Inclusive high $Q^2$ cross sections and QCD and EW fits at HERA

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The HERA accelerator

\[ \begin{align*}
\text{e}^\pm & \quad 27.5 \text{ GeV} \\
\sqrt{s} & = 320 \text{ GeV}
\end{align*} \]

0.5 \text{ fb}^{-1} / \text{experiment}
Longitudinal polarisation of the lepton beam at HERA

\[ P_e = \frac{N_R - N_L}{N_R + N_L} \]

- Transverse polarisation builds up naturally through synchrotron radiation (Sokolov-Ternov effect)
- Spin rotators flip transverse polarisation to longitudinal before interaction regions and back afterwards
- Polarisation measured by two independent Compton polarimeters
- Average polarisation 30-40%
The H1 and ZEUS detectors

- LAr calorimeter (45000 cells)
  - EM: $\frac{\sigma(E)}{E} = \frac{12\%}{\sqrt{E}} \oplus 1\%$
  - HAD: $\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 1\%$

- DU calorimeter (6000 cells)
  - EM: $\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E}}$
  - HAD: $\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}}$
Deep inelastic scattering at HERA

Two deep inelastic scattering processes:

— Neutral current: exchange of $\gamma$ or $Z^0$

— Charged current: exchange of $W^\pm$

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

$x = \frac{Q^2}{2p \cdot q}$ \quad $y = \frac{p \cdot q}{p \cdot k}$

$s = (p + k)^2$ \quad $Q^2 = x \cdot y \cdot s$

$Q^2$ is the probing power

$x$ is the Bjorken scaling variable

$y$ is the inelasticity
Neutral current DIS cross section

\[
\frac{d^2 \sigma^{NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} Y_+ \left[ F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right]
\]

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

Dominant contribution

Sizeable only at high \( y \)

Contribution only important at high \( Q^2 \)

\[
F_2 = F_2^{em} + \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 F_2^Z \propto \sum_{q=u...b} (q + \bar{q})
\]

\[
xF_3 = \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 xF_3^Z \propto \sum_{q=u...b} (q - \bar{q})
\]
Neutral current data

- At lower $Q^2$ $e^+p$ and $e^-p$ cross sections the same
  - $F_2$ (photon exchange) dominates cross section
  - Directly sensitive to sum of quarks and antiquarks

- At high $Q^2$ $e^+p$ and $e^-p$ cross sections different
  - Influence of $xF_3$ term ($Z^0$ exchange)
  - Sensitive to the valence quarks
Charged current DIS at HERA

Electron/positron-proton collisions probe different quark content of proton

\[ \frac{d^2 \sigma^{CC (e^+ p)}}{dxdQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ \bar{u} + c + (1 - y)^2 (d + s) \right] \]

\[ \frac{d^2 \sigma^{CC (e^- p)}}{dxdQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ u + c + (1 - y)^2 (\bar{d} + \bar{s}) \right] \]

Sensitive to density of \( d \) quark

Sensitive to density of \( u \) quark
Charged current data

- Charged current cross sections quark-flavour specific
  - $e^-p$ (shown here) sensitive to u-quark
  - $e^+p$ sensitive to d-quark
Polarised charged current DIS

- Polarisation is asymmetry of helicity states

- Helicity = chirality (neglecting masses)
- Can use polarised beams to directly test chiral structure of the Standard Model

- Standard Model weak interaction left-handed
  - only LH particles (RH anti-particles) interact

\[
P_e = \frac{N_R - N_L}{N_R + N_L}
\]

CC cross section modified by \( P_e \):

\[
\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e) \cdot \sigma_{CC}^{e^\pm p}(P_e = 0)
\]

Polarisation scales \( P_e = 0 \) cross section linearly - clear and large effect at HERA

Standard Model predicts zero cross section for \( P_e = +1(-1) \) in \( e^+p \) scattering
• Clearly demonstrate linear dependence on $P_e$
• Consistent with Standard Model predictions
Polarised NC DIS cross sections

NC cross section modified by $P$:

$$\frac{d^2\sigma(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ H_0^\pm + PH_P^\pm \right]$$

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

Unpolarised contribution

Polarised contribution - only includes $Z$ and $\gamma Z$ terms

$$F_2 = \sum_{q=u...b} \left( e_q^2 - 2e_q v_e e_P Z + (v_e^2 + a_e^2)(v_q^2 + a_q^2)P_Z^2 \right) \cdot x(q + \bar{q})$$

$$xF_3 = \sum_{q=u...b} \left( -2e_q a_q a_e P_Z + 4a_q v_q v_e a_e P_Z^2 \right) \cdot x(q - \bar{q})$$

$$P_Z = \frac{1}{\sin^2\theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$
**Polarised NC DIS cross sections**

NC cross section modified by P:

\[
\frac{d^2 \sigma (e^\pm p)}{dx dQ^2} = \frac{2\pi \alpha^2}{xQ^4} \left[ H_0^\pm + P H_P^\pm \right] \quad P = \frac{N_R - N_L}{N_R + N_L}
\]

Unpolarised contribution

Polarised contribution - only includes Z and $\gamma Z$ terms

\[
F_2^P = \sum_{q=u...b} \left( 2 e_q a_e v_q P_Z - 2 a_e v_e (v_q^2 + a_q^2) P_Z^2 \right) \cdot x(q + \bar{q})
\]

\[
xF_3^P = \sum_{q=u...b} \left( 2 e_q a_q v_e P_Z - 2 a_q v_q (v_e^2 + a_e^2) P_Z^2 \right) \cdot x(q - \bar{q})
\]

\[
P_Z = \frac{1}{\sin^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2}
\]

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ICHEP '08, July 29 - August 5, 2008, Philadelphia.
Polarised NC DIS cross sections

NC cross section modified by $P$:

$$
\frac{d^2 \sigma (e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ H_0^\pm + PH_P^\pm \right]
$$

Unpolarised contribution

Polarised contribution - only includes $Z$ and $\gamma Z$ terms

First see if we can observe subtle polarisation dependence!

Then remember that $P_Z >> P_Z^2$ and $v_e \sim 0.04$

- Axial couplings from $H_0$
- Vector couplings from $H_P$
- $u$-quark should have best precision (coupling to charge)
Polarised NC measurements

High precision measurements

→ polarisation effect observed
Form the polarisation asymmetry:

\[ A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm (P_R) - \sigma^\pm (P_L)}{\sigma^\pm (P_R) + \sigma^\pm (P_L)} \]

to a good approximation

\[ A^\pm \approx \mp ka_e \frac{F_2^{yz}}{F_2} \quad k = \frac{1}{4 \sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2} \]

which is quite insensitive to the PDFs and proportional to \( a_e v_q \) and therefore a direct measure of parity violation
• Simultaneously fit the data for the PDFs and electroweak parameters (Phys. Lett. B 632, 35 (2006))

• QCD fits for PDFs well known
  – H1 follows Eur. Phys. J C30 1, (2003).
  – ZEUS follows Eur. Phys. J C42 1, (2005).
  – See talk of Burkard Reisert

• In both cases fits are to H1/ZEUS data only

• For electroweak parameters, exploit the high precision data with logitudinally polarised beams to extract light-quark axial and vector couplings to the $Z^0$ boson - $a_u$, $a_d$, $v_u$ and $v_d$. 
Combined QCD & EW fit

More sensitive to u-quark
Combined QCD & EW fit

HERA measurements competitive with LEP and Tevatron
Phys. Rep. 427, 257 (2006) & Phys. Rev. D71, 052002 (2005)
Summary

- High-precision high-$Q^2$ measurements
- Simultaneous determinations of the PDFs and EW parameters
- Couplings of $u$ and $d$ quarks to $Z^0$ competitive with determinations from LEP and Tevatron experiments
- Can expect improvements in precision with full data sets
- Need to combine H1 and ZEUS data

- More still to come from HERA!
Electroweak fit

- Fix $G_F$, $M_W$ in CC cross sections to PDG
- Fix $\alpha$, $M_Z$ and $M_W$ in NC cross sections to PDG
- $v_q = I^3_{q,L} - 2e_q \sin^2 \theta_W$ $a_q = I^3_{q,L}$
- Weak radiative corrs modify the couplings to dressed couplings
- Form factors $\rho_{eq}$, $K_e$, $K_q$, $K_{eq}$
- $\rho_{eq} = 1$ assumed (good up to $Q^2 < 10000$ GeV$^2$)
- $\sin^2 \theta_W = \kappa_q (1 - M_W^2/M_Z^2)$
## Electroweak fit

**ZEUS (prel.) result (H1 numbers not available)**

|     | $a_u$               | $a_d$               | $\nu_u$          | $\nu_d$          |
|-----|---------------------|---------------------|-------------------|-------------------|
| ZEUS| 0.51±0.10±0.17      | -0.54±0.32±0.18     | 0.05±0.09±0.05    | -0.64±0.20±0.14  |
| SM  | 0.5                 | -0.5                | 0.196             | -0.346            |

**SM** stands for the Standard Model.
• PDFs fitted
  – U, D, Ubar, Dbar and g
• Form
  – $xq(x) = A_q x^{B_q} (1-x)^{C_q} (1+D_g x+F_q x^3)$
• Starting scale $Q_0^2=4$ GeV
• 10 free parameters for PDFs
• Data sets: NC and CC $e^+p$ and $e^-p$ DIS
ZEUS-JETS fit

- PDFs fitted
  - $u$ and $d$ valence, sea, gluon, $u_{\text{sea}}-d_{\text{sea}}$

- Form
  - $xq(x) = p_1x^{p_2}(1-x)^{p_3}(1+p_4x)$

- Starting scale $Q_0^2=7$ GeV

- 11 free parameters for PDFs

- Data sets: NC and CC $e^+p$ and $e^-p$ DIS, inclusive jets in NC DIS and $\gamma p$ dijets