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on behalf of the H1 Collaboration

Outline

- Introduction
- Analysis strategy
- Results
- Summary
ep collider, HERA, used to be the largest electron microscope
A large number of precisely measured inclusive cross sections
These are primary inputs for all modern PDF sets

• First EW analysis by H1

HERA-II (2003-2007):
• Increased lumi ($x10 e^-$, $x2 e^+$)
• Longitudinally polarised $e^\pm$

This talk reports refined and extended new EW analyses using all HERA-I & -II data
Neutral and Charged Current DIS Interactions

Sensitive to EW parameters (e.g. light quark couplings & W boson mass) in space-like regime

$\mathbf{Event kinematics:}$

$Q^2 = -q^2$: Boson virtuality

$x$: Momentum fraction of struck partons

$y = Q^2/(sx)$: Inelasticity

$\sqrt{s}$: Centre-of-mass energy

$a_q \equiv g_A^q, v_q \equiv g_V^q$
\[
\frac{d^2 \sigma_{\text{NC}}^\pm}{dx dQ^2} \sim Y_+ \tilde{F}_2 \mp Y_- x \tilde{F}_3 \nln\]

\[
g_V^e \sim 0 \rightarrow \text{some of the terms are negligible} \nln\]

\[
\tilde{F}_2 = F_2 - g_V^e \kappa_Z F_2^\gamma Z + (g_V^e g_V^e + g_A^e g_A^e) \kappa_2^Z F_2^Z \nln\]

\[
x \tilde{F}_3 = -g_A^e \kappa_Z x F_3^\gamma Z + 2g_V^e g_A^e \kappa_2^Z x F_3^Z \nln\]

\[
F_2^Z = x \sum_q \left( g_V^q g_V^q + g_A^q g_A^q \right) \{ q + \bar{q} \} \nln\]

\[
x F_3^\gamma Z = 2x \sum_q Q q g_A^q \{ q - \bar{q} \} \nln\]

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

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

\[
g_A^f = \sqrt{\rho_{\text{NC}}} I_{L,f}^3 \nln\]

\[
g_V^f = \sqrt{\rho_{\text{NC}}} \left( I_{L,f}^3 - 2Q_f \kappa_{\text{NC},q} \sin^2 \theta_W \right) \nln\]

In on-shell scheme:

\[
\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2} \nln\]

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

\[
\Delta r = \Delta r(\alpha, m_W, m_Z, m_t, m_h, \cdots) \nln\]
Polarised HERA-II NC Data

\[ \frac{d^2 \sigma_{\text{NC}}^{\pm}}{dx dQ^2} \sim Y_+ \tilde{F}_2 \mp Y_- x \tilde{F}_3 \]

\[ \tilde{F}_2 \approx F_2 - P_e g_A^e \kappa_Z F_2^{\gamma Z} + (g_V^e g_V^e + g_A^e g_A^e) \kappa_Z^2 F_2^Z \]

\[ x \tilde{F}_3 \approx -g_A^e \kappa_Z x F_3^{\gamma Z} + P_e g_A^e g_A^e \kappa_Z^2 x F_3^Z \]

\[ F_2^{\gamma Z} = 2x \sum_q Q_q g_V^q \{ q + \bar{q} \} \]

\[ x F_3^Z = 2x \sum_q g_V^q g_A^q \{ q - \bar{q} \} \]

Longitudinal polarised lepton beams at HERA-II introduces additional terms

\[ P_e : \text{the degree of the longitudinal polarisation} \]

Terms containing \( g_v^e \) have been neglected
\[
\frac{d^2\sigma_{CC}^{\pm}}{dx dQ^2} \simeq (1 \pm P_e) \frac{G_F^2}{4\pi x} \left[ \frac{m_W^2}{m_W^2 + Q^2} \right]^2 \left( Y_+ W_2^\pm + Y_- x W_3^\pm \right)
\]

\[
W_2^- = x \left( \rho_{CC,eq}^2 U + \rho_{CC,eq}^2 \overline{D} \right)
\]

\[
x W_3^- = x \left( \rho_{CC,eq}^2 U - \rho_{CC,eq}^2 \overline{D} \right)
\]

\[
U = u + c
\]

\[
\overline{D} = \overline{d} + \overline{s}
\]
## Used Data Sets

<table>
<thead>
<tr>
<th>Data set</th>
<th>$Q^2$-range [GeV²]</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>$e^+ \text{ combined low-}Q^2$</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>$e^+ \text{ combined low-}E_p$</td>
<td>(1.5) 8.5 – 90</td>
<td>225,252</td>
<td>12.2, 5.9</td>
<td>132 (136)</td>
<td>–</td>
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<tr>
<td>$e^+ \text{ NC 94–97}$</td>
<td>150 – 30 000</td>
<td>301</td>
<td>35.6</td>
<td>130</td>
<td>–</td>
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<tr>
<td>$e^+ \text{ CC 94–97}$</td>
<td>300 – 15 000</td>
<td>301</td>
<td>35.6</td>
<td>25</td>
<td>–</td>
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<tr>
<td>$e^- \text{ NC 98–99}$</td>
<td>150 – 30 000</td>
<td>319</td>
<td>16.4</td>
<td>126</td>
<td>–</td>
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<tr>
<td>$e^- \text{ CC 98–99}$</td>
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<td>319</td>
<td>16.4</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td>$e^- \text{ NC 98–99 high-y}$</td>
<td>100 – 800</td>
<td>319</td>
<td>16.4</td>
<td>13</td>
<td>–</td>
</tr>
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<td>$e^+ \text{ NC 99–00}$</td>
<td>150 – 30 000</td>
<td>319</td>
<td>65.2</td>
<td>147</td>
<td>–</td>
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<td>319</td>
<td>65.2</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td>$e^+ \text{ NC L HERA-II}$</td>
<td>120 – 30 000</td>
<td>319</td>
<td>80.7</td>
<td>137</td>
<td>$-37.0 \pm 1.0$</td>
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<td>80.7</td>
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<tr>
<td>$e^+ \text{ NC R HERA-II}$</td>
<td>120 – 30 000</td>
<td>319</td>
<td>101.3</td>
<td>138</td>
<td>$+32.5 \pm 0.7$</td>
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<td>319</td>
<td>104.4</td>
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<td>47.3</td>
<td>28</td>
<td>$+36.0 \pm 0.7$</td>
</tr>
<tr>
<td>$e^+ \text{ NC HERA-II high-y}$</td>
<td>60 – 800</td>
<td>319</td>
<td>182.0</td>
<td>11</td>
<td>–</td>
</tr>
<tr>
<td>$e^- \text{ NC HERA-II high-y}$</td>
<td>60 – 800</td>
<td>319</td>
<td>151.7</td>
<td>11</td>
<td>–</td>
</tr>
</tbody>
</table>

For the first 2 data sets, only data above 8.5 GeV² are included.
EW parameters fitted together with PDFs
- so that their correlation is properly taken into account
- the uncertainty of the EW parameters is not underestimated

Fits performed with log-normal based likelihood function

\[ \chi^2 = \sum_{i,j} \log \left( \frac{d_i}{\tilde{\sigma}_i} \right) V_{ij}^{-1} \log \left( \frac{d_j}{\tilde{\sigma}_j} \right) \]

Correlation in data (d) taken into account in covariance matrix (V)

Goodness of the fit (e.g. the PDF alone fit)
- \( \chi^2/\text{ndof} = 1435/(1415-17) = 1.03 \)
Fit Strategy

5 sets of PDFs parameterised at starting scale $Q_0^2 = 1.9$ GeV$^2$

\[ xg(x) = A_g x^{B_g} (1 - x)^{C_g} - A'_g x^{B'_g} (1 - x)^{C'_g}, \]

\[ xu_v(x) = A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} (1 + E_{u_v} x^2), \]

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

\[ x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}}, \]

\[ x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}, \]

Momentum sum rule and quark counting rules applied to constrain $A_g, A_{u_v}, A_{d_v}$ ($C'_g$ fixed to 25)

Other constraints applied: $A_{\bar{U}} = A_{\bar{D}}, B_{\bar{U}} = B_{\bar{D}}$

- DGLAP evolution & cross section calculations in NNLO QCD
- and in NLO EW
Determination of W Boson Mass

Determination performed in on-shell scheme:

\[ M_W = 80.407 \pm 0.118 \text{(exp, PDF-fit)} \pm 0.005(M_Z, m_t, m_h) \text{GeV} \]

to be compared with HERA-I result:

\[ M_W = 80.786 \pm 0.205 \text{(exp)}^{+0.063}_{-0.098} \text{(th)} \text{GeV} \]

⇒ A factor ~2 improvement!

- The dominant sensitivity (~120 MeV) comes from the normalisation of the CC cross sections
- The quark and electron couplings to Z boson in the NC cross sections provides additional sensitivity of ~225 MeV
- The W propagator term in CC cross sections provides a sensitivity of ~800 MeV
➤ Significant improvement over HERA-I determination
➤ 2 coupling fit is more precise due to the reduced correlation
➤ The results are competitive with other determinations
• 4 fits for NC form factors
• 1 fit for CC form factors
(all other parameters are set to their SM values)

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

\[ \rho_{CC} \to \rho'_{CC} \rho_{CC} \]

Best constraint for CC form factors, NC form factors for d-type quark less constrained

No significant deviations from SM
1. Fit quark form factors + PDFs only (set other parameters to their SM values)
2. Fit e form factors + PDFs only
3. Fit common fermion (e and quark) form factors + PDFs

No significant scale dependence and deviation from SM
1. Fit up-type form factors + PDFs
2. Fit down-type form factors + PDFs
3. Fit common quark form factors + PDFs
(all other parameters are set to their SM values)

➤ First scale dependence study for CC
➤ No significant scale dependence and deviation from SM
All HERA-I and HERA-II H1 data used to determine EW parameters together with PDFs

- Precision wrt to HERA-I results improved by a factor of ~2
- Thanks to the longitudinal polarised leptons beams and increased statistics precision of HERA-II high $Q^2$ data

The light quark couplings to $Z$ boson are competitive to other determinations

- Complementary test between space-like and time-like regimes

BSM-like form factors and their scale dependence studied

- First such study for $CC$
- Within the uncertainties, no significant deviations from SM