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To cite this version:
Z. Zhang. A determination of electroweak parameters at HERA. PoS - Proceedings of Science, SISSA, 2005, 293 (4 p.). in2p3-00025673

HAL Id: in2p3-00025673
http://hal.in2p3.fr/in2p3-00025673
Submitted on 23 Feb 2006

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A determination of electroweak parameters at HERA

Zhiqing Zhang
Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université de Paris-Sud XI
BP34, F-91898 Orsay, France
E-mail: zhangzq@lal.in2p3.fr

Using the deep inelastic $e^\pm p$ charged and neutral current scattering cross sections previously published, a combined electroweak and QCD analysis is performed to determine electroweak parameters accounting for their correlation with parton distributions. The data used have been collected by the H1 experiment in 1994-2000 and correspond to an integrated luminosity of 117.2 $\text{pb}^{-1}$. A first measurement at HERA is made of the light quark weak couplings to the $Z^0$ boson. An improved measurement is obtained of the $W$ propagator mass in charged current $ep$ scattering. The weak mixing angle $\sin^2\theta_W$ is determined in the on-mass-shell renormalization scheme.

European Physical Society
HEP2005 International Europhysics Conference on High Energy Physics
EPS (July 21st-27th 2005) in Lisboa, Portugal

* On behalf of the H1 Collaboration.
1. The experimental facts and analysis strategies

In the first phase of HERA operation (HERA-I) with the unpolarized $e^\pm$ beam colliding with the proton beam, the H1 experiment has collected three major data samples of $e^\pm p$ in years from 1994 to 1997 at a center-of-mass energy of 301 GeV, $e^- p$ in 1998-1999 and $e^+ p$ in 1999-2000 at 319 GeV. The corresponding integrated luminosities are 35.6 pb$^{-1}$, 16.4 pb$^{-1}$ and 65.2 pb$^{-1}$, respectively. These data have been used to measure neutral current (NC) and charged current (CC) cross sections covering more than 4 orders of magnitude in both $Q^2$, the negative four-momentum transfer squared, and Bjorken $x$. The large kinematic coverage and the different flavor sensitivity of the $e^\pm p$ NC and CC cross section data have enabled 5 sets of parton distribution functions (PDF) to be determined simultaneously in a previous QCD analysis [1]. These five PDF sets are the gluon, up-type and down-type quarks and their anti-quarks distributions.

The inclusive NC and CC cross sections are not only sensitive to PDFs but also to electroweak (EW) parameters. Indeed, the NC cross sections at high $Q^2$ depend on up- and down-type quark couplings to the $Z^0$ boson, $a_q$ and $v_q$ ($q=u, d$), via structure functions, whereas the shape of the CC cross sections as a function of $Q^2$ is controlled by the propagator mass ($M_{prop}$) of the $W$ boson. It is thus natural to extend the QCD analysis of [1] into a combined EW-PDF analysis so that EW parameters can be determined together with the PDFs taking properly into account the small but non-negligible correlation between them.

This is precisely the strategy chosen in [2,3], namely using the same parameterization forms for the five PDF sets for the QCD part. The QCD analysis is performed using the DGLAP evolution equations [4] at next-to-leading order in the modified minimal subtraction renormalization scheme. All quarks are taken as massless. Several combined EW-PDF fits are performed either in a model independent way (fits $a_u-v_u-a_d-v_d$-PDF and $G-M_{prop}$-PDF) or within the Standard Model (SM, fits $M_W$-PDF and $m_t$-PDF).

2. First results on light quark couplings to the $Z^0$ boson at HERA

The sensitivity on the quark couplings at HERA stems from the $\gamma Z$ interference and $Z^0$ exchange contributions in NC interactions at high $Q^2$. The results of the combined $a_u-v_u-a_d-v_d$-PDF fit are shown in Fig.1 and compared with similar results obtained recently by the CDF experiment [5] and combined LEP experiments [6]. The HERA determination has comparable precision to that from the Tevatron. These determinations are sensitive to $u$ and $d$ quarks separately, contrary to other measurements of the light quark-$Z^0$ couplings in $\nu N$ scattering [7] and atomic parity violation [8] on heavy nuclei. They also resolve any sign ambiguity and the ambiguities between $v_q$ and $a_q$ ($q=u,d$) of the determinations based on observables measured at the $Z^0$ resonance [6].

The HERA precision is expected to improve significantly with the data from HERA-II taken at higher luminosity. The longitudinally polarized $e^\pm$ beams at HERA-II will also provide additional sensitivity in constraining the vector couplings $v_q$. 
FIGURE 1. H1 results (shaded area) at 68% confidence level (CL) on the couplings of $u$ quark (left) and $d$ quark (right) to $Z^0$ in comparison with similar results from CDF (dashed curves) and LEP (full curves).

3. Improved $W$ propagator mass measurement at HERA

The cross section data allow a simultaneous determination of the Fermi coupling constant $G_F$ and the $W$ boson mass, and of the PDFs ($G$-$M_{\text{prop}}$-PDF fit). When treating $G$ and $M_{\text{prop}}$ as independent parameters, the sensitivity on $G$ and $M_{\text{prop}}$ originates respectively from the normalization and $Q^2$ dependence of the CC cross sections. The result of the fit is shown in Fig. 2 as the shaded area.

FIGURE 2. The result of the fit to $G$ and $M_{\text{prop}}$ at 68% confidence level (CL) shown as the shaded area. The world average values are indicated with the star symbol. Fixing $G$ to $G_F$, the fit results in a measurement of the propagator mass $M_{\text{prop}}$ shown as the circle with the horizontal error bar.
Fixing $G$ to the measured $G_F$ value [9], one gets a determination of \(M_{\text{prop}}\), also shown in Fig.1, \(M_{\text{prop}} = 82.87 \pm 1.82_{\text{exp}}^{+0.30}_{-0.16}\) GeV where the first error is experimental and the second corresponds to uncertainties due to input parameters and model assumptions as introduced in Table 5 in [1] (e.g., the variation of \(\alpha_s=0.1185\pm0.0020\)). This determination differs from all previous ones in the treatment of the correlation between \(M_{\text{prop}}\) and PDFs and represents the most accurate measurement so far of the CC propagator mass at HERA.

Within the SM, the Fermi coupling constant $G_F$ is connected with the $W$ boson mass $M_W$ through a relation which contains EW radiative corrections including quadratic (logarithmic) dependence on the top quark mass $m_t$ (the Higgs mass $M_H$). A combined EW-PDF fit in the SM gives

\[
M_W = 80.786 \pm 0.205_{\text{exp}}^{+0.048}_{-0.029} \pm 0.025_{\text{model}} - 0.084_{\delta m_t} + 0.033_{\delta (M_H)}\) GeV \quad (1)
\]

where the measured central value corresponds to using the world averaged values of $M_Z = 91.1876\pm0.0021$ GeV, $m_t=178\pm4.3$ GeV and a Higgs mass of 120 GeV. The uncertainty on $M_Z$ has a negligible error on $M_W$ whereas the uncertainty on $m_t$ gives rise to the third quoted error on $M_W$. Varying $M_H$ from 120 GeV to 300 GeV results in the fourth error. The last error is due to higher order radiative correction uncertainties.

Together with the world average value of $M_Z$ given above, the result obtained on $M_W$ from Eqn.(1) represents an indirect determination of $\sin^2 \theta_W$ in the on-mass shell scheme:

\[
\sin^2 \theta_W = 0.2151 \pm 0.0040_{0.0019}\] \quad (2)
\]

where the first error is experimental and the second is theoretical covering all remaining uncertainties in Eqn.(1). The uncertainty due to $\delta M_Z$ is negligible.

Fixing $M_W$ to the world average value and assuming $M_H=120$ GeV, the fit $m_t$-PDF gives $m_t=108\pm44$ GeV where the uncertainty is experimental. The result represents the first determination of the top quark mass through loop effects in the $ep$ data at HERA.

Again the precision of these determinations will be improved by a large amount as the best sensitivity comes from the CC $e^-p$ cross section which was measured from a very limited data sample at HERA-I. Polarized $e^-p$ data corresponding to an increase of one order magnitude in the integrated luminosity from HERA-II are being taken.

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