COMBINED QCD AND ELECTRO-WEAK FITS AT HERA

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The world's only ep-collider HERA can explore the deep inelastic scattering over a wide kinematic region due to its large center-of-mass energy. Therefore, a unique study of a simultaneous determination of parton distribution functions and electro-weak parameters can be performed. The HERA-II high precision data with longitudinally polarized electron beams brought significant improvements on the sensitivity to both parameters.

1. Deep inelastic scattering at HERA

HERA at DESY is the only $e^{\pm}p$ collider in the world. Owing to the large center-of-mass energy of $\sqrt{s} = 318$ GeV, the phase space to explore deep inelastic scattering (DIS) has been significantly extended. The two collider experiments, H1 and ZEUS, collected data samples with integrated luminosities of about 100 (20) pb^{-1} for unpolarized $e^+(e^-)$ and p collisions in the HERA-I running period (1994-2000).

The HERA DIS data has allowed the determination of parton distribution functions (PDFs) of the proton across a wide kinematic region. It spans the proton momentum fraction carried by the struck quark, Bjorken x down to $\sim 10^{-5}$, and the negative square of the four-momentum transfer Q^2 up to ~ 30000 GeV^2. The HERA low-Q^2 data have been used to constrain the gluon and sea quarks in the small x region, and also the HERA jet production data are used for the determination of the middle- to high-x gluon. So far, the high-x PDFs, where valence distributions are dominant, are determined by the precise data from fixed target experiments. However, these are subject to uncertainties from heavy-target corrections, higher-twist contributions or isospin-symmetry assumptions. At HERA, the high-Q^2 data can constrain the PDFs at high-x region without these uncertainties. Although the current precision at high-Q^2 is statistically limited, the determination of high-x PDFs with HERA data alone is now competitive[1,2].

Meanwhile, the high-Q^2 DIS reveal the interaction at small distance, since Q^2 corresponds to the spatial resolution as $\lambda \approx 1/Q$. Thus, DIS at HERA also provides a unique opportunity to test and constrain the electro-weak (EW) parameters in the t-channel, which is complementary to s-channel LEP, SLD and TeVatron measurements. The charged current (CC) cross sections are suppressed at low-Q^2 due to the large mass of the W propagator, but at $Q^2 \gtrsim M_Z^2$ (M_W^2), where M_Z (M_W) is the mass of the Z (W) boson, both CC and neutral current (NC) DIS cross sections become of comparable magnitude. It is a clear demonstration of EW unification at higher energy scale.

To fully exploit the HERA potential, a combined QCD and EW analysis was performed by H1 [3] to determine PDFs and EW parameters simultaneously. The advantage of such a combined analysis is that possible correlations for both parameters are automatically taken into account in the fit.

Since Autumn 2003, the second phase

of HERA operation has been in progress with higher specific luminosity than HERA-I and with longitudinally polarized $e^{\pm}$ beams (HERA-II). The higher luminosity enhances sensitivity in the high-Q^2 region, where PDFs can be accessed at high-x and the EW interaction becomes significant. The longitudinally polarized $e^{\pm}$ beams allow a direct investigation of the helicity structure of the EW interaction. The H1 and ZEUS experiments had collected about 40 (120) pb^{-1} of polarized e^+ (e^-) and p collisions by the end of 2005 running, and they measured the polarized CC and NC DIS cross sections [4]. Recently, ZEUS performed a combined QCD and EW analysis also including HERA-II polarized e^- data. In this paper, the impact of HERA-II data on the combined analysis is reported[5].

2. PDF extraction from QCD fits

H1 and ZEUS collaborations used the CC and NC cross section measurements to extract the PDFs from QCD fits. These are called H1 PDF 2000 and ZEUS-POL fits. The PDFs are parameterized at $Q_0^2 = 4$ (7) GeV^2 as initial scale in H1 PDF 2000 (ZEUS-POL), and evolved in Q^2 using DGLAP equation at NLO in the $\overline{MS}$ renormalization scheme. The treatment of correlated systematic uncertainties is performed using HESSIAN (OFFSET) method [6] in H1 PDF 2000 (ZEUS-POL).

2.1. *PDF parameters*

The fits are extended recently to include the high statistics e^-p data collected in 2005. Though the center values of PDFs are almost unchanged, the precision of high-x PDFs is improved, particularly for the u-valence PDF as shown in Fig. 1. It can be expected that e^-p NC cross sections are proportional to $4u + d$ due to their electromagnetic couplings, where u and d denote the up- and down-type quark density, and e^-p CC only interacts with the u due to it's charge selecting nature. Such an improvement is also observed in the high-Q^2 region (Q^2=10,000 GeV^2). The reduction of PDF uncertainties at high-x and high-Q^2 will provide a precise input to the LHC physics.

3. EW parameter measurements from extended QCD and EW fits

3.1. *M_W in space-like region*

In addition to the PDF parameters, EW parameters can be determined. Firstly, the value of M_W and the Fermi constant, G_F, are left free in the fits. Since CC cross sections of $\sigma_{CC} \propto G_F^2 \frac{M_W^4}{(Q^2+M_W^2)^2}$, the sensitivity to G_F comes from the normalization of CC cross sections, and the sensitivity to M_W arises from its Q^2 dependence.

Fig. 2 shows the 68% confidence level (CL) contours of G_F and M_W obtained with HERA-I data. The result is consistent with G_F obtained from muon lifetime measurements. It demonstrates the universality of CC interactions over a large range of Q^2.

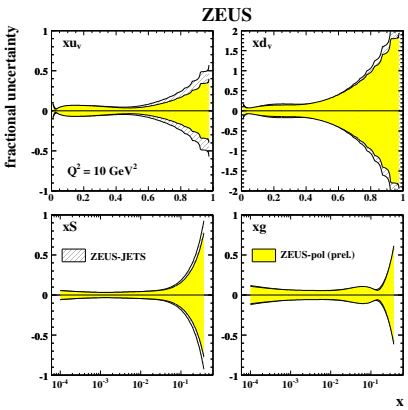

Fig. 1. The total experimental uncertainty on the PDFs at Q^2 = 10 GeV^2 for the ZEUS-POL fit compared to the fit without HERA-II data (ZEUS-JETS). The uncertainties are shown as fractional differences from the central values for u valence (upper left), d valence (upper right), total sea quark (lower left) and gluon (lower right).

By fixing G_F to the world average value in the fit, the M_W was extracted as $M_W = 82.87 \pm 1.82(stat) \pm 0.25(sys)$(GeV), and by including the HERA-II high statistics data, it is improved to $M_W = 79.1 \pm 0.77(stat) \pm 0.99(sys)$(GeV). The measurement of M_W in space-like regions at HERA is complementary with TeVatron and LEP measurements in time-like regions, therefore constitutes an important test of the standard model (SM).

3.2. *Quark couplings to Z*

Next, a_q and v_q, the axial-vector and vector weak NC couplings of quark q to the Z boson, are determined from the fit. Since the light quarks dominate the DIS cross sections, such extraction is complementary to the LEP results, where a_q and v_q are determined via $c\bar{c}$ and $b\bar{b}$ production.

The NC DIS cross section at born level can be expressed as:

$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+(F_2^0 + PF_2^{P,\pm}) + Y_-(xF_3^{0,\pm} + PxF_3^P)],$$

where α is the electromagnetic fine structure constant, $Y_\pm = 1 \pm (1-y)^2$ with y being the inelasticity, and P is $e^\pm$ beams polarization. The longitudinal structure function F_L is ignored in this formula. The structure functions F_2^0 and $xF_3^{0,\pm}$ are for unpolarized $e^\pm p$, and the $F_2^{P,\pm}$ and xF_3^P are introduced from polarized $e^\pm$ beams. The terms involving the electron vector coupling v_e are small due to small value of $v_e = -1/2 + 2\sin^2(\theta_W) \approx -0.05$, where θ_W is the Weinberg angle. In the HERA kinematic region, the effect of weak NC is dominated by the interference between photon and Z rather than by the pure Z exchange. Thus, the structure functions can be written approximately as:

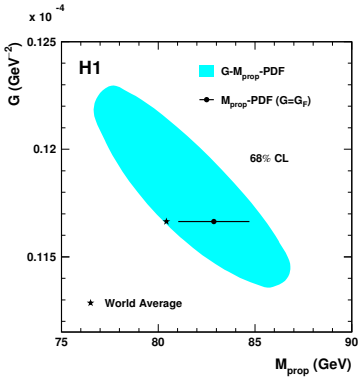

Fig. 2. The results of the fit to M_W and G_F with HERA-I data shown as the shaded area. By fixing G_F to the world average value, M_W was extracted shown as the circle with the horizontal error. The star symbol indicates the world average values for M_W and G_F.

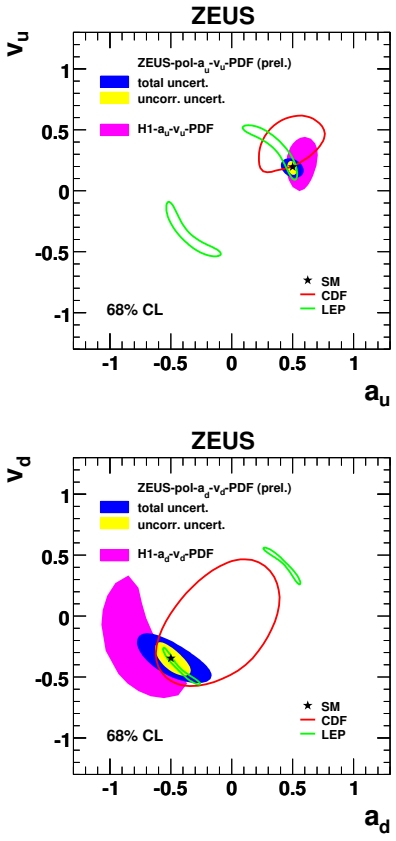

Fig. 3. The determination of a_q and v_q for u (upper plot) and d (lower plot) quarks respectively. The results obtained by H1 using HERA-I data, by CDF at TeVatron and by LEP are also shown. The star symbol indicates the SM values.

$$F_2^0 \approx \sum_q x(q+\overline{q})\ e_q^2,$$
$$F_2^{P,\pm} \approx \sum_q x(q+\overline{q})[\mp 2e_q v_q a_e P_z],$$
$$xF_3^{0,\pm} \approx \sum_q x(q-\overline{q})[\pm 2e_q a_e a_q P_z],$$
$$xF_3^P \approx 0,$$

where q and $\overline{q}$ are the quark and anti-quark PDFs and the sums run over the active quark flavours. e_q is the quark charge in units of the positron charge, and a_e is the axial-vector coupling of electron to Z. P_z is defined as $P_z = \frac{Q^2}{Q^2+M_Z^2}\frac{1}{4\sin^2\theta_W\cos^2\theta_W}$. From these relations, the sensitivity of a_q and v_q via NC DIS comes from $xF_3^{0,\pm}$ and $F_2^{P,\pm}$ respectively.

Fig. 3 shows the contours at 68% CL of a_q and v_q obtained by ZEUS for u (upper plot) and d (lower plot) quarks respectively. The results obtained by H1 using HERA-I data, by CDF at TeVatron and by LEP are also shown. Clearly, the polarized e^- data improved the v_u and v_d determination. Furthermore, due to the HERA-II high statistics data, a_u and a_d were also determined more precisely. In particular, due to the precise u PDF determination, the a_u and v_u are measured with the best precision.

In the SM formalism, a_q and v_q have the relation as: $a_q = T_q^3$, $v_q = T_q^3 - 2e_q\sin^2\theta_W$, where T_q^3 is the third component of weak isospin of quark q. To test the SM, the values of T_u^3, T_d^3 and $\sin^2\theta_W$ are left free with PDF parameters. The extracted values with uncertainties are shown in Fig. 4 as contours. The results were found to be consistent with their SM values.

4. Summary and Outlook

Combined QCD and EW fits were performed on the HERA data also including HERA-II polarized e^- data. Due to the increase of e^- data statistics, the precision of the high-x PDFs are improved, particularly for the u-valence PDF. The space-like measurement of M_W is complementary to and consistent with time-like TeVatron and LEP measurements. The determinations of quark couplings to Z boson using light quarks are excellent.

The polarized DIS data to be delivered until the June of 2007 will further improve the EW parameters. For example, the CC DIS cross section of polarized e^+p can constrain the d PDF more precisely, therefore the measurements of a_d and v_d can be expected to improve.

References

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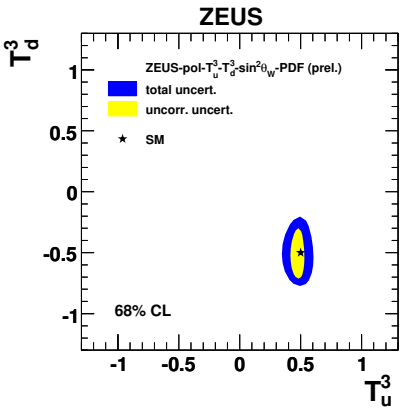

Fig. 4. The extracted values for T_u^3 and T_d^3 shown as contours. The star symbol indicates the SM values.