QCD and electroweak fits to HERA inclusive DIS data

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on behalf of the ZEUS Collaboration

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I. Abt, A.M. Cooper-Sarkar, B. Foster, C. Gwenlan, V. Myronenko, O. Turkot, K. Wichmann
Deep Inelastic Scattering (DIS) is the best tool to probe proton structure.

LO expressions for illustration of the main dependencies on parton distribution functions (PDFs).

The HERA data combination EPJC75(2015)580

DESY, $\sqrt{s} = 252–318$ GeV

(E$_e$ = 27.5 GeV; E$_p$ = 920, 820, 575, 460 GeV)

two general purpose detectors, H1 and ZEUS

collected 0.5 fb$^{-1}$ per experiment, equally between e$^+$ and e$^-$

HERA-II (02–07): polarised lepton beams;

crucial for electroweak measurements
Deep Inelastic Scattering at HERA:

- a super-microscope to study proton structure (PDFs)
- sensitive to EW via t-channel gauge boson exchange


(E$_e$ = 27.5 GeV; E$_p$ = 920, 820, 575, 460 GeV)

two general purpose detectors, H1 and ZEUS
collected 0.5 fb$^{-1}$ per experiment, equally between e$^+$ and e$^-$

HERA-II (02–07): polarised lepton beams;
crucial for electroweak measurements
HERA inclusive NC and CC DIS data

\[ \sigma_{r,NC}^{e\pm p} = \frac{x_{Bj}Q^4}{2\pi\alpha_0^2} \frac{1}{Y_+} \frac{d^2\sigma(e^{\pm}p)}{dx_{Bj}dQ^2} = \tilde{F}_2(x_{Bj}, Q^2) + \frac{Y_+}{Y_+} x\tilde{F}_3(x_{Bj}, Q^2) - \frac{y^2}{Y_+} F_L(x_{Bj}, Q^2) \]

(similar equation for CC cross section)
**NC polarised DIS**

**NC:** $\gamma Z$ interference and $Z$ exchange affected by e-beam polarisation

\[ \tilde{F}_2^\pm = F_2^\gamma - (v_e \pm P_e a_e) \chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e) \chi_Z^2 F_2^Z \]

\[ x\tilde{F}_3^\pm = -(a_e \pm P_e v_e) \chi_Z x F_3^{\gamma Z} + (2v_e a_e \pm P_e (v_e^2 + a_e^2)) \chi_Z^2 x F_3^Z \]

**NC** structure functions in QPM: sensitive to EW vector and axial-vector couplings to light quarks, and $\sin^2 \theta_W$ via

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

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

\[ v_u = 1/2 - 4/3 \sin^2 \theta_W \quad a_u = 1/2 \quad v_d = -1/2 + 2/3 \sin^2 \theta_W \quad a_d = -1/2 \]

**on-shell** scheme used: $\sin^2 \theta_W = 1 - M_W^2/M_Z^2 = 0.22333$ (PDG14)
NC polarised DIS

**NC**: $\gamma Z$ interference and $Z$ exchange affected by e-beam polarisation

\[
\tilde{F}_2^\pm = F_2^\gamma - (\pm P_e a_e)\chi_z F_2^{\gamma Z} \\
x\tilde{F}_3^\pm = -(a_e)\chi_z x F_3^{\gamma Z}
\]

NC structure functions in QPM:

\[
[F_2^\gamma, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q}) \\
x F_3^{\gamma Z}, x F_3^Z] = \sum_q [e_q a_q, v_q a_q] 2x(q - \bar{q})
\]

\[
\chi_z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2} \frac{1}{1 - \Delta R}
\]

\[
v_u = 1/2 - 4/3\sin^2 \theta_W \quad a_u = 1/2 \quad v_d = -1/2 + 2/3\sin^2 \theta_W \quad a_d = -1/2
\]

**on-shell** scheme used: \( \sin^2 \theta_W = 1 - M_W^2/M_Z^2 = 0.22333 \text{ (PDG14)} \)
CC polarised DIS

CC:

\[
\frac{d^2\sigma_{CC}(e^+p)}{dx_{Bj}dQ^2} = (1 + P_e) \frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2 + M_W^2)^2} x [(\bar{u} + \bar{c}) + (1 - y)^2(d + s + b)]
\]

\[
\frac{d^2\sigma_{CC}(e^-p)}{dx_{Bj}dQ^2} = (1 - P_e) \frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2 + M_W^2)^2} x [(u + c) + (1 - y)^2(\bar{d} + \bar{s} + \bar{b})]
\]

\[
G_F = \frac{\pi \alpha_0}{\sqrt{2} \sin^2 \theta_W M_W^2} \frac{1}{1 - \Delta R}
\]

CC provides further sensitivity to PDFs (quark flavour separation) and sensitivity to \(\sin^2 \theta_W\), and \(M_W\) via \(G_F\) and propagator.
QCD and electroweak fit to HERA data

Simultaneous **NLO QCD** and **LO electroweak** fit of PDF and EW parameters

- **HERA NC** and **CC** inclusive **uncombined** data sets as input:
  1. Datasets as used in HERA combination ([EPJ C75 (2015) 580]):
     - HERA I H1 and ZEUS; H1 and ZEUS reduced Ep data; HERA II data from H1 (UNPOLARISED)
  2. **HERA II data from ZEUS (POLARISED)**

- **PDF fit**, closely follows HERAPDF2.0 ([EPJ C75 (2015) 580]):
  - \[ xg(x) = A_g x^B_g (1 - x)^C_g - A'_g x^{B'_g} (1 - x)^{C'_g}, \]
  - \[ xu(x) = A_{u,v} x^{B_u,v} (1 - x)^{C_{u,v}} (1 + E_{u,v} x^2), \]
  - \[ xd_v(x) = A_{d_v} x^{B_{d_v}} (1 - x)^{C_{d_v}}, \]
  - \[ x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}}, \]
  - \[ x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}. \]

  Start scale \( Q_0^2 = 1.9 \text{ GeV}^2 \)

  **Model and parameterisation** uncertainties as in HERAPDF2.0

  ΔR corrections calculated using EPRC code
  
  (H. Spiesberger, desy.de/~hspiesb/eprc.html)

  Fixed, or from sum rules

  13 free PDF parameters, and 4 light quark **NC EW couplings** (or free \( \sin^2 \theta_W / M_W \))
NC and CC polarised DIS data

\[ Q^2_{\text{min}} = 3.5 \text{ GeV}^2 \] – number of data points is 2942, of which 501 are polarised

ZEUS cross section data (\( X^2/\text{NDF} = 1.12 \) for fit with NC couplings free)
agreement with equivalent (13p) fit with EW couplings set to SM values

only weak correlation between PDF and electroweak parameters
(QCD part of fit can be repeated at NNLO with little pull on EW parameters)

(also agrees well with HERAPDF2.0
EPJ C75 (2015), 580)
**NC electroweak couplings**

\[
\begin{align*}
a_u &= +0.50_{-0.05}^{+0.09} \text{ (experimental/fit)} \quad +0.04_{-0.02}^{+0.04} \text{ (model)} \quad +0.08_{-0.01}^{+0.08} \text{ (parameterisation)} \\
ad &= -0.56_{-0.14}^{+0.34} \text{ (experimental/fit)} \quad +0.11_{-0.05}^{+0.11} \text{ (model)} \quad +0.20_{-0.00}^{+0.20} \text{ (parameterisation)} \\
v_u &= +0.14_{-0.08}^{+0.08} \text{ (experimental/fit)} \quad +0.01_{-0.02}^{+0.01} \text{ (model)} \quad +0.00_{-0.03}^{+0.00} \text{ (parameterisation)} \\
v_d &= -0.41_{-0.16}^{+0.24} \text{ (experimental/fit)} \quad +0.04_{-0.07}^{+0.04} \text{ (model)} \quad +0.00_{-0.08}^{+0.00} \text{ (parameterisation)} \\
\end{align*}
\]

- $a_u = 0.5$  
- $a_d = -0.5$  
- $v_u = 0.202$  
- $v_d = -0.351$  

**Standard Model**
NC electroweak couplings – correlations

Vector and axial vector couplings show strong correlation
comparison with other measurements

- excellent sensitivity to u-type quark couplings
- results compatible with SM expectation
improvement from using all HERA polarised data

independent analysis (HH-EW-Z) performed, using also published H1 polarised data (H1 Coll., JHEP 1209 (2012) 061)


HERA II polarised data especially important for vector couplings
comparison with other results

ZEUS Coll., PRD 93, 092002 (2016)  
(arXiv:1603.09628)

I. Abt et al., PRD 94, 052007 (2016)  
(arXiv:1604.05083)

NC coupling determinations from I. Abt et al., included in PDG17 world average
\(\sin^2 \theta_W \text{ and } M_W\)

**ZEUS Coll., PRD 93, 092002 (2016)**

- \(\sin^2 \theta_W \text{ and } M_W\) can also be extracted from the HERA inclusive DIS data

- \(\sin^2 \theta_W\) fitted as parameter, along with PDFs:

\[
\sin^2 \theta_W = 0.2252 \pm 0.0011 \text{ (experimental/fit) } +0.0003_{-0.0001} \text{ (model) } +0.0007_{-0.0001} \text{ (parameterisation)}
\]

- \(M_W\) and PDF parameters fitted simultaneously (\(\sin^2 \theta_W = 0.22333\) fixed):

\[
M_W = 80.68 \pm 0.28 \text{ (experimental/fit) } +0.12_{-0.01} \text{ (model) } +0.23_{-0.01} \text{ (parameterisation) GeV}
\]

\(M_w\) determination from **space-like** process, *complementary* to other measurements

(simultaneous extraction of \(\sin^2 \theta_W \text{ and } M_W\) (and PDFs) also performed as cross check; results consistent with PDG world average – see backups)
effective $\sin^2 \theta_W$

- measurements from full dataset, and in 3 bins of $Q^2$ (PDF parameters fixed) translated$^\dagger$ to effective $\sin^2 \theta_W$

$^\dagger$ procedure from Czarnecki and Marciano, IJMPA 15 (2000) 2365
summary

• HERA polarised inclusive DIS data sensitive to electroweak parameters
  → simultaneous PDF and EW fits

• NC vector and axial-vector couplings to quarks agree with world average and SM expectation

• measurements of u-type quark couplings among most accurate from single collider

• couplings from I. Abt et al. (HH-EW-Z) included in PDG17 world average

• \( \sin^2\theta_W \) determined; first observation of \( \sin^2\theta_W^{\text{eff}} \) running from single machine

• mass of W boson determined in space-like momentum transfer process
extras
HERA: world’s only ep collider

Integrated Luminosity (pb⁻¹)

HERA II e⁻
562 pb⁻¹
Nov 02 – Mar 07

HERA II e⁺

HERA I

193 pb⁻¹
May 93 – Aug 00

days of running
PDF fit results

Comparison with HERAPDF2.0

(EPJ C75 (2015), 580)
Q^2_{\text{min}} = 3.5 \text{ GeV}^2$ – number of data points is 2942, of which 501 are polarised ZEUS cross section data ($X^2/\text{NDF} = 1.12$ for fit with NC couplings free)
**correlation matrix**

ZEUS Coll., PRD 93, 092002 (2016)
(arXiv:1603.09628)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$x_g: B$</th>
<th>$x_g: C$</th>
<th>$x_g: A'$</th>
<th>$x_g: B'$</th>
<th>$x_{w_t}: B$</th>
<th>$x_{w_t}: C$</th>
<th>$x_{w_t}: E$</th>
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Table 2: The correlation matrix of all parameters of the ZEUS-EW-Z fit.
EW parameter cross checks

- studies performed to check stability of EW couplings with respect to various QCD parameters

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<th>(\text{tot})</th>
<th>(a_d)</th>
<th>(\exp)</th>
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**Table 3:** The results on the axial-vector and vector couplings of the Z boson to \(u\)- and \(d\)-type quarks from ZEUS-EW-Z. Given are the experimental/fit (\(\exp\)) and total (\(\text{tot}\)) uncertainties. Also listed are results of fits with the PDFs fixed to ZEUS-13p and HERAPDF2.0, HPDF1 and HPDF2, for which only the couplings of the Z were free parameters. The HPDF1 fit was performed with the on-shell value of \(\sin^2\theta_W\) used in the fit while HPDF2 was performed with the \(\sin^2\theta_W\) value used for the extraction of HERAPDF2.0. Also listed are the predictions of the SM for the \(a\) and \(v\) couplings in the on-shell scheme.
**sin²θ_W and M_W**

DIS inclusive cross sections depend on sin²θ_W through:

**Neutral Current:**
- Xz term in NC cross section:
  \[ χ_Z = \frac{1}{\sin^2 2θ_W} \frac{Q^2}{M_Z^2 + Q^2} \frac{1}{1 - ΔR} \]
- NC vector couplings to quarks:
  \[ v_u = \frac{1}{2} - \frac{4}{3} \sin^2 θ_W \]
  \[ v_d = -\frac{1}{2} + \frac{2}{3} \sin^2 θ_W \]

**Charged Current:**
- CC cross sections, via GF
  \[ G_F = \frac{\pi α_0}{2 \sin^2 θ_W M_W^3} \frac{1}{1 - ΔR} \]
  \[ \frac{d^2σ_{CC}(e^+p)}{dx_Bj dq^2} = (1 + P_e) \frac{G_F^2 M_W^4}{2πx_Bj(Q^2 + M_W^2)^2} x [(\bar{u} + \bar{c}) + (1 - y)^2(d + s + b)] \]
  \[ \frac{d^2σ_{CC}(e^-p)}{dx_Bj dq^2} = (1 - P_e) \frac{G_F^2 M_W^4}{2πx_Bj(Q^2 + M_W^2)^2} x [(u + c) + (1 - y)^2(\bar{d} + \bar{s} + \bar{b})] \]

GF re-expressed through sin²θ_W and M_W meaning both NC and CC used to extract sin²θ_W

X_F and GF are most important for sin²θ_W determination

M_W sensitivity comes from GF and W propagator in CC events
\[ \sin^2 \theta_W \]

<table>
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<tr>
<th>bin</th>
<th>( Q_{\text{min}}^2 ) (GeV(^2))</th>
<th>( Q_{\text{max}}^2 ) (GeV(^2))</th>
<th>scale (GeV)</th>
<th>( \sin^2 \theta_W ) on-shell</th>
<th>exp unc.</th>
<th>( \sin^2 \theta_W ) effective</th>
<th>exp unc.</th>
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**Table 4:** The on-shell and effective values of \( \sin^2 \theta_W \) as determined for three bins in \( Q^2 \) and for all data. Experimental/fit (exp) uncertainties are given as determined by the one-parameter fits for each bin or ZEUS-EW-S, respectively; model and parameterisation uncertainties as determined by ZEUS-EW-S were added in quadrature and are denoted as PDF uncertainties. They are identical for on-shell and effective values at the accuracy given.
\( \sin^2 \theta_W \) and \( M_W \)

Simultaneous extraction of \( \sin^2 \theta_W \) and \( M_W \) (together with PDFs) also performed as cross-check

PDG14:
\[
\sin^2 \theta_W = 0.22333 \pm 0.00011 \text{ (on-shell)}
\]
\[
M_W = 80.385 \pm 0.015
\]

\[
\sin^2 \theta_W = 0.2293 \pm 0.0031 \text{ (experimental/fit)} \pm 0.0005 \text{ (model)} \pm 0.0003 \text{ (parameterisation)}
\]
\[
M_W = 79.30 \pm 0.76 \text{ (experimental/fit)} \pm 0.38 \text{ (model)} \pm 0.48 \text{ (parameterisation)} \text{ GeV}.
\]
comparison of NC light quark couplings


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<th>Value (Model)</th>
<th>Value (Parameterisation)</th>
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<table>
<thead>
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<th>Value (Model)</th>
<th>Value (Parameterisation)</th>
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PDF fit results – HH-EW-Z

comparison with HERAPDF2.0
(EPJ C75 (2015), 580)
NC polarised DIS data from H1 and ZEUS

\[ Q^2_{\text{min}} = 3.5 \, \text{GeV}^2 \quad \text{and} \quad X^2/\text{NDF} = 3556/3231 = 1.10 \text{ for fit with NC couplings free} \]
### Table 1: The correlation matrix of all parameters of the HH-EW-Z fit.

<table>
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<tr>
<th>Parameters</th>
<th>$x_g$: $B$</th>
<th>$x_g$: $C$</th>
<th>$x_g$: $A'$</th>
<th>$x_g$: $B'$</th>
<th>$x_B$: $C$</th>
<th>$x_B$: $C$</th>
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