Determination of electroweak parameters in polarised DIS at HERA

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Zhiqing ZHANG on behalf of the H1 Collaboration

based on arXiv:1806.01176, submitted to EPJC

Outline

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- Results
- Summary

Determination of EW Parameters Using H1 Data

arXiv:1806.01176
Submitted to EPJC

- Deep Inelastic Scattering
- EW Couplings & PDFs
- H1 Detector & Selection
- Fit Methodology
- Neutral & Charged Current Weak Coupling Fits
- BSM Form Factor Deviations in NC and CC DIS

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QCD@LHC
— Dresden —
27th August 2018
Deep Inelastic Scattering

Neutral current scattering

\[ e^{\pm} \rightarrow e^{\pm} + Z/\gamma^* (q) \]

(\(xp+q\))

\[ p \rightarrow X \]

Charged current scattering

\[ e^{\pm} \rightarrow e^{\pm} + W^\pm (q) \]

(\(xp+q\))

\[ p \rightarrow X \]

DIS tests space-like 4-momentum transfer
Complementary to time-like tests (LHC/LEP)

Factorisation in \(ep\) collisions:

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

\[ xf_{p \rightarrow i} = \text{quark / gluon momentum density in proton: parton density function (PDFs)} \]

Use factorisation in \(pp\) collisions at LHC:

\[ \sigma_{pp \rightarrow X} = \int_{p \rightarrow i} \otimes \hat{\sigma}_{i,j \rightarrow X} \otimes \int_{p \rightarrow j} \]

**Signature**

- Isolated electron/positron
- \(pT\) balanced with hadronic system \(X\)

PDFs are not observables - only structure functions are.
Measuring these cross sections allows indirect access to the universal PDFs \(xf_{p \rightarrow i}\)

**Signature**

- No detected lepton (neutrino)
- \(pT\) imbalanced for hadronic system \(X\)
Structure Functions

\[ \frac{d\sigma_{NC}^\pm}{dx dQ^2} = \frac{2\pi\alpha^2}{x} \left[ \frac{1}{Q^2} \right]^2 \left[ Y_+\tilde{F}_2 + Y_+x\tilde{F}_3 - y^2\tilde{F}_L \right] \]

\[ \frac{d\sigma_{CC}^\pm}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_+\tilde{W}_2^\pm + Y_-x\tilde{W}_3^\pm - y^2\tilde{W}_L^\pm \right] \]

**Dominant contribution**

\( \tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i) \)

\( x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i) \)

\( \tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2) \)

**The NC reduced cross section defined as:**

\[ \tilde{\sigma}_{NC}^\pm = \frac{Q^2x}{2\alpha\pi^2} \frac{1}{Y_+} \frac{d^2\sigma}{dx dQ^2} \]

\[ \tilde{\sigma}_{NC}^\pm \sim \tilde{F}_2 + \frac{Y}{Y_+} x\tilde{F}_3 \]

**The CC reduced cross section defined as:**

\[ \sigma_{cc}^\pm = \frac{2\pi x}{G_F^2} \left[ \frac{M_W^2 + Q^2}{M_W^2} \right]^2 \frac{d\sigma_{cc}^\pm}{dx dQ^2} \]

\[ \frac{d\sigma_{cc}^\pm}{dx dQ^2} = \frac{1}{2} \left[ Y_+ W_2^\pm + Y_-xW_3^\pm - y^2W_L^\pm \right] \]

neutral current

charged current

similarly for pure weak CC analogues:

\( W_2^\pm, xW_3^\pm \) and \( W_L^\pm \)

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HERA data cover wide region of $x, Q^2$

NC Measurements
$F_2$ dominates most of $Q^2$ reach
$xF_3$ contributes in EW regime
$F_L$ contributes only at highest $y$

CC Measurements
$W_2$ and $xW_3$ contribute equally
$W_L$ only at high $y$
$P_e =$ lepton beam polarisation

At LO in EW $\kappa = \frac{G_F m_Z^2}{2 \sqrt{2} \pi \alpha}$

pure photon piece

$\tilde{F}_2^\pm = F_2 - (v_e \pm P_e a_e) \kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm P_e 2v_e a_e) \kappa^2 \frac{Q^2}{Q^2 + M_Z^2} F_2^{Z}$

interference piece

$F_2^{\gamma Z} = x \tilde{F}_2^\pm - (a_e \pm P_e v_e) \kappa \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + (2a_e v_e \pm P_e [v_e^2 + a_e^2]) \kappa^2 \frac{Q^2}{Q^2 + M_Z^2} xF_3^{Z}$

pure weak piece

$v_e$ is small $\sim 0.05$ ⇒ terms contribute little

interference piece

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

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

$F_2^{\gamma Z} \rightarrow$ main $v_q$ constraint

$F_2^{Z} \rightarrow$ main constraint on $a_q / v_q$ correlation

$xF_3^{Z} \rightarrow$ main $a_q$ constraint
NC data constrain:
- singlet quarks / gluon PDFs
- non-singlet valence quark PDFs at high $Q^2$
But, flavour sensitivity is weak

Structure Functions

CC data enable flavour decomposition of proton:
\[
\begin{align*}
W_2^- &= x(u + c + \bar{d} + \bar{s}) , \quad W_2^+ = x(\bar{u} + \bar{c} + d + s) , \\
xW_3^- &= x(u + c - \bar{d} - \bar{s}) , \quad xW_3^+ = x(d + s - \bar{u} - \bar{c})
\end{align*}
\]

Requires $e^+$ and $e^-$ scattering data

\[
\frac{d^2\sigma_{CC}^-}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ (u + c) + (1 - y)^2 (\bar{d} + \bar{s}) \right], \quad \frac{d^2\sigma_{CC}^+}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ (\bar{u} + \bar{c}) + (1 - y)^2 (d + s) \right]
\]

For polarised lepton beams CC cross section scales linearly with $P_e$:
- $\sigma_{CC}(e^-p) = 0$ for $P_e = +1$
- $\sigma_{CC}(e^+p) = 0$ for $P_e = -1$

CC $e^+$ data provide strong $d_v$ constraint at high $x$ ($y \sim 0$)
Higher Order EW Corrections

EW quark couplings
\[ e_q, a_q, v_q \]

\[ a_e = \sqrt{\rho_{NC}} \ I^3_{L,f} \]
\[ v_e = \sqrt{\rho_{NC}} \ (I^3_{L,f} - 2e_q \kappa_{NC,q} \sin^2 \theta_W) \]

In on-shell scheme
\[ \sin^2 \theta_W = 1 - \frac{m^2_W}{m^2_Z} \]
\[ G_F = \frac{\pi \alpha}{\sqrt{2} m^2_W} \frac{1}{\sin^2 \theta_W} \frac{1}{(1 - \Delta r)} \]
\[ \Delta r = \Delta r(\alpha, m_W, m_Z, m_t, m_h, \ldots) \]

The \( \rho_{NC,q} \) and \( \kappa_{NC,q} \) are form factors — universal (fermion independent) functions of \( Q^2 \) and encapsulate HO EW loop effects,

\[ \rho_{CC,q}, \rho_{CC,\bar{q}} \]

are inserted for quarks and anti-quarks in the above formulae account for HO EW effects (mainly loop effects)

\[ W^-_2 = x \left( \rho_{CC,eq}^2 U + \rho_{CC,eq}^2 \bar{D} \right), \quad xW^-_3 = x \left( \rho_{CC,eq}^2 U - \rho_{CC,eq}^2 \bar{D} \right) \]
\[ W^+_2 = x \left( \rho_{CC,eq}^2 \bar{U} + \rho_{CC,eq}^2 D \right), \quad xW^+_3 = x \left( \rho_{CC,eq}^2 D - \rho_{CC,eq}^2 \bar{U} \right) \]

\[ \rho_{NC} \rightarrow \rho'_{NC}\rho_{NC} \]

In SM extensions, form factors can be modified
\[ \kappa_{NC} \rightarrow \kappa'_{NC}\kappa_{NC} \]
\[ \rho_{CC} \rightarrow \rho'_{CC}\rho_{CC} \]

Can test for deviations beyond the SM
Neutral current event selection:

High $P_T$ isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways:
energy/angle of hadrons & scattered lepton provides excellent tools for sys cross checks

Removal of scattered lepton provides a high stats "pseudo-charged current sample"
Excellent tool to cross check CC analysis

Final selection: $\sim 10^5$ events per sample at high $Q^2$
$\sim 10^7$ events for $10 < Q^2 < 100$ GeV$^2$

Charged current event selection:

Large missing transverse momentum (neutrino)
Suppress huge photo-production background
Topological finders to remove cosmic muons
Kinematics reconstructed from hadrons
Final selection: $\sim 10^3$ events per sample
HERA-I operation 1993-2000
Ee = 27.6 GeV
Ep = 820 / 920 GeV
$\int L \sim 110 \text{ pb}^{-1}$

HERA-II operation 2003-2007
Ee = 27.6 GeV
Ep = 920 GeV
$\int L \sim 330 \text{ pb}^{-1}$
Longitudinally polarised leptons

Low Energy Run 2007
Ee = 27.6 GeV
Ep = 575 & 460 GeV
Dedicated $F_L$ measurement

First EW analysis performed on HERA-I data
This analysis includes:
full HERA-I and HERA-II dataset
longitudinal lepton polarisation to enhance sensitivity
factor 10 increase in $e^-$ & factor 3 increase in $e^+$ luminosity
much improved systematic uncertainties

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mathcal{L}$</th>
<th>$P_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^- p$</td>
<td>45.9 pb$^{-1}$</td>
<td>$(+36.9 \pm 2.3)%$</td>
</tr>
<tr>
<td>$e^+ p$</td>
<td>98.1 pb$^{-1}$</td>
<td>$(+32.5 \pm 1.2)%$</td>
</tr>
</tbody>
</table>

\[ \mathcal{L} = \text{(expected luminosity)} \]

\[ P_e = \text{(lepton polarisation)} \]
<table>
<thead>
<tr>
<th>Data set</th>
<th>$Q^2$-range [GeV$^2$]</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>$\mathcal{L}$ [pb$^{-1}$]</th>
<th>No. of data points</th>
<th>Polarisation [%]</th>
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</thead>
<tbody>
<tr>
<td>1 $e^+$ combined low-$Q^2$</td>
<td>(0.5) 8.5 – 150</td>
<td>301,319</td>
<td>20, 22, 97.6</td>
<td>94 (262)</td>
<td>–</td>
</tr>
<tr>
<td>2 $e^+$ combined low-$E_p$</td>
<td>(1.5) 8.5 – 90</td>
<td>225,252</td>
<td>12.2, 5.9</td>
<td>132 (136)</td>
<td>–</td>
</tr>
<tr>
<td>3 $e^+$ NC 94–97</td>
<td>150 – 30 000</td>
<td>301</td>
<td>35.6</td>
<td>130</td>
<td>–</td>
</tr>
<tr>
<td>4 $e^+$ CC 94–97</td>
<td>300 – 15 000</td>
<td>301</td>
<td>35.6</td>
<td>25</td>
<td>–</td>
</tr>
<tr>
<td>5 $e^-$ NC 98–99</td>
<td>150 – 30 000</td>
<td>319</td>
<td>16.4</td>
<td>126</td>
<td>–</td>
</tr>
<tr>
<td>6 $e^-$ CC 98–99</td>
<td>300 – 15 000</td>
<td>319</td>
<td>16.4</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td>7 $e^-$ NC 98–99 high-(y)</td>
<td>100 – 800</td>
<td>319</td>
<td>16.4</td>
<td>13</td>
<td>–</td>
</tr>
<tr>
<td>8 $e^+$ NC 99–00</td>
<td>150 – 30 000</td>
<td>319</td>
<td>65.2</td>
<td>147</td>
<td>–</td>
</tr>
<tr>
<td>9 $e^+$ CC 99–00</td>
<td>300 – 15 000</td>
<td>319</td>
<td>65.2</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td>10 $e^+$ NC L HERA-II</td>
<td>120 – 30 000</td>
<td>319</td>
<td>80.7</td>
<td>136</td>
<td>$-37.0 \pm 1.0$</td>
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<tr>
<td>11 $e^+$ CC L HERA-II</td>
<td>300 – 15 000</td>
<td>319</td>
<td>80.7</td>
<td>28</td>
<td>$-37.0 \pm 1.0$</td>
</tr>
<tr>
<td>12 $e^-$ NC R HERA-II</td>
<td>120 – 30 000</td>
<td>319</td>
<td>101.3</td>
<td>138</td>
<td>$+32.5 \pm 0.7$</td>
</tr>
<tr>
<td>13 $e^+$ CC R HERA-II</td>
<td>300 – 15 000</td>
<td>319</td>
<td>101.3</td>
<td>29</td>
<td>$+32.5 \pm 0.7$</td>
</tr>
<tr>
<td>14 $e^-$ NC L HERA-II</td>
<td>120 – 50 000</td>
<td>319</td>
<td>104.4</td>
<td>139</td>
<td>$-25.8 \pm 0.7$</td>
</tr>
<tr>
<td>15 $e^-$ CC L HERA-II</td>
<td>300 – 30 000</td>
<td>319</td>
<td>104.4</td>
<td>29</td>
<td>$-25.8 \pm 0.7$</td>
</tr>
<tr>
<td>16 $e^-$ NC R HERA-II</td>
<td>120 – 30 000</td>
<td>319</td>
<td>47.3</td>
<td>138</td>
<td>$+36.0 \pm 0.7$</td>
</tr>
<tr>
<td>17 $e^-$ CC R HERA-II</td>
<td>300 – 15 000</td>
<td>319</td>
<td>47.3</td>
<td>28</td>
<td>$+36.0 \pm 0.7$</td>
</tr>
<tr>
<td>18 $e^+$ NC HERA-II high-(y)</td>
<td>60 – 800</td>
<td>319</td>
<td>182.0</td>
<td>11</td>
<td>–</td>
</tr>
<tr>
<td>19 $e^-$ NC HERA-II high-(y)</td>
<td>60 – 800</td>
<td>319</td>
<td>151.7</td>
<td>11</td>
<td>–</td>
</tr>
</tbody>
</table>
Unpolarised High $Q^2$ NC Cross Sections

H1 Collaboration

H1 precision 1.5% for $Q^2 < 500 \text{ GeV}^2$
⇒ factor 2 reduction in error wrt HERA-I

Statistics limited at higher $Q^2$ and high $x$

Extended reach at high $x$

This $x$ region is the ‘sweet spot’
High precision with long $Q^2$ lever arm
$x$-range relevant for Higgs production

Combination of high $Q^2$ data
HERA-I and HERA-II

Larger HERA-II luminosity
⇒ improved precision at high $x / Q^2$

Data well described by NLO QCD in this case H1PDF2012 — qualitatively similar to HERAPDF
Unpolarised High $Q^2$ CC Cross Sections

Electron scattering

$$\frac{d^2\sigma_{CC}^-}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ (u + c) + (1 - y)^2 (\bar{d} + \bar{s}) \right]$$

Positron scattering

$$\frac{d^2\sigma_{CC}^+}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ (\bar{u} + \bar{c}) + (1 - y)^2 (d + s) \right]$$

H1 combination of high $Q^2$ CC data (HERA-I+II)

Improvement of total uncertainty

Dominated by statistical errors

Provide important flavour decomposition information

CC $e^+$ data provide strong $d_v$ constraint at high x

Precision limited by statistics: typically 5-10%

HERA-I precision of 10-15% for $e^+p$
Dedicated PDF fit required to avoid bias (EW params used in PDF fits) 
Combine NC and CC HERA-I data from H1 
Complete MSbar NNLO QCD fit 
\( \alpha_s = 0.1176 \) (fixed in fit)

```
Each PDF parameterised by form 
\[ x_f (x, Q_0^2) = A \cdot x^B \cdot (1 - x)^C \cdot (1 + D x + Ex^2) \]

\[ x_g \]
\[ x u_v \]
\[ x d_v \]
\[ x U \]
\[ x D \]

13 free PDF params. + 4 polarisation params. 
1410 measurements + 4 polarisation measurements
```

\[ \chi^2 / n_{dof} = 1432 / (1414 - 17) = 1.03 \]

Excellent consistency of data allows standard statistical error definition: \( \Delta \chi^2 = 1 \)

- Combined QCD / EW fit accounts for correlations in uncertainties
- Fits constructed very similar to HERAPdf2.0 at NNLO QCD

Apply momentum/counting sum rules:
\[
\int_0^1 dx \cdot (x u_v + x d_v + x U + x D + x g) = 1 \\
\int_0^1 dx \cdot u_v = 2 \\
\int_0^1 dx \cdot d_v = 1
\]

Parameter constraints:
\[ A_{Ubar} = A_{Dbar} \]
\[ B_{Ubar} = B_{Dbar} \]
\[ \text{sea} = 2 \times (Ubar + Dbar) \]
\[ C'_g = 25 \text{ (fixed)} \]

\[ Q_0^2 = 1.9 \text{ GeV}^2 \text{ (below } m_c) \]
\[ Q^2 > 8.5 \text{ GeV}^2 \]
\[ 2 \times 10^{-4} < x < 0.65 \]

Fits performed using ZM-VFNS
Perform fit to $W$ mass - sensitivity mainly from CC cross section normalisation (i.e. via $G_F$)

$$m_W = 80.520 \pm 0.070_{\text{stat}} \pm 0.055_{\text{syst}} \pm 0.074_{\text{PDF}}[\pm 0.115_{\text{total}}]\text{GeV}$$

\begin{tabular}{l|l}
\textbf{W-boson mass} & \textbf{ALEPH} \hline
ATLAS & ALEPH  \\
CDF & ALEPH  \\
D0 & ALEPH  \\
DELPHI & ATLAS  \\
L3 & ATLAS  \\
OPAL & ATLAS  \\
H1 & OPAL  \\
\textbf{PDG 2017} & \end{tabular}

Indirect measurement of $m_W$, or equivalently $\sin^2 \theta_W$:

$$\sin^2 \theta_W = 0.022029 \pm 0.002233$$

in on-shell scheme

$$G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2} \frac{1}{\sin^2 \theta_W} \frac{1}{(1 - \Delta r)}$$

$$\Delta r = \Delta r(\alpha, m_W, m_Z, m_t, m_h, \ldots)$$

$$\frac{d^2 \sigma_{CC}}{dx dQ^2} \propto G_F^2 \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2$$

Can also test the space-like charged current propagator mass = 80.62 ± 0.79 GeV
Weak Couplings

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The SM expectation at 1–2 standard deviations. The parameters of individual light quarks and for electrons are shown in figure one. The results are presented in table 4:

- Table 4: Results for type are fixed, i.e. the couplings of one quark type are fit parameters, and the couplings of the other quark type are fixed, i.e. the PDF fits, respectively. In these fits, the other quark type are fixed, i.e. the PDF fits, respectively. In these fits, the other quark type are fixed, i.e. the PDF fits, respectively. In these fits, the other quark type.

- Figures 4: Results for the weak neutral-current couplings of the quark in the leading, , and -interference term (see equations (4a) and (4b)).

- Similar sensitivity to and as LEP and D0.

Perform 4-coupling and two 2-coupling fits:

- 4-coupling fits extract and axial and vector couplings and are taken as other input EW parameters.

- 2-coupling fit extracts u-type axial / vector couplings.

- 2-coupling fit extracts d-type axial / vector couplings.

- LEP & SLD (d=s,u)

- D0 ($\Delta\chi^2 = 4.72$)

- SM

- H1 (PDF fit)
due to the very strong correlations between the EW parameters. The exception is to the limited scale of the panel. For comparison, also the result of the Figure 5: Results for the

\[ g_A^q = \sqrt{\rho_{NC,q} I_3^q}, \]
\[ g_A^q = \sqrt{\rho_{NC,q} (I_3^q - 2Q_q \kappa_{NC,q} \sin^2 \theta_W)} \]

The same formulae also apply to the lepton couplings

\[ \rho_{NC} \rightarrow \rho'_{NC} \rho_{NC} \]
\[ \kappa_{NC} \rightarrow \kappa'_{NC} \kappa_{NC} \]
\[ \rho_{CC} \rightarrow \rho'_{CC} \rho_{CC} \]

Perform 4 variants of NC fits
u-type form factors fitted
d-type form factors fitted
u-type = d-type form factors fitted
electron form factors fitted

All fits consistent with SM < 2 std deviations
d-type fits have larger uncertainty
\[ \rightarrow \text{lower d charge } \pm \frac{1}{2} \]
\[ \rightarrow \text{smaller contribution to cross section} \]
\[ \rightarrow \text{smaller d density in proton} \]

α, m_W, m_Z, m_t, m_H fixed to SM values
Unfitted ρ' and κ' set to unity

Perform 1 CC fit
high sensitivity to ρ'_{eq} of ~2%
lower sensitivity to ρ'_{eqbar} due to smaller cross section

Consistency with SM at level of ~1σ
Scale Dependence of NC Weak Form Factors

Divide data with $Q^2 > 500$ GeV$^2$ into four $Q^2$ bins to probe scale dependence

Can repeat fits in bins of $Q^2$ scale of DIS data:
1. fit PDFs and quark form factors
2. fit PDFs and electron form factors
3. fit PDFs and common fermion form factors

Error bars / bands show full uncertainties
Set $\rho'$ and $\kappa'$ = unity for $Q^2 < 500$ GeV$^2$

Best sensitivity at $Q \sim 60$ GeV of $\sim 6\%$
Results consistent with SM at $< 1.5\sigma$
First test of flavour and scale dependence of CC weak form factors

All CC data divided into four $Q^2$ bins to probe scale dependence

Repeat fits in bins of $Q^2$ scale of DIS data:
1. fit PDFs and eq form factors
2. fit PDFs and eqbar form factors
3. fit PDFs and common fermion form factors

Error bars / bands show full uncertainties

Precision on $\rho_{\text{eqbar}}' \sim 4\%$
Precision on $\rho_{\text{eq}}' \sim 1.3 \text{ — } 3\%$
Precision on $\rho_{\text{i}}' \sim 0.8 \text{ — } 1.8\%$

No significant deviations from SM
This study completes analysis of legacy HERA polarised data

Light quark weak couplings consistent with SM
Analysis tests complementarity of time-like and space-like regimes
H1 sensitivity similar to Tevatron and LEP

Search of indirect BSM effects in weak coupling scale dependencies
First determination of scale and flavour dependence in CC DIS
No significant deviations from SM observed

arXiv:1806.01176
Submitted to EPJC
Size of 1-loop EW corrections for NC and CC vs $Q^2$ (excl. vacuum polarisation & virtual photon corrections)
Corrections vary by < 0.1% for polarised case, or for $e^-$ scattering
Electroweak Precision Observables - $\sin^2\theta_{\text{eff}}$

$\sin^2\theta_W$ is a fundamental parameter of the SM - specifies the mixing between EM and weak fields
Relates the Z and W couplings $g_Z$ and $g_W$ (and their masses)

At leading order

$$\sin^2 \theta_W = 1 - \frac{g_W^2}{g_Z^2} = 1 - \frac{m_W^2}{m_Z^2}$$

Higher order EW corrections modify this to an effective mixing angle dependent on fermion flavour $f$

$$\sin^2 \theta_{\text{eff}}^f = (1 - \frac{m_W^2}{m_Z^2}) \cdot (1 + \Delta r)$$

$\Delta r$ encapsulates radiative corrections
Is EW scheme dependent

With known $m_h$ EW sector of SM is over-constrained
- $m_Z = 91.1876$ GeV
- $G_\mu = 1.16637 \times 10^{-5}$ GeV$^{-2}$
- $\alpha_{\text{QED}}(0) = 1/137.035$

EW scheme dependent corrections incorporated into $\Delta r \rightarrow \Delta r(m_H, m_{\text{top}}, \text{new physics})$
Measurement of one observable can predict the other

$m_W \leftrightarrow \sin^2\theta_W$

$m_W$ and $\sin^2\theta_{\text{eff}}$ allows self-consistency check of SM
New physics may hide in the indirect higher order corrections
Valuable in absence of direct signals

GFitter 2014

Previous results on $\sin^2\theta_{\text{eff}}$

- LEP: $29 \times 10^{-5}$
- CDF/D0: $35 \times 10^{-5}$
- SLD: $26 \times 10^{-5}$
- CMS(7TeV): $320 \times 10^{-5}$
- ATLAS(7TeV): $120 \times 10^{-5}$

Uncertainty of $\pm 50 \times 10^{-5}$ in $\sin^2\theta_{\text{eff}}$ is equivalent to $\pm 25$ MeV in $m_W$

Eram Rizvi
Typically experiments measure $A_{FB}$

→ unfold detector effects / dilution → fit for $\sin^2 \theta_{\text{eff}}$
→ or, perform detector level template fits to $A_{FB}$
→ estimate PDF uncertainties on extraction

**D0 + CDF combination 2017**

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23148 \pm 0.00027 \quad \text{(stat.)}$$

$$\pm 0.00005 \quad \text{(syst.)}$$

$$\pm 0.00018 \quad \text{(PDF)}$$

**ATLAS 7 TeV**

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.2308 \pm 0.0005 \text{(stat.)} \pm 0.0006 \text{(syst.)} \pm 0.0009 \text{(PDF)} = 0.2308 \pm 0.0012 \text{(tot.)}$$

**CMS 7 TeV**

$$\sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020 \text{ (stat.)} \pm 0.0025 \text{ (syst.)} \pm 0.00130 \text{ (PDF)}$$
dominated by PDF

**LHCb 7 & 8 TeV**

$$\sin^2 \theta_{\text{eff}}^{W} = 0.23142 \pm 0.00073 \text{ (stat)} \pm 0.00052 \text{ (sys)} \pm 0.00056 \text{ (theo)}$$
dominated by PDF

At LHC / Tevatron largest uncertainty ~ PDFs worse at LHC due to pp collisions worse at larger $\sqrt{s}$ due to lower x (more dilution)
Electroweak Precision Observables

Figure 2

68% and 95% CL contours
- fit w/o $M_W$ and $m_t$ measurements
- fit w/o $M_W$, $m_t$ and $M_H$ measurements
- direct $M_W$ and $m_t$ measurements

$m_t$ world comb. ± 1σ
- $m_t = 173.34$ GeV
- $σ = 0.76$ GeV
- $σ = 0.76 \pm 0.50_{\text{theo}}$ GeV

$M_W$ world comb. ± 1σ
$M_W = 80.385 \pm 0.015$ GeV

Direct measurements compared to EW fits and indirect constraints
New ATLAS measurement of $m_W$ reaches ±19 MeV precision \(\text{arXiv:1701.07240}\)

ATLAS approaches precision of combined LEP + Tevatron measurement

Theory prediction from EW fit has uncertainty ±8 MeV