Electroweak and new physics fits to HERA DIS data

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On behalf of H1 and ZEUS Collaborations

- Inclusive data combination and HERAPDF2.0
- Electroweak physics at HERA
- Beyond Standard Model analysis using the simultaneous fit of BSM parameter and PDFs
HERA — world only $e^\pm p$ collider

HERA data provides unique opportunity to study the structure of the proton.


$e^\pm$ energy 27.5 GeV; $p$ energies 920, 820, 575 and 460 GeV.

Kinematics of the $e^\pm p$ collisions:

$$Q^2 = - (k - k')^2$$

$$x_{Bj} = \frac{Q^2}{2 P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

H1 and ZEUS — two collider experiments at HERA:

~ 0.5 $fb^{-1}$ of luminosity recorded by each experiment.
Combined Inclusive DIS

H1 and ZEUS have presented the combination of inclusive DIS measurements, but for zero beams polarisation.

H1 and ZEUS

- 2927 data points combined to 1307
- up to 8 data points combined to 1
- data consistent between two experiments and data taking periods:

\[ \chi^2 / \text{ndf} = 1685 / 1620 \]
Combined Inclusive DIS

H1 and ZEUS

\[ \frac{d\sigma}{dQ^2} \text{(pb/GeV}^2) \]

at low \( Q^2 \), \( \gamma \) exchange (NC DIS) dominates

\[ \gamma Z^0 \text{ interference difference in NC } e^+ \text{ and } e^- \]

Effects of electroweak unification clearly seen.

NC and CC DIS cross sections become comparable at \( Q^2 \sim M_Z^2, M_W^2 \)
QCD analysis of combined DIS data

Neutral Current:

\[
\frac{d^2 \sigma_{\text{NC}}^{e^+p}}{dx_B j dQ^2} = \frac{2\pi \alpha^2}{x_B Q^4} \cdot (Y_+ \cdot F_2 \pm Y_- \cdot x \cdot F_3 - y^2 \cdot F_L)
\]

\(Y_+ = 1 \pm (1 - y)^2\)

\[
F_2 = \frac{4}{9} (xU + x\bar{U}) + \frac{1}{9} (xD + x\bar{D})
\]

\[x \cdot F_3 \sim x u_v + x d_v\]

Similar equation for CC DIS.

**Parton Density Functions** parametrization at starting scale \(Q^2 = 1.9 \text{ GeV}^2\):

- \[x g(x) = A_g x^{B_g} (1 - x)^{C_g} - A'_g x^{B'_g} (1 - x)^{C'_g}\]
  - fixed or calculated by sum-rules

- \[x u_v(x) = A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2)\]
  - set equal

- \[x d_v(x) = A_{d_v} x^{B_{d_v}} (1 - x)^{C_{d_v}}\]

- \[x \bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x)\]
  - Evolve to any \(Q^2\) with DGLAP at NLO.

- \[x \bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}\]
  - Use Thorne-Roberts GMVFN scheme for Heavy quarks.
PDFs set **HERAPDF2.0**: 

Combination of measurements of inclusive deep inelastic $e^\pm p$ scattering cross sections and QCD analysis of HERA data

This paper is dedicated to the memory of Professor Guido Altarelli who sadly passed away as it went to press. The results which it presents are founded on the principles and the formalism which he developed in his pioneering theoretical work on Quantum Chromodynamics in deep-inelastic lepton-nucleon scattering nearly four decades ago.

H1 and ZEUS Collaborations
In NC DIS polarisation affects $\gamma Z^0$ interference and $Z^0$ exchange:

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

$$F_2^+ = F_2^\gamma - \left( v_e + P_e a_e \right) \chi Z F_2^{\gamma Z} + \left( v_e^2 + a_e^2 + 2 P_e v_e a_e \right) \chi Z F_2^Z$$

$$x F_3^+ = - \left( a_e + P_e v_e \right) \chi Z x F_3^{\gamma Z} + \left( 2 v_e a_e + P_e \left( v_e^2 + a_e^2 \right) \right) \chi Z x F_3^Z$$

$$v_e = - \frac{1}{2} + 2 \sin^2(\Theta_W) \quad a_e = - \frac{1}{2}$$

In the on-shell scheme:

$$\sin^2(\Theta_W) = 1 - \frac{M_W^2}{M_Z^2}$$

$$\chi Z = \frac{1}{\sin^2(2\Theta_W)} \frac{Q^2}{M_Z^2 + Q^2} \frac{1}{1 - \Delta R}$$
In $\text{CC}$ DIS polarisation scales the whole cross section:

$$
\frac{d^2 \sigma^{e+p}_{\text{CC}}}{dx_{Bj} dQ^2} = \left(1 - P_e \right) \frac{G_F^2 M_W^4}{2 \pi x_{Bj} (Q^2 + M_W^2)^2} \times
$$

$$
\times x \left[ (u+c) + (1-y)^2 (\bar{d} + \bar{s} + \bar{b}) \right]
$$

$$
\frac{d^2 \sigma^{e+p}_{\text{CC}}}{dx_{Bj} dQ^2} = \left(1 + P_e \right) \frac{G_F^2 M_W^4}{2 \pi x_{Bj} (Q^2 + M_W^2)^2} \times
$$

$$
\times x \left[ (\bar{u} + \bar{c}) + (1-y)^2 (d+s+b) \right]
$$

In the on-shell scheme:

$$
M_W = \frac{A_0}{\sin^2(\Theta_W) \sqrt{1 - \Delta R}}
$$

$$
G_F = \frac{\pi \alpha_0}{\sqrt{2} \sin^2(\Theta_W) M_W^2} \frac{1}{1 - \Delta R}
$$

$\Delta R$ — radiative corrections.
Used uncombined datasets:

- Same as in the data combination:
  - All HERA I data from H1 and ZEUS, unpolarised
  - Reduced $E_p$ data from H1 and ZEUS
  - HERA II data from H1, unpolarised

- Different from the data combination:
  - HERA II data from ZEUS, polarised

Data from $Q^2 = 3.5 \, \text{GeV}^2$

PDFs fits:

- Closely follow HERAPDF2.0
- One parameter less for better fit stability:
  \[
  x \bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1 - x)^{C_{\bar{U}}}
  \]
- $\Delta R$ calculated with EPRC code:  
  [desy.de/~hspiesb/eprc.html]

- Simultaneous PDFs fits with 4 couplings of $Z^0$ to quarks, or $\sin^2(\Theta_W)$ and $M_W$
ZEUS light quark couplings

In quark parton model:

\[
[F_2^γ, F_2^{γZ}, F_2^Z] = \sum_q [e_q^2, 2e_qv_q, v_q^2 + a_q^2] \chi(q + \bar{q})
\]

\[
[\chi F_3^{γZ}, \chi F_3^Z] = \sum_q [e_qa_q, v_qa_q] 2\chi(q - \bar{q})
\]
Comparison to other measurements

**ZEUS**

\[ a_d = -0.56^{+0.34}_{-0.14}/exp + 0.11/fit - 0.05/\text{mod} - 0.00/\text{param} \]

\[ \nu_d = -0.41^{+0.24}_{-0.16}/exp + 0.04/fit - 0.07/\text{mod} - 0.08/\text{param} \]

\[ a_u = 0.50^{+0.09}_{-0.05}/exp + 0.04/fit - 0.02/\text{mod} - 0.01/\text{param} \]

\[ \nu_u = 0.14^{+0.08}_{-0.08}/exp + 0.01/fit - 0.00/\text{mod} - 0.01/\text{param} \]
Remarkable sensitivity to \textit{u-type} quark couplings
Correlations

Fit shows high correlation of axial-vector and vector couplings between quark types:

Their correlations to PDF parameters are small.
Simultaneous extraction of $M_W$ and $\sin^2(\Theta_W)$:

\[
\begin{align*}
M_W & = 79.30 \pm 0.76 \quad \text{(exp/fit)} - 0.08 \quad \text{(mod)} - 0.10 \quad \text{(param)} \\
\sin^2(\Theta_W) & = 0.2293 \pm 0.0031 \quad \text{(exp/fit)} - 0.001 \quad \text{(mod)} - 0.001 \quad \text{(param)}
\end{align*}
\]

Good agreement with world average:

\[
\begin{align*}
M_W^{PDG14} & = 80.385 \pm 0.015 \\
\sin^2(\Theta_W)^{PDG14 on-shell} & = 0.22333 \pm 0.00011
\end{align*}
\]
Effective $\sin^2(\Theta_W)$

On-shell measurements for the whole data and for three bins in $Q^2$ translated to effective $\sin^2(\Theta_W)$:

First observation of $\sin^2(\Theta_W)^{\text{eff}}$ running from one experiment.
H1 QCD + EW fits

Used uncombined datasets:

- Same as in the data combination:
  - All HERA I data from H1, unpolarised
  - Reduced $E_p$ data from H1

- Different from the data combination:
  - HERA II data from H1, polarised

Data from $Q^2 = 12 \text{ GeV}^2$

PDFs fits:

- Basics similar to ZEUS approach
- DGLAP evolution at NNLO
- Calculations strictly in on-shell scheme
- Polarisation values fitted within uncertainties as 4 additional parameters
- New C++ fitter and Alpos code used
- Different (log-normal) $\chi^2$ definition, but results similar to using $\chi^2$ from HERAPDF2.0
Comparison to other measurements

Comparable precision for \(u\)-type quark couplings
Comparison to ZEUS result

H1 preliminary
H1 (HERA I)
ZEUS-EW-Z
Standard model

Oleksii Turkot  Electroweak and new physics fits to HERA DIS data  18
$M_W$ and $\sin^2(\Theta_W)$, $G_F$, $M_Z$

Simultaneous extraction of pairs of parameters:

\[
\begin{align*}
\sigma_{NC}(\alpha, \sin^2(\Theta_W), M_Z, M_W) \\
\sigma_{CC}(G_F[\alpha, \sin^2(\Theta_W), M_W], M_W)
\end{align*}
\]

Determined mass of W boson using external mass of $Z^0$:

\[
\begin{align*}
\sigma_{NC}(\alpha, \sin^2(\Theta_W)[M_Z, M_W], M_Z) \\
\sigma_{CC}(G_F[\alpha, M_Z, M_W], M_W)
\end{align*}
\]

\[m_W = 80.407 \pm 0.118_{\text{exp, pdf}} \pm 0.005_{m_Z, m_t, m_H} \]

Result consistent with PDG2014: $M_W^{\text{DPG14}} = 80.385 \pm 0.015$
On-shell measurement for seven bins in $Q^2$:

$$\sin^2(\Theta_W) = 0.2252 \pm 0.0011$$

Good agreement with world average:

$$\sin^2(\Theta_W)^{PDG\ 14\ on-shell} = 0.22333 \pm 0.00011$$
One of the possible parameterisations of deviations from SM – spatial distribution or substructure of electrons and/or quarks:

\[
\frac{d \sigma}{d Q^2} = \frac{d \sigma^{SM}}{d Q^2} \left(1 - \frac{R_e^2}{6} Q^2\right)^2 \left(1 - \frac{R_q^2}{6} Q^2\right)^2
\]

\(R_e, R_q\) – root mean square radii of the electroweak charge distributions in the electron and quark.

**Same dependence** expected for NC and CC e\(^+\)p and e\(^-\)p.

We assume \(R^2_e = 0\) and consider both, positive and negative values of \(R^2_q\).

HERA data is a core of any PDF extraction, and thus simultaneous fit, PDF+BSM, is necessary for any BSM analysis. For \(R^2_q\) such fit provide:

\[R^2_{q,\text{Data}} = -[0.14 \cdot 10^{-16} \text{ cm}]^2\]

in agreement with SM expectation of \(R^2_{q,\text{Data}} = 0\).
Frequentist approach

Monte Carlo replicas of the whole data set were generated as:

\[ \mu_i = \left[ m_0^i + \delta_{\text{tot. uncor.}}^i \cdot r_{\text{tot. uncor.}}^i \cdot \mu_0^i \right] \cdot \left(1 + \sum_j \gamma_j \cdot r_{\text{sys.sh.}}^j \right) \]

\( r^i, r^j \) – Gaussian random numbers.

Previous method \( R_q \)-only

\( R_q^2 \) parameter fitted with PDFs fixed to SM PDFs.

And two different procedures were tested:

New method PDF+\( R_q \)

\( R_q^2 \) parameter fitted simultaneously with PDFs.

For example, for \( R_q^{\text{True}} = 0.48 \cdot 10^{-16} \text{ cm} \):
For each replica fit $R_{q}^{2}$ with fixed PDFs

Choose $R_{q}^{2 \text{ True}}$ and generate Monte Carlo replicas using SM PDFs

Evaluate fraction of $R_{q}^{2 \text{ Fit}} < R_{q}^{2 \text{ Data}}$

For each replica fit PDFs + $R_{q}^{2}$

Plot $\text{Prob}(R_{q}^{2 \text{ Fit}} < R_{q}^{2 \text{ Data}})$ as a function of $R_{q}^{2 \text{ True}}$

Calculate $R_{q}^{2 \text{ Limit}}$ for $CL = 95\%$

Analysis Flowchart

Previous method $R_{q}\text{-only}$

New method $\text{QCD} + R_{q}$
$R_q$-only

Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$

$R_q$ limit = $0.40 \cdot 10^{-16}$ cm
Fractions close to 5% fitted with:

\[ f(x) = 5 \cdot \exp((x - A) \cdot B) \]

\[ R_q^{\text{Limit}} = 0.43 \cdot 10^{-16} \text{ cm} \]
Negative $R_{q}^2$ limit:

Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$

$R_{q}^2$ limit:

$$R_{q}^2 \text{ Limit} = - [0.47 \cdot 10^{-16} \text{ cm}]^2$$
Comparison of $R_q^2$ exclusion limits to HERA NC ep DIS data.
Summary

- HERA polarised inclusive data allows to determine electroweak parameters simultaneously with PDFs
- Couplings of u-type quarks among the most accurate in the world
- Unique observations of $\sin^2(\Theta_W)$ and $\sin^2(\Theta_W)^{\text{eff}}$ running from one experiment
- First BSM limits based on the new approach: simultaneous fit of PDF and BSM contribution; it shows that limits obtained with “previous” method $\sim$10-20% too strong.
QCD analysis of combined DIS data

Charged Current:

\[
\frac{d^2 \sigma^{e^+p}_{CC}}{dx dQ^2} = \frac{G_F^2}{4 \pi x} \cdot \kappa^2 \cdot \left( Y_+ \cdot W_2^\mp + Y_- \cdot x \cdot W_3^\mp - y^2 \cdot W_L^\mp \right)
\]

\[
\kappa = \frac{M_W^2}{M_W^2 + Q^2}
\]

\[
W_2^- = x (U + \bar{D}) \quad W_2^+ = x (D + \bar{U})
\]

\[
x W_3^- = x (U - \bar{D}) \quad x W_3^+ = x (D - \bar{U})
\]
BSM QCD analysis of combined DIS data

ZRqPDF set compared to HERAPDF2.0:
Quark form factor and CC DIS data

Comparison of $R_q^2$ exclusion limits to HERA CC ep DIS data.