**High-$Q^2$ $e^+p$ Neutral Current Cross Sections at HERA and Determination of the Structure Function $xF_3$**

Friederike Januschek  
DESY  
On Behalf of the ZEUS Collaboration  

**DIS 2012, 26-30 March, Bonn, Germany**

1. Polarised Cross Sections  
2. Unpolarised Cross Sections  
   - $xF_3$ extraction
The HERA Collider

- **HERA**: electron-proton collider with $\sqrt{s} = 318$ GeV

Integrated luminosity: 0.5 fb$^{-1}$ per experiment

- 27.5 GeV
- 920 GeV

- Four experiments: HERA B, HERMES; H1 and ZEUS
- Two data-taking periods: HERA I (92-00) and HERA II (03-07)
- HERA-II: longitudinally polarised lepton beam
The ZEUS Detector

Uranium-Scintillator Calorimeter
Energy and position of particles
- covering 99.7 % of the solid angle
- electromagnetic CAL: $\frac{\sigma_{em}(E)}{E} = 18\% \sqrt{E}$
- hadronic CAL: $\frac{\sigma_{had}(E)}{E} = 35\% \sqrt{E}$

Tracking System
Direction and momentum of charged particles
- **CTD**: cylindric drift chamber
  (length: 241 cm, $0.3 < \theta < 2.85$)
- **MVD**: silicon strip detector
Deep Inelastic Scattering

Variables which characterise DIS:

- $Q^2$ probing power, negative 4-momentum squared:
  \[ Q^2 = -q^2 = -(k - k') \]

- Bjorken $x$, momentum fraction of proton carried by struck quark:
  \[ x = Q^2 / 2P \cdot q \]

- Inelasticity $y$:
  \[ y = P \cdot q / P \cdot k \]

- $s$ is the centre-of-mass energy squared:
  \[ s = (P + k)^2 \]

- These are related by:
  \[ Q^2 = sxy \]

- Neutral Current (NC), $\gamma$ or $Z$ exchange.
  \[ e^\pm p \rightarrow e^\pm X \]

- Charged Current (CC), $W^\pm$ exchange.
  \[ e^\pm p \rightarrow \nu X \]
Neutral Current Events in the ZEUS Detector

- Well measured scattered $e^\pm$.
- $e^\pm$ energy deposits and jet(s) balanced in $\phi$.
- Kinematics may be reconstructed in multiple ways.

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Proton Structure Functions

\[
\frac{d^2 \sigma_{NC}^{e\pm p}}{dx dQ^2} = \frac{2\pi \alpha^2}{xQ^4} \left[ Y_+ \tilde{F}_2(x, Q^2) \mp Y_- x \tilde{F}_3(x, Q^2) - y^2 \tilde{F}_L(x, Q^2) \right]
\]

where \( Y_\pm = 1 \pm (1 - y)^2 \)

dominant \hspace{1cm} relevant at high \( Q^2 \) \hspace{1cm} relevant at high \( y \)
Proton Structure Functions

\[
\frac{d^2 \sigma_{NC}^{e^\pm p}}{dx dQ^2} = \frac{2 \pi \alpha^2}{x Q^4} \left[ Y_+ \tilde{F}_2(x, Q^2) \mp Y_- x \tilde{F}_3(x, Q^2) - y^2 \tilde{F}_L(x, Q^2) \right]
\]

- dominant
- relevant at high \( Q^2 \)
- relevant at high \( y \)
- polarisation of \( e \)

\[
\tilde{F}_2^{\pm} = F_2^\gamma - (v_e \mp P_e a_e) \chi_Z F_2^\gamma Z + (v_e^2 + a_e^2 \mp 2 P_e v_e a_e) \chi_Z^2 F_2^Z
\]

\[
x \tilde{F}_3^{\pm} = - (a_e \mp P_e v_e) \chi_Z x F_3^\gamma Z + (\mp P_e (v_e^2 + a_e^2) + 2 v_e a_e) \chi_Z^2 x F_3^Z
\]

- axial-vector coupling of \( e \) to \( Z \)
- vector coupling of \( e \) to \( Z \)
Proton Structure Functions

\[ \frac{d^2 \sigma_{NC}^{e^\pm p}}{dx dQ^2} = \frac{2\pi \alpha^2}{xQ^4} \left[ Y_+ \tilde{F}_2(x, Q^2) \mp Y_- x \tilde{F}_3(x, Q^2) - y^2 \tilde{F}_L(x, Q^2) \right] \]

dominant relevant at high \( Q^2 \)

\[ \tilde{F}_2^\pm = F_2^\gamma - (v_e \mp Pe a_e) \chi Z F_2^\gamma Z + (v_e^2 + a_e^2 \mp 2 Pe v_e a_e) \chi^2 Z F_2^Z \]

relevant at high \( y \)

\( \text{polarisation of } e \)

\[ x \tilde{F}_3^\pm = - (a_e \mp Pe v_e) \chi Z xF_3^\gamma Z + (\mp Pe (v_e^2 + a_e^2) + 2 v_e a_e) \chi^2 Z xF_3^Z \]

axial-vector coupling of \( e \) to \( Z \)

vector coupling of \( e \) to \( Z \)

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Proton Structure Functions

\[
\frac{d^2 \sigma_{\text{NC}}^{e^\pm p}}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} \left[ Y_+ \tilde{F}_2(x, Q^2) \mp Y_- x \tilde{F}_3(x, Q^2) - y^2 \tilde{F}_L(x, Q^2) \right]
\]

dominant
relevant at high \( Q^2 \)
relevant at high \( y \)
polarisation of \( e \)

\[
\tilde{F}_2^{\pm} = F_2^\gamma - (\nu_e \mp P_e a_e) \chi Z F_2^{\gamma Z} + (\nu_e^2 + a_e^2 \mp 2 P_e \nu_e a_e) \chi Z^2 F_2^Z
\]

\[
x \tilde{F}_3^{\pm} = - (a_e \mp P_e \nu_e) \chi Z x F_3^{\gamma Z} + (\mp P_e (\nu_e^2 + a_e^2) + 2 \nu_e a_e) \chi Z^2 x F_3^Z
\]

axial-vector coupling of \( e \) to \( Z \)
vector coupling of \( e \) to \( Z \)
Proton Structure Functions

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\frac{d^2 \sigma_{NC}^{e^+p}}{dx dQ^2} = \frac{2\pi \alpha^2}{xQ^4} \left[ Y_+ \tilde{F}_2(x, Q^2) \mp Y_- \tilde{F}_3(x, Q^2) - y^2 \tilde{F}_L(x, Q^2) \right]
\]

dominant relevant at high \(Q^2\) relevant at high \(y\)

\[
\tilde{F}_2^\pm = F_2^\gamma - (\nu_e \mp P_e a_e) \chi_Z F_2^{\gamma Z} + (\nu_e^2 + a_e^2 \mp 2 P_e \nu_e a_e) \chi_Z ^2 F_2^Z
\]

\[
x \tilde{F}_3^\pm = - (a_e \mp P_e \nu_e) \chi_Z xF_3^{\gamma Z} + (\mp P_e (\nu_e^2 + a_e^2) + 2 \nu_e a_e) \chi_Z ^2 xF_3^Z
\]

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High-\(Q^2\) \(e^+p\) Neutral Current Cross Sections at HERA and Determination of the Structure Function \(xF_3\)

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

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

- \(\tilde{F}_L \approx \frac{\alpha_s}{8.3} xg\)
Importance of High-$Q^2$ NC Measurements

- The NC cross sections are a powerful probe of the parton distributions (PDFs).
- The NC cross sections are sensitive to all flavours.
- The difference between the $e^+ p$ and $e^- p$ NC cross sections gives direct access to the structure function $x\tilde{F}_3$.
- The longitudinal polarisation asymmetry, $A^+ \approx a_e \nu_q$ allows parity violation to be directly measured.
HERA and the LHC

- HERA has a large kinematic reach.
- HERA PDFs can be extrapolated into the LHC region (DGLAP evolution).
- HERA data crucial for calculations of measurements and new physics at the LHC.
Neutral Current Sample (e+p Data)

- ZEUS-prel-11-003.
  - This data completes the HERA-II ZEUS high-\(Q^2\) inclusive analyses.

\[ e^+ p \text{ data, taken 2006-07, } \mathcal{L} = 135 \text{ pb}^{-1} \]

- \( P_e = +32\% \)
- \( P_e = -36\% \)

\[ \mathcal{L} = 78.8 \text{ pb}^{-1} \]
\[ \mathcal{L} = 56.7 \text{ pb}^{-1} \]

Kinematic range: \( Q^2 > 185 \text{ GeV} \) and \( y < 0.9 \).

- Data well described.
**dσ/dx and dσ/dy with Pe > 0 and Pe < 0**

**ZEUS**

![Graphs showing the results of ZEUS NC e^+ p interactions at HERA](image)

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High-\( Q^2 \) e^+ p Neutral Current Cross Sections at HERA and Determination of the Structure Function \( xF_3 \)
**Motivation**

**Summary**

\[ d\sigma/dx \text{ and } d\sigma/dy \text{ with } P_e > 0 \text{ and } P_e < 0 \]

**ZEUS**

\[ Q^2 > 185 \text{ GeV}^2 \]

- ZEUS NC (prol.)
  - e^+p (78.8 pb\(^{-1}\))
  - SM (HERAPDF1.5)
  \( P_e = +0.32 \)

\[ Q^2 > 3000 \text{ GeV}^2 \]

- ZEUS NC (prol.)
  - e^+p (78.8 pb\(^{-1}\))
  - SM (HERAPDF1.5)
  \( P_e = +0.32 \)

\[ Q^2 > 185 \text{ GeV}^2 \]

- ZEUS NC (prol.)
  - e^+p (56.7 pb\(^{-1}\))
  - SM (HERAPDF1.5)
  \( P_e = -0.36 \)

\[ Q^2 > 3000 \text{ GeV}^2 \]

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  - e^+p (56.7 pb\(^{-1}\))
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  \( P_e = -0.36 \)

**Contributors**

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The difference between the two polarisation states clearly seen at higher-$Q^2$.

$\leftarrow$ **RH**: $d\sigma/dQ^2$ with positive $P_e$.

$\leftarrow$ **LH**: $d\sigma/dQ^2$ with negative $P_e$.

$\leftarrow$ **RH/LH**: ratio of cross sections with positive $P_e$/negative $P_e$.

These results are not included in the shown SM expectation (HERAPDF1.5).
Asymmetry

\[ A^+ = \frac{2}{P_+ - P_-} \frac{\sigma^+(P_+) - \sigma^+(P_-)}{\sigma^+(P_+) + \sigma^+(P_-)} \]

- \( A^+ \approx a_e \chi Z \frac{F_2^{\gamma Z}}{F_2} = a_e \chi Z \frac{2e_qv_q}{e_q^2} \propto a_e v_q \)
- \( A^+ \) sensitive to \( v_q \).
- \( A^+ \) increases with \( Q^2 \).
̃σ with $P_e > 0$ and $P_e < 0$

- Closed circles $\rightarrow$ positive $P_e$.
- Open circles $\rightarrow$ negative $P_e$.
- Effect of polarisation visible at high-$Q^2$.

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High-\(Q^2\) $e^+p$ Neutral Current Cross Sections at HERA and Determination of the Structure Function $xF_3$
\[ \frac{d\sigma}{dQ^2}, \frac{d\sigma}{dx} \text{ and } \frac{d\sigma}{dy} \text{ with } P_e = 0 \]

- Measurement over large kinematic ranges.
- The results will help further constraining the PDFs.

**ZEUS**

- ZEUS NC (prel.)
  \( e^+ p (135.5 \text{pb}^{-1}) \)
  \( \text{SM (HERAPDF1.5)} \)
  \( P_e = 0 \text{ (corrected)} \)
\[ \tilde{\sigma} \text{ with } P_e = 0 \text{ for } e^+p \text{ and } e^-p \]

- **Closed circles →** Full \( e^+p \) data set.
- **Open circles →** Previously measured unpolarised \( e^-p \tilde{\sigma} \).
- Difference between \( e^+p \) and \( e^-p \) clearly seen.
  - Described well by SM predictions.

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High-\( Q^2 \) \( e^+p \) Neutral Current Cross Sections at HERA and Determination of the Structure Function \( xF_3 \)
**x\tilde{F}_3 Extraction**

\[ \tilde{\sigma}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y^+} \frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2} = \]
\[ \tilde{F}_2(x, Q^2) \mp \frac{y^2}{Y^+} x\tilde{F}_3(x, Q^2) - \frac{y^2}{Y^+} \tilde{F}_L(x, Q^2) \]

- Difference of \( e^+p \) and \( e^-p \)
  \[ \Rightarrow x\tilde{F}_3\text{-extraction}. \]

- Expected to contribute at high-\( Q^2 \).

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High-\( Q^2 \) \( e^+p \) Neutral Current Cross Sections at HERA and Determination of the Structure Function \(xF_3\)
For $e^+ p$ and $e^- p$ data combination to extract $x \tilde{F}_3$.

- Difference between $e^+ p$ and $e^- p$ gives $xF_3$.

\[
x \tilde{F}_3(x, Q^2) = \frac{Y_+}{2Y_-} \left( \tilde{\sigma} e^- p - \tilde{\sigma} e^+ p \right)
\]
Motivation

Summary

\( \tilde{F}_3 \) Extraction

- 135.5 pb\(^{-1}\) e\(^+\) data and 169.9 pb\(^{-1}\) e\(^-\)p data combined to extract \( \tilde{F}_3 \).
- Difference between e\(^+\)p and e\(^-\)p gives \( xF_3 \).

\[
\tilde{F}_3(x, Q^2) = \frac{Y_+}{2Y_-} \left( \tilde{\sigma}e^-p - \tilde{\sigma}e^+p \right)
\]

- Most precise \( \tilde{F}_3 \) measurement.

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High-\( Q^2 \) e\(^+\)p Neutral Current Cross Sections at HERA and Determination of the Structure Function \( xF_3 \)
Both the single differential and reduced NC $e^+p$ cross sections have been precisely measured for right- and left-handed polarisation.

This data completes the ZEUS HERA-II High-$Q^2$ inclusive data.

Effects of polarisation are clearly visible in the $e^+p$ data.

Through the polarisation asymmetry parity violation has been directly measured.

$x\tilde{F}_3$ was extracted → measurement of the valence quarks

Data will help in better constraining the PDFs.
BACKUP
Luminosity and Polarisation

- Luminosity measurement through Bethe-Heitler process $ep \rightarrow e'p\gamma$
- Two independent measurements by Photon Calorimeter and Spectrometer
- Precision: 1.8%
- For this analysis: $\mathcal{L}_{\text{Int}} = 135.5\text{pb}^{-1}$

- Spin rotators to get longitudinal polarisation
- Two independent polarisation measurements
- For 2006/07 $e^+p$: $P_e(RH) \approx +0.32$ ($\mathcal{L}_{\text{Int}} = 78.8\text{ pb}^{-1}$) and $P_e(LH) \approx -0.36$ ($\mathcal{L}_{\text{Int}} = 56.7\text{ pb}^{-1}$)

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The polar angles of the electron and the hadronic system are used for the reconstruction of the kinematic variables ($\gamma_{had}$, $\theta_e$).

Result does not depend on the absolute calorimeter energy measurement in the detector.

Best-suited two-variable method.
Reconstruction of Variables - Double-Angle Method

- The polar angles of the electron and the hadronic system are used for the reconstruction of the kinematic variables ($\gamma_{\text{had}}, \theta_e$).
- Result does not depend on the absolute calorimeter energy measurement in the detector.
- Best-suited two-variable method.

\[
Q_{DA}^2 = e^2 \frac{\sin(\gamma_{\text{had}})(1+\cos(\theta_e))}{\sin(\gamma_{\text{had}})+\sin(\theta_e)-\sin(\gamma_{\text{had}}+\theta_e)}
\]

\[
X_{DA} = \frac{E_e}{E_p} \cdot \frac{\sin(\gamma_{\text{had}})+\sin(\theta_e)+\sin(\gamma_{\text{had}}+\theta_e)}{\sin(\gamma_{\text{had}})+\sin(\theta_e)-\sin(\gamma_{\text{had}}+\theta_e)}
\]

\[
Y_{DA} = \frac{\sin(\theta_e)(1-\cos(\gamma_{\text{had}}))}{\sin(\gamma_{\text{had}})+\sin(\theta_e)-\sin(\gamma_{\text{had}}+\theta_e)}
\]