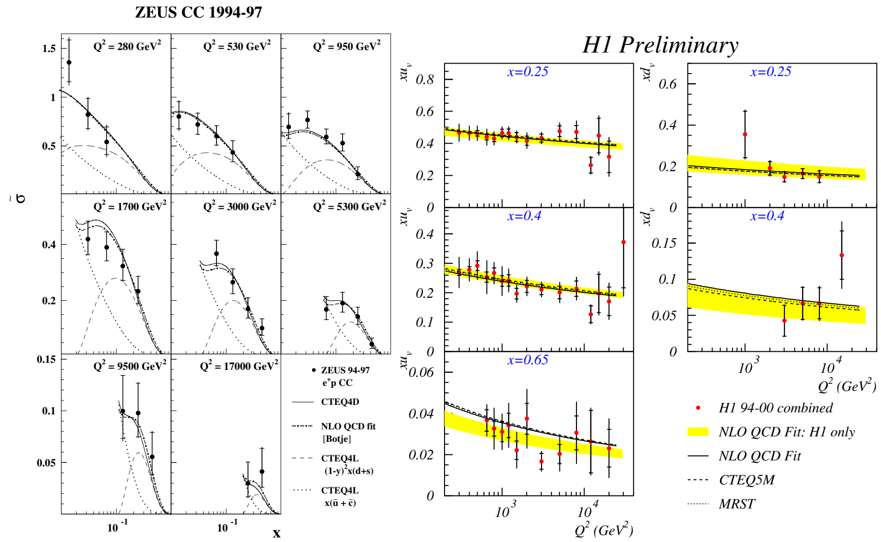

Figure 3. The reduced CC cross section, $\tilde{\sigma}_{CC}$, for e^+p scattering measured by the ZEUS collaboration (left), plotted at fixed values of Q^2 as a function of x. The ZEUS data are confronted with the Standard Model prediction evaluated using the CTEQ4D PDFs and ZEUS NLO QCD fit predictions. The values of the u and d valence quark densities extracted by the H1 collaboration are shown (right) for fixed values of x as a function of Q^2. The extracted quark densities are compared with the Standard Model prediction evaluated using the CTEQ5M, MRST and H1 NLO QCD fit PDFs.

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