Determination of Electroweak Parameters using H1 Inclusive Deep Inelastic Scattering Data

Zhiqing Zhang[*][†]

LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
E-mail: zhangzq@lal.in2p3.fr

An improved determination of electroweak parameters using H1 inclusive neutral and charged current deep inelastic scattering cross section data is presented. The analysis benefits from the use of the previously published data with longitudinally polarised lepton beams. The parameters are determined in a combined fit of the electroweak parameters together with PDFs. The predictions include NNLO QCD corrections for the PDF and structure function calculations, and the corrections at the leptonic vertex are obtained in the on-shell scheme including the full set of one-loop corrections. The analysis determines the weak neutral-current couplings of the light quarks as well as potential contributions beyond the SM. The mass of the W-boson is determined with a precision of 115 MeV in the space-like regime.

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[*]Speaker.

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The deep inelastic scattering (DIS) of leptons off nucleons has played an important role in revealing the structure of matter, in the discovery of weak neutral current interactions and in the foundation of the Standard Model (SM) as the theory of strong and electroweak (EW) interactions. At HERA, electrons (or positrons) of 27.6 GeV were colliding with protons of up to 920 GeV in the first data taking period, HERA-I, from 1993 to 2000 with unpolarised lepton beams, and in the second period, HERA-II, from 2003 to 2007 with the longitudinally polarised lepton beams, P_e, to a level between -37% and 36%. In addition, the integrated luminosity value of the e^+p and e^-p collisions at HERA-II has increased by a factor of 1.5 and 15 over that at HERA-I, respectively. Both neutral current (NC) and charged current (CC) interactions occur in ep collisions and a large set of precise NC and CC cross sections was measured by the H1 experiment. In terms of Q^2, the negative four-momentum transfer squared, the kinematic coverage includes the region where the weak and electromagnetic interactions become of comparable strength.

A first determination of EW parameters including the vector and axial-vector weak neutral couplings of the light quarks, $q = u, d$, to the Z-boson was performed using HERA-I H1 data [1]. In this proceedings, we present the final results from H1 by including NC and CC cross section data from HERA-II [2].

NC interactions in the process $e^\pm p \to e^\pm X$, with X standing for any hadronic final state, are mediated by a virtual photon (γ) or Z boson in the t-channel, and the cross section is expressed in terms of generalised structure functions $\tilde{F}_2^\pm$, $x\tilde{F}_3^\pm$ and $\tilde{F}_L^\pm$ at EW leading order (LO) as $\frac{d^2\sigma^{\mathrm{NC}}(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm(x,Q^2) \mp Y_- x\tilde{F}_3^\pm(x,Q^2) - y^2\tilde{F}_L^\pm(x,Q^2)\right]$, where α is the fine structure constant and x denotes the Bjorken scaling variable. The helicity dependence of the interaction is contained in the terms $Y_\pm = 1 \pm (1-y)^2$ with y being the inelasticity of the scattering process. The generalised structure functions can be separated into contributions from pure γ- and Z-exchange and their interference, $\tilde{F}_2^\pm = F_2 - (g_V^e \pm P_e g_A^e)\varkappa_Z F_2^{\gamma Z} + \left[(g_V^e g_V^e + g_A^e g_A^e) \pm 2P_e g_V^e g_A^e\right]\varkappa_Z^2 F_2^Z$, $\tilde{F}_3^\pm = -(g_A^e \pm P_e g_V^e)\varkappa_Z F_3^{\gamma Z} + \left[2g_V^e g_A^e \pm P_e(g_V^e g_V^e + g_A^e g_A^e)\right]\varkappa_Z^2 F_3^Z$, and similarly for $\tilde{F}_L$. The variables g_A^e and g_V^e stand for the axial-vector and vector couplings of the lepton $e^\pm$ to the Z boson, respectively. The Q^2-dependent coefficient $\varkappa_Z$ accounts for the Z-boson propagator, $\varkappa_Z(Q^2) = \frac{Q^2}{Q^2+m_Z^2}$ $\frac{1}{4\sin^2\theta_W\cos^2\theta_W} = \frac{Q^2}{Q^2+m_Z^2}\frac{G_F m_Z^2}{2\sqrt{2}\pi\alpha}$. It can be normalised using the weak mixing angle, $\sin^2\theta_W = 1 - m_W^2/m_Z^2$, i.e. using the W and Z boson masses, m_W and m_Z, or the Fermi coupling constant G_F. The structure functions are related to linear combinations of the quark and anti-quark momentum distributions, xq and $x\bar{q}$. For instance, the F_2 and xF_3 structure functions in the naive quark-parton model, i.e. at LO in QCD, are: $\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q\left[Q_q^2, 2Q_q g_V^q, g_V^q g_V^q + g_A^q g_A^q\right]\{q + \bar{q}\}, x\left[F_3^{\gamma Z}, F_3^Z\right] = x\sum_q\left[2Q_q g_A^q, 2g_A^q g_A^q\right]\{q - \bar{q}\}$. The axial-vector and vector couplings of the quarks q to the Z boson, g_A^q and g_V^q, depend on the electric charge, Q_q, in units of the positron charge, and on the third component of the weak-isospin of the quarks, $I_{L,q}^{(3)}$. In terms of $\sin^2\theta_W$, they are given by the standard EW theory:

$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}}I_{L,q}^{(3)}, \quad g_V^q = \sqrt{\rho_{\mathrm{NC},q}}\left(I_{L,q}^{(3)} - 2Q_q\kappa_{\mathrm{NC},q}\sin^2\theta_W\right), \tag{1}$$

where the Q^2-dependent form factors $\rho_{\mathrm{NC},q}$ and $\kappa_{\mathrm{NC},q}$ account for universal higher-order corrections [3]. The same formulae also apply to the lepton couplings $g_{A/V}^e$.

The CC cross section at LO is written as $\frac{d^2\sigma^{\mathrm{CC}}(e^\pm p)}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2+Q^2}\right]^2$

$\left(Y_+ W_2^{\pm}(x,Q^2) \mp Y_- x W_3^{\pm}(x,Q^2) - y^2 W_{\mathrm{L}}^{\pm}(x,Q^2)\right)$. In the quark-parton model, $W_{\mathrm{L}}^{\pm} = 0$, and the structure functions $W_2^{\pm}$ and $x W_3^{\pm}$ are obtained from the parton distribution functions. For electron scattering, only positively charged quarks contribute:

$$W_2^- = x\left(\rho_{\mathrm{CC},eq}^2 U + \rho_{\mathrm{CC},e\bar{q}}^2 \overline{D}\right), \quad x W_3^- = x\left(\rho_{\mathrm{CC},eq}^2 U - \rho_{\mathrm{CC},e\bar{q}}^2 \overline{D}\right), \tag{2}$$

while negatively charged quarks contribute to positron scattering:

$$W_2^+ = x\left(\rho_{\mathrm{CC},eq}^2 \overline{U} + \rho_{\mathrm{CC},e\bar{q}}^2 D\right), \quad x W_3^+ = x\left(\rho_{\mathrm{CC},e\bar{q}}^2 D - \rho_{\mathrm{CC},eq}^2 \overline{U}\right), \tag{3}$$

where higher-order EW corrections are collected in form factors $\rho_{\mathrm{CC},eq/e\bar{q}}$. Below the top-quark threshold, one has $U = u + c$, $\overline{U} = \bar{u} + \bar{c}$, $D = d + s$, $\overline{D} = \bar{d} + \bar{s}$.

In the on-shell (OS) scheme, the independent parameters of the SM EW theory are determined by the fine structure constant α and the masses of the gauge bosons, the Higgs boson m_H, and the fermions m_f. The weak mixing angle is then fixed, and G_{F} is a prediction, given by $G_{\mathrm{F}} = \frac{\pi\alpha}{\sqrt{2}m_W^2}\frac{1}{\sin^2\theta_W}\frac{1}{(1-\Delta r)}$, where higher-order corrections enter through the quantity $\Delta r = \Delta r(\alpha, m_W, m_Z, m_H, m_t, \ldots)$ [4].

The analysis is performed at next-to-next-to-leading order (NNLO) in QCD including one-loop EW correction [2]. The DGLAP formalism [5] is used to describe the evolution of the PDFs with Q^2. The PDFs are parameterised with 13 parameters at a starting scale of $1.9\,\mathrm{GeV}^2$ following Ref. [6]. The EW parameters are determined together with PDF parameters in combined EW and QCD fits to all NC and CC cross section data from HERA-I and HERA-II measured by H1. The PDF fit alone, i.e. all EW parameters set to their SM values [3], yields a fit quality of χ^2 per degree of freedom of 1.03.

In one fit, m_W is treated as a free parameter, it is determined together with the PDF parameters with the result $m_W = 80.502 \pm 0.070_{\mathrm{stat}} \pm 0.055_{\mathrm{syst}} \pm 0.074_{\mathrm{PDF}} = 80.520 \pm 0.115_{\mathrm{total}}$ GeV. The total uncertainty is improved by a factor of two in comparison to earlier result based on HERA-I data only. This W-mass determination in the space-like regime is found to be consistent with other single experiments [7] as well as with the world average value of 80.385 ± 0.015 GeV [3].

For the determination of the weak NC couplings of the quarks to the Z boson, the couplings are treated as free parameters together with the PDF parameters. The precision of the vector couplings is significantly improved as compared to that of HERA-I [1], mainly due to the polarised lepton beams at HERA-II. The H1 results are compared in figure 1 (left) to those from LEP+SLC [8] and D0 [9] at Tevatron. The different contour shapes, particularly for the u-type quarks, show the potential to achieve an ultimate precision if they would be combined, in particular since the HERA result does not exhibit sign ambiguities or ambiguities between axial-vector and vector couplings, which are for example present in determinations from Z-decays at the pole.

Additional fits are performed allowing deviations from the SM predictions by replacing form factors in equations (1), (2) and (3) with $\rho_{\mathrm{NC},q} \to \rho_{\mathrm{NC},q}'\rho_{\mathrm{NC},q}$, $\kappa_{\mathrm{NC},q} \to \kappa_{\mathrm{NC},q}'\kappa_{\mathrm{NC},q}$, $\rho_{\mathrm{CC},eq/e\bar{q}} \to \rho_{\mathrm{CC},eq/e\bar{q}}'\rho_{\mathrm{CC},eq/e\bar{q}}$. The results for the NC channel are shown in figure 1 (middle). The results are consistent with the SM predictions in $1-2$ standard deviations.

Potential scale dependence of these BSM form factors are further checked by performing alternative fits in four Q^2 bins with a common set of PDF parameters. The CC study (figure 1 (right)) represents the first determination of the $\rho_{\mathrm{CC},eq/e\bar{q}}'$ parameters for separate quark flavours and also its first scale dependence test.
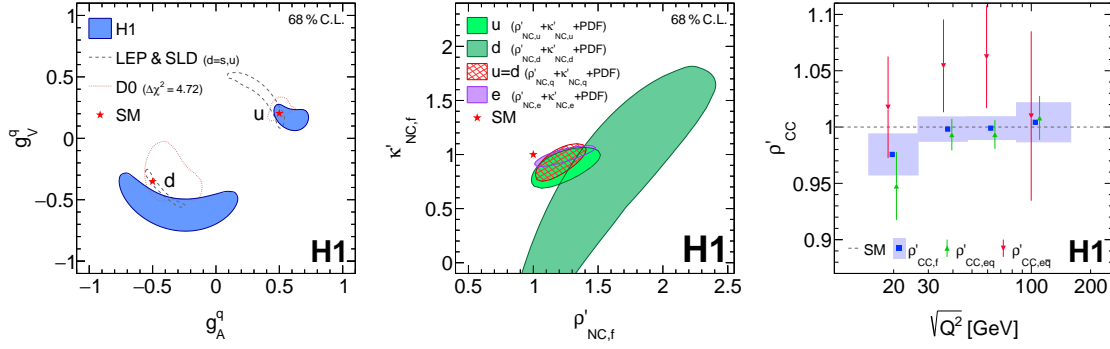
Figure 1: Left: Weak NC couplings of the *u*- and *d*-type quarks at the 68% confidence level (C.L.). Middle: Parameters $\rho'_{NC,f}$ and $\kappa'_{NC,f}$ for *u*- and *d*-type quarks and electrons at 68% C.L.. Right: Parameters ρ'_{CC} determined for four different values of Q^2. The error bars, as well as the height of the shaded areas, indicate the total uncertainties of the measurement. The width of the shaded areas indicates the Q^2 range probed by the selected data. The values for the $\rho'_{CC,eq}$ and $\rho'_{CC,e\bar{q}}$ parameters are horizontally displaced for better visibility. The plots are taken from [2].

To conclude, the inclusive deep-inelastic scattering cross section data measured by H1 at HERA-II with the longitudinally polarised lepton beams and higher integrated luminosity have provided additional sensitivity for improving the precision of the electroweak parameters. The Q^2 dependence of the H1 data allows for a study of the scale dependence of the ρ'_{NC}, κ'_{NC} and ρ'_{CC} parameters in the range $12 < \sqrt{Q^2} < 100$ GeV.

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