Introduction

Structure Functions

H1 Measurements at High $Q^2$

Combined QCD / EW Fit

Results

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Colliders At The Electroweak Scale

HERA data probes t-channel boson exchange
Sensitive to
- boson masses
- EW couplings
- PDFs

Extraction of EW parameters requires simultaneous QCD & EW fit

\[ \sigma(ep) = \sigma(eq) \otimes \text{PDFs} \]

EW \otimes \text{QCD}
HERA NC and CC cross sections test Standard Model in region of large space-like momentum transfer, $Q^2$

At fixed $\sqrt{s}$ only two kinematic variables: $x$ & $Q^2$

$Q^2 = s \cdot x \cdot y$

$x = \text{momentum fraction of proton carried by struck quark}$

At HERA: $10^{-6} - 1$
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 $y$
Where Are We Going?

$\log(Q^2) [\text{GeV}^2]$

$LHC$: largest mass states at large $x$

For central production $x=x_1=x_2$

$M = x\sqrt{s}$

i.e. $M > 1$ TeV probes $x > 0.1$

Searches for high mass states require precision knowledge at high $x$

$Z'$ / quantum gravity / susy searches...

DGLAP evolution allows predictions to be made

High $x$ predictions rely on

- data (DIS / fixed target)
- sum rules
- behaviour of PDFs as $x \to 1$
Structure Functions

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

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

\[ \frac{d\sigma_{\text{CC}}^\pm}{dx dQ^2} = (1 - P_e) \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_+ \tilde{W}_2^\pm + Y_- x\tilde{W}_3^\mp - y^2 \tilde{W}_L^\pm \right] \]

\[ P_e \text{ is the degree of lepton polarisation} \]

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

Dominant contribution

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

Only sensitive at high \( Q^2 \sim M_Z^2 \)

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

Only sensitive at low \( Q^2 \) and high \( y \)

similarly for pure weak CC analogues:

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

The NC reduced cross section defined as:

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

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

The CC reduced cross section defined as:

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

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

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

interference piece

$$xF_3^\pm = -(a_e \pm P_e v_e) \kappa \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + (2a_e v_e \pm P_e [v_e^2 + a^2_e]) \kappa^2$$

pure weak piece

$$\frac{Q^2}{Q^2 + M_Z^2} \rightarrow$$

pure weak piece

$v_e$ is small $\sim 0.05$

$\Rightarrow$ terms contribute little

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

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

<table>
<thead>
<tr>
<th>Function</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_2^{\gamma Z}$</td>
<td>main $v_q$ constraint</td>
</tr>
<tr>
<td>$F_2^{\gamma Z}$</td>
<td>main constraint on $a_q / v_q$ correlation</td>
</tr>
<tr>
<td>$xF_3^{\gamma Z}$</td>
<td>main $a_q$ constraint</td>
</tr>
</tbody>
</table>
NC data constrain:
- singlet quarks / gluon PDFs
- non-singlet valence quark PDFs at high $Q^2$
But, flavour sensitivity is weak

**CC data enable flavour decomposition of proton:**

\[
W_2^- = x(u + c + \bar{d} + \bar{s}),
W_2^+ = x(\bar{u} + \bar{c} + d + s),
\]

\[
xW_3^- = x(u + c - \bar{d} - \bar{s}),
xW_3^+ = x(d + s - \bar{u} - \bar{c})
\]

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

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

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

For polarised lepton beams CC cross section scales linearly with $P$

CC $e^+$ data provide strong $d_v$ constraint at high $x$
($y \sim 0$)
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  
\( \mathcal{L} \sim 110 \text{ pb}^{-1} \) per experiment

**HERA-II operation 2003-2007**
Ee = 27.6 GeV  
Ep = 920 GeV  
\( \mathcal{L} \sim 330 \text{ pb}^{-1} \) per experiment  
Longitudinally polarised leptons

**Low Energy Run 2007**
Ee = 27.6 GeV  
Ep = 575 & 460 GeV  
Dedicated \( F_L \) measurement
Table 5: Integrated luminosities and longitudinal beam polarisation for each data set are given in Table 5 below.

Data sets are termed the inclusive NC and CC single differential cross sections where samples of left handed and right handed longitudinal polarisation yield a centre-of-mass energy of 920 GeV.

The inclusive NC and CC single differential cross sections are very sensitive to the high momentum transfers domain, which is of direct relevance to all predictions for stringent constraints on the proton PDFs for Bjorken x. In particular, high production cross sections of new high-mass states in the LHC kinematic region between phenomenological models and perturbatively stable fixed order QCD calculations are very sensitive to the heavy quark production threshold region to the kinematic domain of scattering mediated by the electroweak bosons. In particular, the high cross sections of neutral current interactions are defined as the process (e^-p X e^-p) → (ν X X) whereas inclusive charged current interactions are defined as (e^+p X e^+p) → (e X X).

The data reach a precision of 2% in the NC channel and cover the x range from 0 to 0.65.

The precision measurements utilise the complete HERA II data set delivered with longitudinally polarised electron and positron beams. Inclusive charged current interactions are defined as (e^+p X e^+p) → (e X X) whereas inclusive neutral current interactions are defined as (e^-p X e^-p) → (ν X X).

1 Together with previous H5 measurements at lower energies, the precision measurements utilise the complete HERA-II data set delivered with longitudinally polarised electron and positron beams. Inclusive charged current interactions are defined as (e^+p X e^+p) → (e X X) whereas inclusive neutral current interactions are defined as (e^-p X e^-p) → (ν X X).

Precision measurements of proton structure in neutral current and charged current processes mediated via electroweak and QCD interactions to be simultaneously probed at the highest energies and four-momentum transfers allow the chiral structure of deep inelastic scattering with polarised lepton beams to provide a critical test of our understanding of parton dynamics and QCD as well as allowing the chiral structure of the axial and vector couplings of the light quarks to the electroweak interactions to be simultaneously probed at the highest energies.
Summary of HERA-I datasets

<table>
<thead>
<tr>
<th>Data Set</th>
<th>( x ) Range</th>
<th>( Q^2 ) Range ( \text{GeV}^2 )</th>
<th>( \mathcal{L} ) pb(^{-1} )</th>
<th>( e^+/e^- )</th>
<th>( \sqrt{s} ) GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 svx-mb</td>
<td>( 5 \times 10^{-6} ) 0.02</td>
<td>0.2 12</td>
<td>2.1</td>
<td>( e^+p )</td>
<td>301-319</td>
</tr>
<tr>
<td>H1 low ( Q^2 )</td>
<td>( 2 \times 10^{-4} ) 0.1</td>
<td>12 150</td>
<td>22</td>
<td>( e^+p )</td>
<td>301-319</td>
</tr>
<tr>
<td>H1 NC</td>
<td>0.0032 0.65</td>
<td>150 30000</td>
<td>35.6</td>
<td>( e^+p )</td>
<td>301</td>
</tr>
<tr>
<td>H1 CC</td>
<td>0.013 0.40</td>
<td>300 15000</td>
<td>35.6</td>
<td>( e^+p )</td>
<td>301</td>
</tr>
<tr>
<td>H1 NC</td>
<td>0.0032 0.65</td>
<td>150 30000</td>
<td>16.4</td>
<td>( e^-p )</td>
<td>319</td>
</tr>
<tr>
<td>H1 CC</td>
<td>0.013 0.40</td>
<td>300 15000</td>
<td>16.4</td>
<td>( e^-p )</td>
<td>319</td>
</tr>
<tr>
<td>H1 NC HY</td>
<td>0.0013 0.01</td>
<td>100 800</td>
<td>16.4</td>
<td>( e^-p )</td>
<td>319</td>
</tr>
<tr>
<td>H1 NC</td>
<td>0.0013 0.65</td>
<td>100 30000</td>
<td>65.2</td>
<td>( e^+p )</td>
<td>319</td>
</tr>
<tr>
<td>H1 CC</td>
<td>0.013 0.40</td>
<td>300 15000</td>
<td>65.2</td>
<td>( e^+p )</td>
<td>319</td>
</tr>
</tbody>
</table>

Summary of HERA-II datasets

<table>
<thead>
<tr>
<th>Data Set</th>
<th>( \mathcal{L} ) pb(^{-1} )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 CC e^-p</td>
<td>149 pb(^{-1} )</td>
<td>H1prelim-09-043</td>
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<tr>
<td>H1 CC e^+p</td>
<td>180 pb(^{-1} )</td>
<td>H1prelim-09-043</td>
</tr>
<tr>
<td>H1 NC e^-p</td>
<td>149 pb(^{-1} )</td>
<td>H1prelim-09-042</td>
</tr>
<tr>
<td>H1 NC e^+p</td>
<td>180 pb(^{-1} )</td>
<td>H1prelim-09-042</td>
</tr>
</tbody>
</table>
Precision data from H1 for $Q^2 < 150$ GeV$^2$
Typical uncertainty of 1.3 - 2 %
Provides strong constraints on PDFs
- gluon and singlet quarks

**F**

H1 Collaboration

Precision F$_2$ at Medium $Q^2$

DESY-09-005
Neutral Current Control Distributions

Kinematic distributions are well described by MC
~3% normalisation shift
within preliminary luminosity uncertainty ±2.1%
Monte Carlo (MC) contributions from the charged current (CC) band. The contribution from the background processes are shown as the full line, the total uncertainty is represented by the shaded histogram.

Within errors normalisation is fine.
At high $Q^2$, $x F_3$ arises due to $Z^0$ effects and enhanced $e^-$ cross section wrt $e^+$
Difference is $x F_3$
Sensitive to valence PDFs

$$x F_3 = \frac{Y^+}{2Y^-} \left( \tilde{\sigma}_F - \tilde{\sigma}_F \right) \approx a_e \chi Z x F_3^{\gamma Z}$$

$$x F_3 \propto \sum (xq_i - xq_i)$$
Figure 17: The reduced cross section $\tilde{\sigma}_{CC}$ in unpolarised $e^-p$ scattering using the complete HERA-I+II data sets. The data are compared to the Standard Model prediction from H1 PDF 2009. The inner error bars represent the statistical uncertainties and the outer error bars represent the total errors. The normalisation uncertainty is not included in the error bars. The separate contributions from quarks and anti-quarks are shown as the dashed and dashed-dotted curves.

Figure 18: The reduced cross section $\tilde{\sigma}_{CC}$ in unpolarised $e^+p$ scattering using the complete HERA-I+II data sets. The data are compared to the Standard Model prediction from H1 PDF 2009. The inner error bars represent the statistical uncertainties and the outer error bars represent the total errors. The normalisation uncertainty is not included in the error bars. The separate contributions from quarks and anti-quarks are shown as the dashed and dashed-dotted curves.

Dashed lines show quark flavour composition
High $x$ d of is not well constrained by NC data
Good constraints from CC $e^+$ data
Figure 5: The dependence of the $e^\pm p \rightarrow \nu X$ cross section on the lepton beam polarisation $P_e$. The inner and outer error bars represent respectively the statistical and total errors. The uncertainties on the polarisation measurement are smaller than the symbol size. The data are compared to the Standard Model prediction based on the HERAPDF 1.0 parametrisation (dark shaded band). The light shaded band corresponds to the resulting one-sigma contour drawn in the data shown as the central line.

Clear linear scaling of CC cross section Verifies absence of weak right-handed currents
NC parity violating effects are more subtle
Measure NC polarisation asymmetry

\[
A = \frac{2}{P_R - P_L} \cdot \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)}
\]
**QCD & EW Fit**

**Combined QCD & EW Fit**

Combined NC and CC HERA-I data from H1
No usage of other experimental data (e.g. non-DIS)
Complete MSbar NLO fit

NLO: standard parameterisation with 14 parameters

Fit PDFs and light quark axial/vector couplings

**PDFs parameterised at starting scale $Q_0^2$**

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1 - x)^C \cdot (1 + Dx + Ex^2 + Fx^3)$$

- $xg$
- $xU = xu + xc$
- $xD = xd + xs$
- $x\bar{U} = x\bar{u} + x\bar{c}$
- $x\bar{D} = x\bar{d} + x\bar{s}$

**Parameter constraints:**

- $B_{uv} = B_{dv}$
- $B_{Ubar} = B_{Dbar}$
- $2 \times (Ubar + Dbar)$
- $Ubar = Dbar$ at $x=0$

**EW parameters from PDF2009:**

- $M_{top} = 171.3$ GeV
- $M_W = 80.398$ GeV
- $\alpha_S = 0.1176$

**Apply momentum/counting sum rules:**

- $\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$
- $\int_0^1 dx \cdot u_v = 2$
- $\int_0^1 dx \cdot d_v = 1$

- $Q_0^2 = 4$ GeV$^2$
- $Q^2 > 3.5$ GeV$^2$
- $2 \times 10^{-4} < x < 0.65$

Fits performed in massless HQ scheme
Alternative parametric form included as uncertainty
Taken from HERAPDF1.0 QCD fit

\[ xf(x, Q^2_0) = A \cdot x^B \cdot (1 - x)^C \cdot (1 + Dx + Ex^2 + Fx^3) \]

\[
\begin{align*}
  xg & \quad xg \\
  xu'_v & \quad xU = xu + xc \\
  xd'_v & \quad xD = xd + xs \\
  x\bar{U} & \quad x\bar{U} = x\bar{u} + x\bar{c} \\
  x\bar{D} & \quad x\bar{D} = x\bar{d} + x\bar{s}
\end{align*}
\]

\[
\begin{align*}
  xg(x) & = A_g x^{B_g} (1 - x)^{C_g}, \\
  xu'_v(x) & = A_{u'_v} x^{B_{u'_v}} (1 - x)^{C_{u'_v}} \left(1 + E_{u'_v} x^2\right), \\
  xd'_v(x) & = A_{d'_v} x^{B_{d'_v}} (1 - x)^{C_{d'_v}}, \\
  x\bar{U}(x) & = A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}}, \\
  x\bar{D}(x) & = A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}.
\end{align*}
\]

**HERAPDF1.0**
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with 10 parameters
\( \alpha_s = 0.1176 \) (fixed in fit)
Experimental systematic sources of uncertainty allowed to float in fit
Include model assumptions into uncertainty:

\[ f_s, m_c, m_b, Q^2_0, Q^2_{\text{min}} \]

<table>
<thead>
<tr>
<th>Variation</th>
<th>Standard Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
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</thead>
<tbody>
<tr>
<td>( f_s )</td>
<td>0.31</td>
<td>0.23</td>
<td>0.38</td>
</tr>
<tr>
<td>( m_c ) [GeV]</td>
<td>1.4</td>
<td>1.35(^{(a)})</td>
<td>1.65</td>
</tr>
<tr>
<td>( m_b ) [GeV]</td>
<td>4.75</td>
<td>4.3</td>
<td>5.0</td>
</tr>
<tr>
<td>( Q^2_{\text{min}} ) [GeV(^2)]</td>
<td>3.5</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>( Q^2_0 ) [GeV(^2)]</td>
<td>1.9</td>
<td>1.5(^{(b)})</td>
<td>2.5(^{(c,d)})</td>
</tr>
</tbody>
</table>

\(^{(a)}Q^2_0 = 1.8\)
\(^{(b)}f_s = 0.29\)
\(^{(c)}m_c = 1.6\)
\(^{(d)}f_s = 0.34\)

Excellent consistency of input data allow standard statistical error definition:
\[ \Delta \chi^2 = 1 \]

Uncertainties

<table>
<thead>
<tr>
<th>a_u</th>
<th>( v_u )</th>
<th>a_d</th>
<th>( v_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+0.02)</td>
<td>(\pm0.01)</td>
<td>(+0.03)</td>
<td>(\pm0.01)</td>
</tr>
<tr>
<td>(+0.02)</td>
<td>(\pm0.01)</td>
<td>(+0.03)</td>
<td>(\pm0.02)</td>
</tr>
<tr>
<td>(+0.03)</td>
<td>(\pm0.02)</td>
<td>(+0.06)</td>
<td>(\pm0.06)</td>
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<tr>
<td>(+0.04)</td>
<td>(\pm0.02)</td>
<td>(+0.07)</td>
<td>(\pm0.06)</td>
</tr>
<tr>
<td>(+0.06)</td>
<td>(\pm0.08)</td>
<td>(+0.19)</td>
<td>(\pm0.27)</td>
</tr>
</tbody>
</table>

New combined QCD & EW fit performed
Takes into account full correlation of uncertainties
\[ \chi^2 / \text{ndf} = 1184 / 1230 = 0.96 \]
QCD/EW Fit gives good description of precision $F^2$ data

$E_p=920\,\text{GeV}$

PDF a la HERAPDF1.0

PDF a la H1PDF2000
Polarised LH / RH neutral current cross sections in e⁻p scattering

Eram Rizvi
Results

Polarised LH charged current cross sections in $e^-p$ scattering

- $Q^2=300\text{GeV}^2$
- $Q^2=500\text{GeV}^2$
- $Q^2=1000\text{GeV}^2$
- $Q^2=2000\text{GeV}^2$
- $Q^2=3000\text{GeV}^2$
- $Q^2=5000\text{GeV}^2$
- $Q^2=8000\text{GeV}^2$
- $Q^2=15000\text{GeV}^2$

PDF a la HERAPDF1.0
PDF a la H1PDF2000

$e^-p, P_e=-0.2603$
and the CDF experiment \cite{3}( The stars show the expected SM values. 1shaded contours2 in comparison with the corresponding results published previously using the

**Figure:** Results at \( d_1 b_2 \) quarks to the

<table>
<thead>
<tr>
<th>Fit</th>
<th>( v_u-a_u-v_d-a_d )-PDF</th>
<th>( v_u-a_u )-PDF</th>
<th>( v_d-a_d )-PDF</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_u )</td>
<td>0.49 ± 0.06 ± 0.04</td>
<td>0.53 ± 0.04</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>( v_u )</td>
<td>0.23 ± 0.08 ± 0.02</td>
<td>0.23 ± 0.04</td>
<td>-</td>
<td>0.191</td>
</tr>
<tr>
<td>( a_d )</td>
<td>-0.67 ± 0.19 ± 0.07</td>
<td>-</td>
<td>-0.61 ± 0.15</td>
<td>-0.5</td>
</tr>
<tr>
<td>( v_d )</td>
<td>-0.31 ± 0.27 ± 0.06</td>
<td>-</td>
<td>-0.44 ± 0.13</td>
<td>-0.346</td>
</tr>
<tr>
<td>( \chi^2/\text{dof} )</td>
<td>1183.8/1230</td>
<td>1184.5/1232</td>
<td>1184.2/1232</td>
<td>-</td>
</tr>
</tbody>
</table>

Fits with new polarised HERA-I data shown in 68% CL blue contour

Improved sensitivity to vector couplings compared to HERA-I unpolarised data (blue shaded area)

Competitive determinations to CDF and LEP

HERA data resolves LEP sign ambiguity
Conclusions

- HERA data provide some of the most stringent constraints on PDFs
- Stress-test of QCD over 4 orders of mag. in $Q^2$
- HERA data provide a self-consistent data set for complete flavour decomposition of the proton
- Combined QCD & EW analysis performed gives improved precision on axial & vector couplings

Soon to publish final HERA-II data