High-$Q^2$ Charged and Neutral Current Cross Sections With Polarised Positron Beam At ZEUS

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HERA II with Longitudinal Polarised $e^{\pm}$ Beams

- p beam: 920 GeV
- $e^{\pm}$ beam: 27.5 GeV
- centre-of-mass energy: 318 GeV
- Two general purpose experiments, H1 and ZEUS (ZEUS data to be shown).
- $\approx 0.5{ fb}^{-1}$ taken by each experiment.
- HERA II upgrade:
  - Increased luminosity.
  - Longitudinally polarised $e^{\pm}$ beams.
- Mean longitudinal polarisation,
  $$P_e = \frac{N_R - N_L}{N_R + N_L} \approx 30 - 40\%$$
Deep Inelastic Scattering

**Variables which characterize 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:
  \[ Q^2 = s x y \]

**Neutral Current (NC), $\gamma$ or $Z_0$ exchange.**

\[ e^\pm p \rightarrow e^\pm X \]

**Charged Current (CC), $W^\pm$ exchange.**

\[ e^\pm p \rightarrow \nu X \]

\[ p \]

\[ P_p \]

\[ k \]

\[ k' \]

\[ q = k - k' \]

\[ \gamma/\gamma^0, W^\pm \]

\[ \text{current jet} \]

\[ P_q = x P_p \]
Charged and Neutral Current events in the ZEUS detector

### Charged Current

- $\nu$($\bar{\nu}$) escapes the detector volume.
- Jet energy deposits not balanced by $e^\pm$ deposits.
- Characterised by missing-$P_t$.

### Neutral Current

- Well measured scattered $e^\pm$.
- $e^\pm$ energy deposits and Jet(s) balanced in $\phi$. 
Motivation

Why are High Precision High-$Q^2$ CC and NC measurements important?

- The CC cross sections give a powerful probe of the flavour specific parton distributions (PDFs).
- The NC cross sections are sensitive to all flavours.
- The difference between the $e^+ p$ and $e^- p$ NC cross sections give direct access to the structure function $xF_3$.
- The longitudinal polarisation asymmetry, $A^+ \approx a_{e\nu q}$ allows parity violation to be directly measured.
Charged Current Cross Section

In the SM the $W^\pm$ interact only with left(right) (anti-)particles.

$$\sigma_{CC}^{e^\pm p} = (1 \pm P_e)\sigma_{CC,P_e=0}^{e^\pm p}$$

$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x} \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

where $\tilde{\sigma}_{CC}^{e^\pm p}$ is the reduced cross section. $e^+$ and $e^-$ sensitive to different quark densities:

$$\tilde{\sigma}_{CC}^{e^+ p} = x[(\bar{u} + \bar{c}) + (1 - y)^2(d + s)]$$

$$\tilde{\sigma}_{CC}^{e^- p} = x[(u + c) + (1 - y)^2(\bar{d} + \bar{s})]$$
Charged Current Sample ($e^+p$ Data)

- Results published in 2010.
- $e^+p$ data, taken 2006-07,
  - $\mathcal{L} = 132\text{pb}^{-1}$
    - $P_e = +33\%$, $\mathcal{L} = 75.8\text{pb}^{-1}$
    - $P_e = -36\%$, $\mathcal{L} = 56.0\text{pb}^{-1}$
- Data well understood.
Total cross section with $+$ve and $-$ve $P_e$

The total cross section as a function of the longitudinal polarisation of the lepton beam.

- Results from the $e^+ p$ analysis are shown as filled squares for $+$ve and $-$ve polarisation (circled in red).
- Previous $e^+ p$ and $e^- p$ results from H1 and ZEUS also shown.

- Results not included in SM predictions (HERAPDF1.0).
- Measurements consistent with SM expectations.
**dσ/dQ^2 with +ve and -ve P_e**

- Overall shift in cross sections due to effect of polarisation.
- Will help constrain PDF fit.
- Good agreement with SM expectation.
$d\sigma/dx$ and $d\sigma/dy$ with $+ve$ and $-ve$ $P_e$
\[ \tilde{\sigma} \text{ with } +\text{ve and } -\text{ve } P_e \]

- Effect of polarisation clearly seen.
- Adding this data will further constrain the PDF fits.
- Good agreement with SM predictions

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The $e^+p$ CC reduced cross section constrain the $d$ quark density.

As seen earlier, the reduced cross section, $\tilde{\sigma}$, at LO can be written as a sum of $x(\bar{u} + \bar{c})$ and $(d + s)$ contributions.
Total cross section at multiple polarisation values

- **CC $e^+p$ Cross section becomes 0 for $P_e = -1$ positron beam.**
  - A non-zero cross section might point to the existence of a right-handed $W$ boson, $W_R$.

- Extrapolation to $P_e = -1$ consistent with 0.

- Limit placed on $\sigma^{CC}(P_e = -1)$ and $M_{W_R}$ GeV consistent with other experiments.

![Graph showing CC cross section results with polarised positron beam at ZEUS](graph.png)

- ZEUS CC $e^+p$ (132 pb$^{-1}$)
- ZEUS CC $e^+p$ (60.9 pb$^{-1}$, $P_e = 0$)

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Neutral Current Cross Section

- Mediated by both $\gamma$ and $Z_0$

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

\[
\tilde{\sigma}_{NC}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_+} \frac{d^2\sigma_{NC}^{e^+p}}{dxdQ^2} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L
\]

- Where $\tilde{F}_2, x \tilde{F}_3$ and $\tilde{F}_L$ are the generalised structure functions.

- $Y_\pm$ is given by:

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

- The generalized structure functions are given by:

\[
\tilde{F}_2 = F_2^\gamma + \kappa (-\nu_e \pm P_e a_e) F_2^{\gamma Z} + \kappa^2 (\nu_e^2 + a_e^2 \pm 2P_e \nu_e a_e) F_2^Z \\
x\tilde{F}_3 = \kappa (-a_e \mp P_e \nu_e) xF_3^{\gamma Z} + \kappa^2 (2\nu_e a_e \pm P_e (\nu_e^2 + a_e^2)) xF_3^Z
\]

where \( \kappa = \frac{1}{\sin^2 2\theta_w} \frac{Q^2}{Q^2 + M_Z^2} \)

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

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

- \( \tilde{F}_2 \) dominates \( \tilde{\sigma}_{e^\pm p} \).
- \( x\tilde{F}_3 \) contributes only at high \( Q^2 \).
- \( \tilde{F}_L \) contributes at high \( y \).
Neutral Current Sample ($e^+p$ Data)

- New result (**ZEUS-prel-11-003**).
  - Missing result of the HERA-II ZEUS high-$Q^2$ inclusive analyses.

- $e^+p$ data, taken 2006-07,
  - $L = 135 pb^{-1}$
  - $P_e = +32\%$, $L = 78.8 pb^{-1}$
  - $P_e = -36\%$, $L = 56.7 pb^{-1}$

- Kinematic range: $Q^2 > 185 GeV$ and $y < 0.9$.
- Data well described.
$d\sigma/dQ^2$ with $+ve$ and $-ve \, P_e$

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

$\leftarrow$ RH: $d\sigma/dQ^2$ with $+ve \, P_e$.

$\leftarrow$ LH: $d\sigma/dQ^2$ with $-ve \, P_e$.

$\leftarrow$ RH/LH: ratio of cross sections $+ve \, P_e/-ve \, P_e$.

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

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

- $A^+ \approx a_e \kappa \frac{F_2^{\gamma Z}}{F_2^{\gamma}}$
- $a_e \nu_q$
- $A^+$ sensitive to $\nu_q$. 
- $A^+$ increase with $Q^2$. 

![Graph showing Asymmetry](image)
$d\sigma/dx$ and $d\sigma/dy$ with $+ve$ and $-ve$ $P_e$

**ZEUS**

- **QE > 185 GeV**: ZEUS NC (prel.) $e^+p (78.8pb^{-1})$
  - SM (HERAPDF1.5) $P_e = +0.32$

- **QE > 3000 GeV**: ZEUS NC (prel.) $e^+p (56.7pb^{-1})$
  - SM (HERAPDF1.5) $P_e = +0.32$

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These results will help constrain the PDFs.
$\tilde{\sigma}$ with $+ve$ and $-ve$ $P_e$

- Closed circles $\rightarrow +ve$ $P_e$.
- Open circles $\rightarrow -ve$ $P_e$.
- Effect of polarisation visible at high-$Q^2$.
\tilde{\sigma} \text{ with } P_e = 0

- **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.
  - This gives us $xF_3$. 

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Summary

Charged Current:
- Polarised single and reduced CC $e^+ p$ cross sections have been measured.
- Results already included in HERAPDF1.5.

Neutral Current:
- Both the single differential and reduced NC $e^+ p$ cross sections have been measured for right and left-handed polarisation.
  - Effects of polarisation clearly seen in the $e^+ p$ data.
  - The missing piece from the HERA-II High-$Q^2$ inclusive data.
  - Data will help better constrain HERAPDF.
Due to the helicity structure of the W boson, it couples only to left(right)-handed (anti-)fermions.

- The angular distribution of $e^+ \bar{q}$ distribution should be flat ($x(\bar{u} + \bar{c})$) in the positron-quark centre-of-mass scattering angle $\theta^*$. 

- The $e^+ q$ distribution should exhibit a $(1 + \cos \theta^*)^2$ as $(1 - y)^2 = (1 + \cos \theta^*)^2 / 4$.

- At LO QCD the y-int gives the $(\bar{u} + \bar{c})$ contribution, and the slope the $(d + s)$ contribution.