Electroweak Measurements at High Q^2 at HERA.

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Over 15 years of data taking at the HERA ep collider the H1 and ZEUS experiments collected together about 1 fb^{-1} of neutral and charge current deep inelastic scattering data at an ep center-of-mass energy of 320 GeV. This allowed to determine the parton distribution functions in the proton and study electroweak effects using data at high four momentum transfer squared, Q^2, where the $W^{\pm}$ and Z^0 boson exchange contributes significantly to the cross section.

1 Introduction.

At HERA 27.6 GeV leptons (electrons and positrons) were collided with the 920 GeV protons (820 GeV till 1997), leading to an ep center-of-mass energy of 320 GeV. Therefore the HERA facility with the two collider experiments H1 and ZEUS offers the unique possibility to probe the structure of the proton down to distances of about 10^{-18} m.

The dominant contribution to the neutral current (NC) deep-inelastic ep scattering (DIS) at low four-momentum transfer squared, Q^2, is due to photon exchange between the incoming lepton and a quark in the proton. At high Q^2 the contributions to the NC and charged current (CC) processes due to the exchange of a massive vector boson, Z^0 and $W^{\pm}$ become important, allowing the investigation of electroweak (EW) effects in lepton-proton reactions.

Over 15 years of data taking from 1992 to 2007, the H1 and ZEUS experiments collected together a total integrated luminosity of about 1 fb^{-1}. The NC and CC cross sections measured by H1 and ZEUS using data collected from 1992 to 2000 (HERA-I) [1, 2, 3] have been combined into one averaged data set and analyzed in terms of QCD, providing a set of parton distribution functions (PDF) in the proton, HERAPDF 1.0 [4].

During the second phase of the HERA program (2003-2007) the amount of the collected luminosity was increased by a factor of 2 for e^+p and by a factor of 9 for e^-p. In addition spin rotators installed in the beam pipe provided the longitudinal polarization of the lepton beam in the H1 and ZEUS ep interaction regions.

This paper concentrates on the investigation of EW effects in NC [7, 8] and CC [9, 10] reactions using data with longitudinally polarized lepton beam from HERA-II and combined unpolarized data from HERA-I and HERA-II.

2 The Neutral Current Cross Section.

The Born cross section [5, 6] of the NC DIS reaction $e^{\pm}p \to e^{\pm}X$ can be written as

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(\tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{y_+}\tilde{F}_L\right) \equiv \frac{2\pi\alpha^2 Y_+}{xQ^4}\cdot\tilde{\sigma}^{\pm}_{NC}(x,Q^2) \qquad (1)$$

where α is the fine structure constant and the functions $Y_{\pm} = 1 \pm (1-y)^2$ describe the helicity dependence of the electroweak interactions. The "$\pm$" sign corresponds to the $e^{\pm}p$ scattering. Eq. 1 defines the reduced NC cross section $\tilde{\sigma}^{\pm}_{NC}$ which is a combination of the structure functions $\tilde{F}_2$, $x\tilde{F}_3$ and $\tilde{F}_L$.

The generalized proton structure functions $\tilde{F}_{2,3}$ may be written as a linear combination of the structure functions F_2, $F^{\gamma Z}_{2,3}$, and $F^{Z}_{2,3}$ containing information on the parton dynamics as well as on the EW couplings of the quarks to the neutral vector bosons.

$$\tilde{F}^{\pm}_2 = F_2 - (v_e \pm P_e a_e)\kappa\frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z} + (v_e^2 + a_2^2 \pm P_e 2v_e a_e)\kappa^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z \qquad (2)$$

$$x\tilde{F}^{\pm}_3 = -(a_e \pm P_e v_e)\kappa\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + (2a_e v_e \pm P_e\left[v_e^2 + a_e^2\right])\kappa^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z \qquad (3)$$

The function F_2 is associated with the pure photon exchange, $F^{\gamma Z}_{2,3}$ correspond to γZ^0 interference and $F^{Z}_{2,3}$ correspond to the the pure Z^0 exchange. In addition the longitudinal structure function $\tilde{F}_L$ may be similarly decomposed, however this contribution is important only at high y and is expected to be negligible at large x and Q^2. In Eq. 2, 3 $\kappa^{-1} = 4\frac{M_W^2}{M_Z^2}(1-\frac{M_W^2}{M_Z^2})$ in the on-mass shell scheme, M_W and M_Z are the weak vector boson masses. The longitudinal polarization is defined as $P_e = (N_R - N_L)/(N_R + N_L)$, where $N_R(N_L)$ is the number of right (left) handed leptons in the beam.

In the quark parton model (QPM), the hadronic structure functions are related to linear combinations of sums and differences of the quark and anti-quark momentum distributions $xq(x,Q^2)$ and $x\bar{q}(x,Q^2)$

$$\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q\left[e_q^2, 2e_q v_q, v_q^2 + a_q^2\right](q+\bar{q}),\ \left[xF_3^{\gamma Z}, xF_3^Z\right] = 2x\sum_q\left[e_q a_q, v_q a_q\right](q-\bar{q}) \quad (4)$$

where v_q and a_q are the vector and axial-vector couplings of the light quarks and e_q is the charge of the quark of flavor q.

Longitudinally polarized lepton beams allow to measure polarization effects related to the chiral structure of the neutral electroweak exchange. The polarization asymmetry, A, defined as

$$A(e^{\pm}p) \equiv \frac{2}{P_R - P_L}\frac{\sigma^{\pm}_{NC}(P_R) - \sigma^{\pm}_{NC}(P_L)}{\sigma^{\pm}_{NC}(P_R) + \sigma^{\pm}_{NC}(P_L)} \approx \mp\kappa a_e\frac{F_2^{\gamma Z}}{F_2} \approx \pm\kappa\frac{1+d_v/u_v}{4+d_v/u_v}. \qquad (5)$$

is to a very good approximation proportional to the structure functions ratio $(F_2^{\gamma Z}/F_2)$. At large x the asymmetry is related to d/u ratio of the valence quark distribution.

The polarization asymmetry is determined using the polarized cross sections measured at HERA-II. The H1 results are shown in Fig. 1 in comparison with the Standard Model (SM) expectation based on the H1 PDF 2009 fit. The measured asymmetry is about zero at low Q^2 and significantly above (below) zero for e^+p (e^-p) as expected in SM.

The polarized $e^+p(e^-p)$ data sets from HERA-II were merged to obtain the unpolarized cross sections for the $e^+p(e^-p)$ processes after a small correction for a residual polarization.

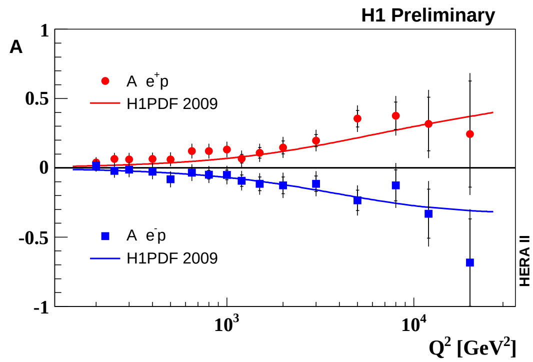

Figure 1: The Q^2 dependence of the polarization asymmetry for $e^{\pm}p$ interactions as measured in the H1 experiment in comparison with the SM prediction based on H1 PDF 2009 fit.

The unpolarized cross sections from HERA-II were combined then with the HERA-I results to improve the precision of the measurement. The $e^{\pm}p$ cross sections measured by ZEUS are shown in Fig. 2a for $Q^2 > 3000$ GeV ^{2}. At relatively small values of the Q^2 the e^-p cross section is found to be in agreement with the e^+p measurements as is expected for a solely electromagnetic interaction. At larger values of Q^2, however, the e^-p data lie at low x generally above the e^+p results. This is due to a positive (negative) contribution from xF_3 to the e^-p (e^+p) cross section as given in Eq. 1.

The structure function $x\tilde{F}_3$ can be obtained using the equation

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left[\tilde{\sigma}^-(x,Q^2) - \tilde{\sigma}^+(x,Q^2)\right] \approx xF_3^{\gamma Z}\frac{a_e \kappa Q^2}{(Q^2+M_Z^2)} \tag{6}$$

From Eq. 3 one can see that the dominant contribution to $x\tilde{F}_3$ arises from the γZ interference term, since the pure Z exchange term is suppressed by $\kappa[Q^2/(Q^2+M_Z^2)]^2$ and, in the case of unpolarized scattering, by the small vector coupling v_e.

Since the dependence of the non-singlet structure function $xF_3^{\gamma Z}$ on Q^2 is weak, the data obtained at different Q^2 are transformed to one Q^2 value at 1500 GeV^2 for H1 experiment and then averaged. This averaging allows to improve the statistical precision of the measurement. The averaged $xF_3^{\gamma Z}$ is shown in Fig. 2b. It is directly sensitive to the valence quark distributions. The SM prediction using H1 PDF 2009 and HERAPDF 1.0 is also shown and found to be in a good agreement in both shape and magnitude with the data.

3 The Charged Current Cross Section.

Similarly to the NC cross section, the electroweak Born level CC cross section [6] for the collision of polarized leptons with unpolarized protons can be expressed as

$$\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} = (1-P_e)\frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2\left(Y_+\tilde{W}_2^{\pm} - Y_{\mp}x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right) \equiv \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\tilde{\sigma}_{CC}(e^{\pm}p) \tag{7}$$

G_F is the Fermi constant, $\tilde{W}_2^{\pm}$, $x\tilde{W}_3^{\pm}$ and $\tilde{W}_L^{\pm}$ are CC structure functions for $e^{\pm}p$ scattering and $\tilde{\sigma}_{CC}(e^{\pm}p)$ is the reduced cross section.

In the QPM, where $W_L^{\pm} \equiv 0$, the reduced cross section for the $e^{\pm}p$ CC process may be expressed as the sum and difference of the quark and anti-quark momentum distributions, $xq(x,Q^2)$ and $x\bar{q}(x,Q^2)$:

$$\tilde{\sigma}_{CC}(e^-p) = (xu + xc) + (1-y)^2(x\bar{d} + x\bar{s}) \tag{8}$$

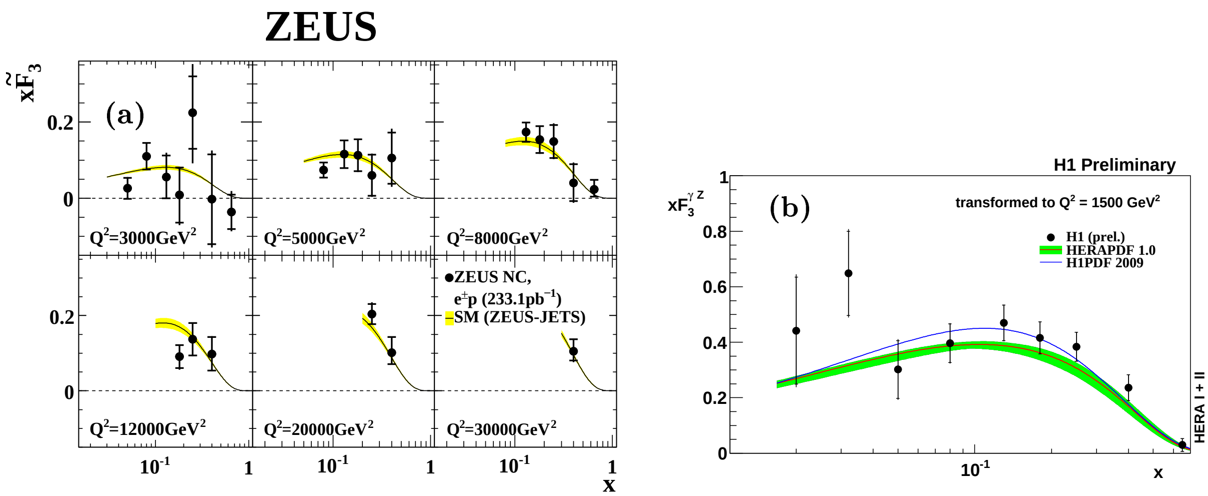

Figure 2: **(a)** The unpolarized $e^{\pm}p$ NC cross section measurements by ZEUS for Q^2 above 3000 GeV^2 compared with the Standard Model expectation from ZEUS-JETS. **(b)** The structure function $xF_3^{\gamma Z}$ extracted from all HERA data by H1 experiment shown together with the theory prediction based on H1 PDF 2009 (solid curve) and HERAPDF 1.0 (shaded band).

$$\tilde{\sigma}_{CC}(e^+p) = (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs) \tag{9}$$

The total CC cross section, σ_{CC}^{tot}, was measured by H1 and ZEUS as an integrated cross section in the kinematic region $Q^2 > 400$ GeV^2 and $y < 0.9$ using polarized data from HERA-II and unpolarized data from HERA-I. The results are shown in Fig. 3a compared to the SM expectation using HERAPDF 1.0. The data exhibit a clear linear polarization dependence of the cross section consistent with the absence of the right handed charged currents, such that the extrapolated cross section is zero for a fully right handed electron beam, $P_e = 1$, or a fully left handed positron beam.

To obtain unpolarized cross section measurements, the left and right handed $e^{\pm}p$ samples were combined into unpolarized data sets, correcting for small residual polarization. The resulting $e^{\pm}p$ cross sections for the H1 experiment were combined with the HERA-I measurement.

The single differential unpolarized cross section for CC together with the single differential NC cross section is shown in Fig 3b. The measurements are compared with the theoretical expectation from HERAPDF 1.0. At low Q^2 the NC cross section is larger than the CC cross section by two orders of magnitude. Approaching the mass of the Z and W bosons, the NC and CC processes cross sections become of the same magnitude demonstrating an unification of the electroweak interactions.

4 The Electroweak Fit.

The NC and CC double differential cross sections measurements allow the determination of the parton densities together with the electroweak parameters. According to Eq. 3 the NC cross section at high Q^2 depends on the weak vector v_q and axial-vector a_q couplings of up- and down-type quarks ($q = u, d$) to the Z boson via structure functions. The longitudinal polarized electron beam at HERA-II provides additional sensitivity on the quark couplings (see Eq. 2, Eq. 3).

The results of the EW fits[11, 12] to the quark couplings from the H1 and ZEUS experiments are shown in Fig. 4a for the u quark and Fig. 4b for the d quark and compared with similar results obtained by the CDF experiment [13] and combined LEP experiments [14]. The HERA determination has smaller uncertainties than the CDF result in particular for the u quark.

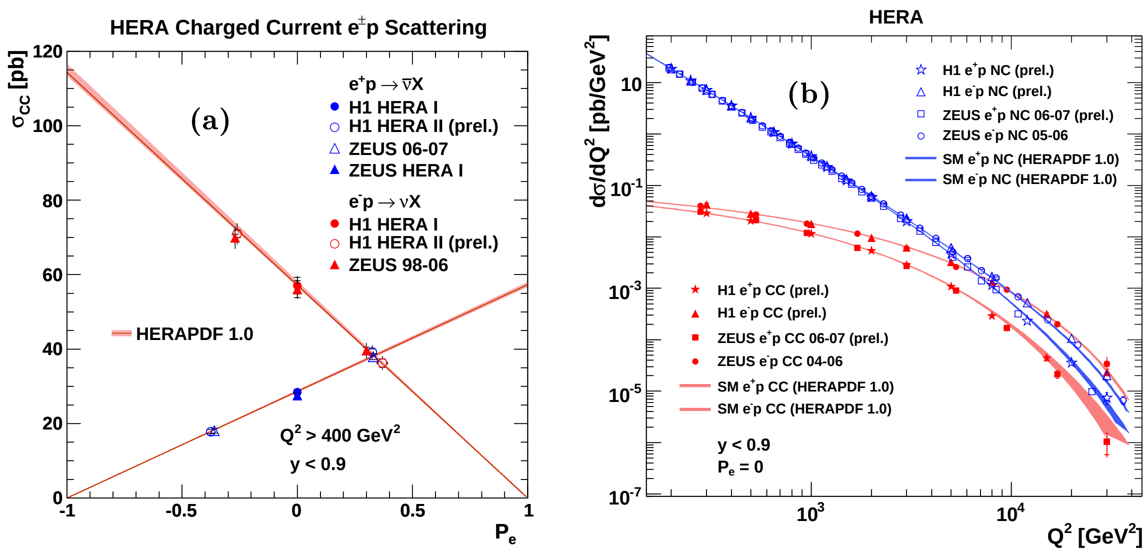

Figure 3: **(a)** The dependence of the $e^{\pm}p$ CC cross section on the lepton beam polarization P_e in comparison with the SM prediction based on the HERAPDF 1.0 parametrisation. **(b)** The Q^2 dependence of the unpolarized $e^{\pm}p$ NC and CC cross sections $d\sigma/dQ^2$ compared with the SM expectation from the HERAPDF 1.0 fit.

These determinations are sensitive to the u and d quarks separately, contrary to the other measurements from the light quark-Z couplings in νN scattering and atomic parity violation on heavy nuclei. They resolve the sign ambiguity in the determinations of v_q and a_q based on observables measured at the Z resonance [14].

5 Summary.

Measurements of the polarized NC and CC $e^{\pm}p$ cross sections using the HERA-II were presented. For the NC process the polarization asymmetry was measured. Unpolarized cross sections were obtained and combined with the HERA-I results. This allowed the precise determination of the $xF_3^{\gamma Z}$ structure function. Both the polarization asymmetry and the $xF_3^{\gamma Z}$ structure function measured are found to be in a good agreement with the theoretical predictions.

For the CC process the total polarized cross sections were measured and combined with the unpolarized measurements from HERA-I. The results verify the left handed structure of the weak interactions.

The EW fit to the HERA-I and HERA-II data is used to determine the couplings of up- and down-quarks to the Z^0 boson. The results are in a good agreement with the Standard Model predictions.

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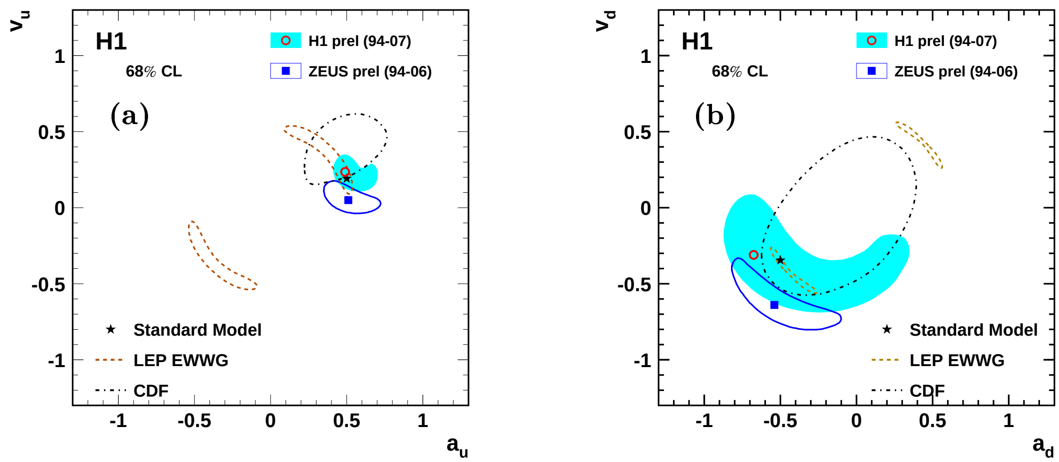

Figure 4: Results at 68% confidence level (CL) on the weak neutral current couplings of **(a)** u and **(b)** d quarks to the Z^0 boson determined in the analysis.

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