Fit of Electroweak Parameters in Polarised Deep-Inelastic Scattering using data from the H1 experiment

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Deep-inelastic scattering

**Kinematic variables**
- virtuality of exchanged boson
  \[ Q^2 = -q^2 = -(k - k')^2 \]
- Bjorken scaling variable
  \[ x = \frac{Q^2}{2p \cdot q} \]
- Inelasticity
  \[ y = \frac{p \cdot q}{p \cdot k} \]

**Neutral current scattering**
\[ ep \rightarrow e'X \]

**Charged current scattering**
\[ ep \rightarrow \nu_e X \]

**Factorization in ep collisions**
Hard scattering coefficients and parton distribution functions (PDFs)

\[ \sigma_{ep \rightarrow eX} = \int p \rightarrow i \otimes \hat{\sigma}_{ei \rightarrow eX} \]

**PDFs are not observables – only structure functions are**
PDFs are largely determined from DIS data
Polarised deep-inelastic ep scattering

Neutral and charged current at tree level

\[ \frac{d\sigma_{NC}^{\pm}}{dQ^2 dx} = 2\pi\alpha^2 \left( \frac{1}{Q^2} \right)^2 \left( Y_+ F_2 + Y_+ x F_3 + y^2 F_L \right) \]

\[ \frac{d\sigma_{CC}^{\pm}}{dQ^2 dx} = \frac{1 \pm P}{2} \frac{G_F}{4\pi x} \left( \frac{m_W^2}{m_W^2 + Q^2} \right)^2 \left( Y_w W^z_2 \pm Y_w x W^z_3 - y^2 W_L^z \right) \]

\[ Y_\pm = 1 \pm (1 - y)^2 \]

Generalised structure functions

\[ F_2 = F_2^Y + \kappa_Z (v_e \mp Pa_e) F_2^{YZ} + \kappa_Z^2 (v_e^2 + a_e^2 \pm P v_e a_e) F_2^Z \]

\[ x F_3 = + \kappa_Z (\pm a_e + P v_e) F_3^{YZ} + \kappa_Z^2 \left( \pm 2 v_e a_e - P (v_e^2 + a_e^2) \right) x F_3^Z \]

\[ Z^0-exchange \]

\[ \kappa_Z (Q^2) = \frac{Q^2}{Q^2 + m_Z^2} \frac{G_F m_Z^2}{2\sqrt{2} \pi \alpha} \]

Structure functions in QPM

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

\[ [x F_3^{YZ}, x F_3^Z] = x \sum_q \left[ 2 e_q a_q, 2 v_q a_q \right] [q \bar{q}] \]

Weak couplings to Z-boson

\[ v_f = I_{f,L}^{[3]} - 2 e_f \sin^2 \theta_W \]

\[ a_f = I_{f,L}^{[3]} \quad (f = e, u, d, ...) \]

Calculations in on-shell scheme

\[ G_F = \frac{2\pi\alpha}{2\sqrt{2} m_W^2} \left( 1 - \frac{m_W^2}{m_Z^2} \right)^{-1} \left( 1 + \Delta r \right) \]

Corrections to G_F

\[ \Delta r = \Delta r \left( \alpha, m_W, m_Z, m_t, m_H, ... \right) \]

Parameters to calculations

Parameters to cross section calculation: \( \alpha, m_Z, m_W, (m_t, m_H, ...) \)

More general, also couplings: \( v_e, a_e, v_u, a_u \) and \( v_d, a_d \)
HERA Operation

**HERA-I operation 1993-2000**
- $E_e = 27.6$ GeV
- $E_p = 820 / 920$ GeV
- $\sqrt{s} = 301 \ & \ 318$ GeV
- int. Lumi. $\sim 110$ pb$^{-1}$

**HERA-II operation 2003-2007**
- $E_e = 27.6$ GeV
- $E_p = 920$ GeV
- $\sqrt{s} = 318$ GeV
- int. Lumi. $\sim 330$ pb$^{-1}$
- Longitudinally polarised leptons

Polarisation:

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

**Low-Energy Run 2007**
- $E_e = 27.6$ GeV
- $E_p = 575 \ & \ 460$ GeV
- $\sqrt{s} = 225 \ & \ 251$ GeV
- Dedicated $F_L$ measurement
The H1 Detector

**H1 multi-purpose detector**
- Asymmetric design

**Trackers**
- Silicon tracker
- Jet chambers
- Proportional chambers

**Calorimeters**
- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

**Superconducting solenoid**
- 1.15T magnetic field

**Muon detectors**

**Excellent control over experimental uncertainties**
- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 1.5 - 2.5%
- Continuous upgrades with time
# H1 Structure Function Data

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$Q^2$ min</th>
<th>$Q^2$ max</th>
<th>No. Points</th>
<th>Polarisation [%]</th>
<th>Reference</th>
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<td>150</td>
<td>81 [262]</td>
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Fit methodology I

Determine light-quark couplings
• Use iterative minimisation procedure (‘fit’) of cross section predictions to data

Unfortunate correlation
• PDFs have considerable uncertainties
• These PDFs are essentially determined from H1 structure function data
  -> Large correlations
• Consider PDF uncertainty by simultaneous fit of PDFs and light quark couplings

Consistency of fit-parameters in SM formalism
• Perform calculations strictly in on-shell scheme
  Parameters are: $\alpha$, $m_Z$, $m_W$, ($m_t$, $m_H$, ...)

Polarisation measurement
• Measurements of the beam polarisations are measurements on their own
  -> Consider these measurements as independent measurements in fit

1-loop EW corrections
• May be considered in terms of ‘EW form factors’
• Are ignored in the present analysis, but will be included in the future
**Fit methodology II**

**New C++-based fitting code for PDF and more general fits developed (Alpos)**

- DGLAP evolution of PDFs in NNLO QCD (QCDNUM with ZMVFNS)
- PDFs are parameterised at starting scale $Q_0^2 = 1.9 \text{GeV}^2$ (similar to HERAPDF2.0)

\[
\begin{align*}
  x_g & \to x_g \\
  x_{u,v} & \to x_U = x_u + x_c \\
  x_d & \to x_D = x_d + x_s \\
  x_{\bar{U}} & \to x_{\bar{U}} = x_{\bar{u}} + x_{\bar{c}} \\
  x_{\bar{D}} & \to x_{\bar{D}} = x_{\bar{d}} + x_{\bar{s}}
\end{align*}
\]

- Use only data with $Q^2 \geq 12 \text{ GeV}^2$

**$\chi^2$ Definition**

- Uncertainties on cross sections are assumed to be 'log-normal' distributed (relative uncertainties)
- Uncertainties on polarisation measurements are assumed to be 'normal' distributed
- Correlations of syst. uncertainties between different datasets are considered

\[
\chi^2 = \left( \log(d) - \log(t) \right)^T V_R^{-1} \left( \log(d) - \log(t) \right) + \left( d - t \right)^T V_A^{-1} \left( d - t \right)
\]

**Fit parameters**

- 13 PDF parameters
- 4 polarisation values
- 4 Light-quark couplings (or other SM parameters)
- More general also 'nuisance parameters' of syst. uncertainties
Light quark couplings

**Couplings of light quarks to Z-boson**
- $\chi_2^2 / \text{ndf} = 1370.5 / (1388 - 21)$
- $u$-type coupling better constrained than $d$-type coupling
  -> sensitivity from valence quarks
- Results compatible with SM expectation
- PDF uncertainties are small

**Comparison to H1 HERA-I**
- Considerably improved sensitivity using final H1 HERA-II data
- Polarisation in HERA-II important for vector couplings

**Fit: PDF + 2 couplings**
- Reduced correlations and uncertainties
- Correlations between $a_u-a_d$ and $v_u-v_d$ are large
Light quark couplings

**Couplings of light quarks to Z-boson**
  Effective couplings from asymmetry at Z-pole
- D0 [Phys. Rev. D 84 (2011) 012007]
  Forward-backward charge asymmetry

**Comparable precision of complementary processes**
Study of Standard Model Parameters

**Standard Model is now overconstrained**
- Important to study consistency in many complementary processes
- HERA: Space-like momentum transfers
- Only purely virtual exchange of bosons

\( (m_W - m_Z) + PDF \) fits
- Assume \( \alpha \) is known
- On-shell masses \( m_W \) and \( m_Z \) are only free EW parameters
- Agreement within PDG14 SM values
- Large correlation between \( m_W \) and \( m_Z \)

**Mass of W-boson**
Take other masses \( (m_Z) \) as external input to calculations

\[
m_W = 80.407 \pm 0.118 \text{ (exp, pdf-fit)} \pm 0.005 \text{ (} m_Z, m_t, m_H \text{)} \text{ GeV}
\]

Approx. half the exp. uncertainty may be attributed to PDFs

Compare to H1 HERA-I: \( m_W = 80.786 \pm 0.205 \text{ (exp)} +0.063_{-0.098} \text{ (th)} \text{ GeV} \)

\[
m_{W,PDG} = 80.385 \pm 0.015 \text{ GeV}
\]
**Study of Standard Model Parameters**

**Different view on SM parameters**
- Fermi coupling constant $G_F$
  \[ G_F = \frac{\pi \alpha}{\sqrt{2} m_w^2 \sin^2 \theta_W} \left(1 + \Delta r \right) \]
- Weak mixing angle
  \[ \sin^2 \theta_W = 1 - \frac{m_w^2}{m_Z^2} \]

**Perform calculations consistently in on-shell scheme ($\alpha, m_Z, m_w$)**
- Calculate $m_Z$ (iteratively) from $G_F$ or $\sin^2 \theta_W$

**Results from fits together with PDF and $m_w$**
- H1 values consistent with precise values from PDG
- Correlation to $m_w$ are different for $m_Z$, $\sin^2 \theta_W$ and $G_F$
Exploit $Q^2$ dependence of data

**Virtually exchanged bosons allow for SM tests at various energy scales**

- Weak mixing angle is extracted for different scales $\mu = \sqrt{Q^2}$
- Simultaneous fit of PDF and values of $\sin^2 \theta_W$
- Data are subdivided into different $Q^2$ regions each with independent $\sin^2 \theta_W(Q^2)$

**Results**

- Results compatible with precise value from Z-pole measurements
- Unique measurement of weak mixing angle at different scales
- Comparison to MSbar values straight forward

**Graphs**

- On-shell scheme
- MS scheme
- PDG14
Summary and Outlook

*Light quark couplings to Z-boson*
- Couplings determined from all H1 structure function data
- Longitudinal polarisation improves significantly H1 HERA-I result
- Values are consistent with SM expectations and compatible with other collider data

*Standard model tests*
- SM parameters are tested in deep-inelastic scattering
- Good consistency is found for $m_Z$, $m_W$, $G_F$ and $\sin^2\Theta_W$
- Weak mixing angle is determined at different scales in a single experiment

*W-boson mass*
- W-boson mass determined with an experimental precision of 118 MeV
- Fitted value consistent with precise direct measurements
- Significantly improves H1 HERA-I results ($\Delta m_W \sim 200$ MeV)

*Outlook*
- Calculations to be supplemented with full 1-loop EW corrections
- $\rightarrow$ NNLO-QCD + NLO-EW fit to H1 data