High $Q^2$ Measurements from HERA

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Lake Louise Winter Institute, 14-20 February 2010, Alberta, Canada
The H1 and ZEUS Experiments at HERA

- Two multi-purpose experiments located at the ep interaction points
- The world’s most powerful electron microscope, underneath the Volkspark in Hamburg
- Particle energies allow us to probe proton structure down to $\Delta x \approx 10^{-18}$m

\[ e^{\pm} \rightarrow 27.5 \text{ GeV} \quad \text{p} \rightarrow 920 \text{ GeV} \quad \sqrt{s}=320 \text{ GeV} \]
Data Taking at HERA 1994-2007

- Large increase in data per experiment after the luminosity upgrade for HERA II (x3)
- Large increase (x12) in data taken from e⁻p collisions: HERA I mostly e⁺p data

Final HERA I+II dataset ~ 0.5 fb⁻¹ / experiment

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

\[ P_R > 0 \]
\[ P_L < 0 \]

HERA II: Longitudinally Polarised Lepton Beam: 4 modes of running
Deep Inelastic Scattering at HERA

\[ Q^2 = -(k - k')^2 \]

Virtuality of the exchanged boson

\[ x = \frac{Q^2}{2P \cdot (k - k')} \]

Fraction of proton momenta carried by the struck quark

\[ y = \frac{P \cdot (k - k')}{P \cdot k} \]

Inelasticity: fraction of lepton energy transferred in the proton rest frame

Presented today: NC and CC cross section measurements using up to the full HERA I+II data in the range \( 200 < Q^2 < 30,000 \text{ GeV}^2 \)
Neutral Current Cross Sections

The dominant contribution
Sizeable only at high $y$ - Measure with special low energy runs
Only important at high $Q^2$ - Measure using difference of $e^+p$ and $e^-p$ cross sections

\[
\begin{align*}
\frac{d^2 \sigma^{NC}(e^\pm p)}{dx dQ^2} &= \frac{2\pi \alpha^2}{x Q^4} Y_+ \left[ F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right] \\
Y_\pm &= \pm \sqrt{1 - y^2} \\
F_2 &= F_2^{em} + \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 F_2^Z \propto \sum_{q = u \ldots b} (q + \bar{q}) \\
xF_3 &= \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 xF_3^Z \propto \sum_{q = u \ldots b} (q - \bar{q}) \\
\end{align*}
\]

In addition, the NC cross section is also sensitive to the lepton polarisation, but only via the $Z$ and $\gamma Z$ interference terms: small effect only visible at high $Q^2$
Unpolarised Cross Sections: HERA I+II

High precision of full HERA I+II data set and comparison to various PDF fits
Unpolarised Reduced NC Cross Section: $e^-p$ vs. $e^+p$

**Separation of $e^+p$ and $e^-p$ cross sections at high $Q^2$**

**Influence of $\gamma Z$ interference term**

Visible difference in the $e^+p$ and $e^-p$ cross sections is described well by the SM predictions

\[
\tilde{\sigma}_{NC}^+ = \tilde{F}_2 - \frac{V^2}{Y_+} \tilde{F}_L + \frac{Y_-}{Y_+} x \tilde{F}_3
\]
Evaluation of $x F_3$

$xF_3$ is calculated from the difference in the unpolarised reduced cross sections at high $Q^2$.

$$x F_3 = \frac{Y_+}{2Y_-} \left[ \sigma^-(x, Q^2) - \sigma^+(x, Q^2) \right]$$
Polarised Reduced NC Cross Section: -P vs. +P

**electron data**

- $Q^2 = 150 \text{ GeV}^2$
- $Q^2 = 200 \text{ GeV}^2$
- $Q^2 = 250 \text{ GeV}^2$
- $Q^2 = 300 \text{ GeV}^2$
- $Q^2 = 400 \text{ GeV}^2$
- $Q^2 = 500 \text{ GeV}^2$
- $Q^2 = 650 \text{ GeV}^2$
- $Q^2 = 800 \text{ GeV}^2$
- $Q^2 = 1000 \text{ GeV}^2$
- $Q^2 = 1200 \text{ GeV}^2$
- $Q^2 = 1500 \text{ GeV}^2$
- $Q^2 = 2000 \text{ GeV}^2$
- $Q^2 = 3000 \text{ GeV}^2$
- $Q^2 = 5000 \text{ GeV}^2$
- $Q^2 = 8000 \text{ GeV}^2$
- $Q^2 = 12000 \text{ GeV}^2$

**positron data**

- $Q^2 = 150 \text{ GeV}^2$
- $Q^2 = 200 \text{ GeV}^2$
- $Q^2 = 250 \text{ GeV}^2$
- $Q^2 = 300 \text{ GeV}^2$
- $Q^2 = 400 \text{ GeV}^2$
- $Q^2 = 500 \text{ GeV}^2$
- $Q^2 = 800 \text{ GeV}^2$
- $Q^2 = 1000 \text{ GeV}^2$
- $Q^2 = 1200 \text{ GeV}^2$
- $Q^2 = 1500 \text{ GeV}^2$
- $Q^2 = 2000 \text{ GeV}^2$
- $Q^2 = 3000 \text{ GeV}^2$
- $Q^2 = 5000 \text{ GeV}^2$
- $Q^2 = 8000 \text{ GeV}^2$
- $Q^2 = 12000 \text{ GeV}^2$

**H1 Preliminary**

- $H1 e^+ p \text{NC (prel.), } P_\perp = +36.9\%$
- $H1 e^+ p \text{NC (prel.), } P_\perp = -26.0\%$
- $H1 e^+ p \text{NC (prel.), } P_\perp = +32.5\%$
- $H1 e^+ p \text{NC (prel.), } P_\perp = -37.6\%$

**HERA II**

- $10^2, 10^1, 10^{-1}, 1^1$
- $10^2, 10^1, 10^{-1}, 1^1$
Polarised Reduced NC Cross Section: -P vs. +P

Influence of lepton beam polarisation visible at high $Q^2$: separation of measurements
HERA II Polarisation Asymmetry in NC

Form polarisation asymmetry from HERA II Neutral Current measurements
- clear observation of parity violation of NC electroweak exchange
Nicely illustrates the properties of the different polarisation and lepton charge data
Well described by the SM prediction

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

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

\[ P_R > 0 \]
\[ P_L < 0 \]
Charged Current Cross Sections

**e^+p cross section:**

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

Sensitive to the density of the \(d\) quark

**e^-p cross section:**

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

\(\tilde{\sigma}(x,Q^2)/x\)

Sensitive to the density of the \(u\) quark

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**CC cross section modified by polarisation \(P_e\):**

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

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

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

SM predicts zero cross section for \(P_e=+1(-1)\) in \(e^- (+) p\) scattering
Charged Current Cross Section vs. Polarisation

Data exhibit linear dependence of average polarisation and HERA I and II measurements agree with the SM prediction.

Measurements made by ZEUS using various polarisation values
Single Differential CC Cross Sections $d\sigma/dQ^2$

W propagator: cross section much lower than NC

Higher cross section of $e^-p$ data visible, difference due to quark content
Opposite polarisation dependence of data sets visible
Good agreement with SM model prediction based on ZEUS-JETS QCD fit
Unpolarised Reduced CC Cross Section: $e^-p$ vs. $e^+p$

CC interaction allows for a clean flavour decomposition:
- $e^-p$: u-type quarks dominate;
- $e^+p$: d-type dominates at high $x$, sea dominates at low $x$
Summary

- Measurements of polarised and unpolarised neutral and charged current cross sections at HERA
  - Observed polarisation asymmetry in NC agrees with the SM prediction
  - Polarisation dependence of the CC cross section established in both e^+p and e^-p data: no right handed charged currents
  - The HERA I and II data have been combined to form unpolarised measurements and xF_3 is extracted

- Both H1 and ZEUS heading towards final publication of full HERA data, with more combined measurements to follow
  - Providing more constraints on the proton structure and input into new QCD fits such as HERA PDF
Single Differential NC Cross Sections $d\sigma/dQ^2$

**H1 Preliminary**

- **electron data RH**
  - $P_e = +36.9\%$
  - $y < 0.9$

- **positron data RH**
  - $P_e = +32.5\%$
  - $y < 0.9$

- **electron data LH**
  - $P_e = -26.0\%$
  - $y < 0.9$

- **positron data LH**
  - $P_e = -37.6\%$
  - $y < 0.9$

**Excellent description of the $Q^2$ dependence of the data by the SM (from a QCD fit)**
Unpolarised Reduced NC Cross Section: Full HERA I+II

![Graph showing unpolarised reduced NC cross section for different Q^2 values]
Extraction of $xF_3$
Extraction of $xF_3^{\gamma Z}$

\[ xF_3^{\gamma Z} \simeq x\tilde{F}_3 \left( \frac{Q^2 + M_Z^2}{\alpha_e \kappa Q^2} \right) \]
Similarly from H1, double differential cross sections show clear polarisation asymmetry.