EW measurements with longitudinal polarised leptons in deep inelastic positron-proton scattering

Julian Rautenberg on behalf of the H1 and ZEUS Collaborations

- Deep inelastic scattering at HERA I
- Polarisation at HERA II
- CC and NC Measurements
The Hadron-Elektron-Ringanlage (HERA)

World-wide unique accelerator at DESY, Hamburg

HERA-circumference: 6.3 km
Bunch-distance: 32 m ≈ 96 ns ≈ 100 MHz

Protonen/ Elektronen
E = 820 GeV/ 920 GeV

Positronen/ Elektronen
E = 27.5 GeV
**DIS at HERA**

**Neutral Current (NC)**

\[ e(k) \rightarrow e(k') + \gamma, Z^0(q) \]

\[ p(P) \rightarrow X(P') \]

**Charged Current (CC)**

\[ e(k) \rightarrow \nu(k') + W^\pm(q) \]

\[ p(P) \rightarrow X(P') \]

**Invariant kinematic quantities:**

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

Negative four-momentum transfer squared

\[ x = \frac{Q^2}{2P \cdot q} \]

In proton infinite-momentum frame: fraction of proton momentum

\[ y = \frac{P \cdot q}{P \cdot k} \]

In proton rest-frame: energy-transfer

\[ s = (k + P)^2 = \frac{Q^2}{xy} \]

Squared cms energy

\[ k, P \text{ fixed } \& \text{ 4-momentum conservation} \]

\[ \Rightarrow 2 \text{ independent kinematic Quantities} \]

**Deep inelastic \( \equiv Q^2 \gg 1 \text{ GeV}^2 \), here \( Q^2 \sim 100 \text{ GeV}^2 \)**
NC & CC DIS measurement: events

Neutral Current (NC)

- **Signature:**
  - the DIS electron
- **Background-rejection:**
  - $ep$-collision vertex
  - trans. ($p_t$) and long. ($E - p_z$)
  - momentum conservation

Charged Current (CC)

- **Signature:**
  - $\nu$ undetected $\Rightarrow$ trans. momentum
- **Background-rejection:**
  - $ep$-collision vertex
  - sphericallity
Unpolarised inclusive cross sections

Neutral Current (NC)

\[
\frac{d^2\sigma^{e\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \times \left[ Y_F^{NC} + y^2 F_L^{NC} \right]
\]

\[ F_2^{NC} = x \sum_{q=u\ldots b} A_f [q + \bar{q}] \]

\[ xF_3^{NC} = x \sum_{q=u\ldots b} B_f [q - \bar{q}] \]

\[ \tilde{\sigma} = \frac{xQ^4}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dxdQ^2} \]

Helicity-factor:
\[ Y_{\pm} = 1 \pm (1 - y)^2 \]

\[ F_2^{NC} \] parity conserving (EM)
\[ F_3^{NC} \] parity violating (weak)

Charged Current (CC)

\[
\frac{d^2\sigma^{e\pm p}}{dxdQ^2} = \frac{G_F^2}{4\pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \times \left[ 1 + y^2 F_C^{CC} \right]
\]

in CC \( F_i \) depend on lepton charge

\[ F_2^{CC} = x [d + s + \bar{u} + \bar{c}] \]

\[ xF_3^{CC} = x [d + s - (\bar{u} + \bar{c})] \]

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

\[ F_2^{CC} \] purely weak
\[ F_i^{CC} \] coupling independent
Inclusive HERA I measurements

Electron ideal (EW) “probe” for $F_i$-measurements
⇒ Input for PDF extractions
⇒ Input for SM predictions

CONFIRMATION OF SM EW-SECTOR

at scale up to $Q^2 \approx M_W^2$ & above

$\frac{d\sigma}{dQ^2} (\text{pb/GeV}^2)$

$Q^2 (\text{GeV}^2)$

$y < 0.9$

$F_i(Q^2, x)$ \stackrel{\text{DGLAP}}{\rightarrow} F_i(Q^2, x)$
⇒ Test of QCD
Parity violating $xF_3$:
- None-zero $xF_3$ measured at HERA
- Precision limited by low statistics of $e^-p$ sample

Composition of $xF_3$:

$$xF_3 = -ae\chi_Z xG_3 + 2aeve\chi_Z^2 xH_3$$

- $xG_3$ stems from $\gamma-Z$ interference
- $xH_3$ arises from pure $Z$-exchange
- $\chi_Z = \kappa_W \cdot Q^2/(M_Z^2 + Q^2)$
- $2aeve\chi_Z^2 xH_3$ negligible
- Straight forward extract $xG_3$
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- Compare to low $Q^2$ fixed-target BCDMS
EW at HERA I: helicity-structure in CC

$W$ couples to left-(right-)handed (anti-)particles

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<td>one</td>
<td>dominantly forward</td>
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$$\sum_{e^+q} S_i = 0$$

$\bar{e} \Rightarrow \bar{\nu}' \Leftrightarrow \bar{u}, \bar{c}$

$\bar{d}, \bar{s}' \Leftrightarrow$ CMS

$\sum_{e^+q} S_i = 1$

$\bar{e} \Rightarrow \bar{\nu}' \Rightarrow d, s$

$u', c' \Rightarrow$
**EW at HERA I: helicity-structure in CC**

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Down-type (anti-)quarks contribution suppressed by helicity:

\[
\bar{\sigma}^{e^-p} = x \left[ u + c + (1-y)^2 (\bar{d} + \bar{s}) \right]
\]
\[
\sigma^{e^+p} = x \left[ \bar{u} + \bar{c} + (1-y)^2 (d + s) \right]
\]

Helicity-structure of EW confirmed

Assuming $q_s = \bar{q}_s \Rightarrow \bar{\sigma}^{e^-p} - \sigma^{e^+p} = xu_v - (1-y)^2 x d_v$

⇒ access to valence PDFs

**ZEUS**

- $x = 0.068$
- $x = 0.13$
- $x = 0.24$

ZEUS e$^+p$ 99-00
ZEUS e$^-p$ 98-99
ZEUS-S
$\bar{x}(u+c)$
$x(u+c)$
HERA II: longitudinally polarised leptons

Longitudinal polarisation of lepton beam provides direct EW sensitivity

Sokolov-Termov effect builds-up transverse polarisation
Since 2002 spin-rotators also around H1 & ZEUS (before only Hermes)

Polarisation measured at HERMES (LPOL) & HERA-west (TPOL)

Polarisation builds-up fast and stable at up to \(\sim 50\%\)
HERA II: $e^+p$ 2003-04 data-taking period

History of long. pol.: 20% — 50%

HERA delivered luminosity:

Cross-section data-sets:

<table>
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<th>$L/\text{pb}^{-1}$</th>
<th>$P$</th>
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<tr>
<td>15.3</td>
<td>+33.0%</td>
</tr>
<tr>
<td>21.7</td>
<td>-40.2%</td>
</tr>
<tr>
<td>14.1</td>
<td>+31.8%</td>
</tr>
<tr>
<td>16.4</td>
<td>-40.2%</td>
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Cross sections for polarised lepton beam

\[ CC: \quad \sigma_{CC}(P) = (1 + P) \cdot \sigma_{CC}(P = 0) \]

\[ \text{NC:} \quad \frac{d\sigma^{\pm}_{e^+p\rightarrow e^+X}}{dQ^2dx} = \frac{2\pi\alpha^2}{xQ^4} \left[ \sigma_0 + \sigma_i^\pm(\lambda) + \sigma_Z^\pm(\lambda) \right] \]

\[
\begin{align*}
\sigma_0 &= Y_+ \hat{F}_2 \\
\sigma_i^\pm(\lambda) &= P_Z \left[ Y_+(-\nu \mp \lambda a) \tilde{G}_2 + Y_+(\pm a + \lambda \nu)x\tilde{G}_3 \right] \\
\sigma_Z^\pm(\lambda) &= P_Z^2 \left[ Y_+(\nu^2 + a^2 \pm \lambda \nu a) \hat{H}_2 + Y_-(\mp 2\nu a - (\nu^2 + a^2)\lambda)x\hat{H}_3 \right]
\end{align*}
\]

\[
\begin{align*}
\hat{F}_2 &= x \sum_q (q + \bar{q}) \cdot q_q^2 \\
\tilde{G}_2 &= x \sum_q (q + \bar{q}) \cdot 2vq_qq \\
\hat{H}_2 &= x \sum_q (q + \bar{q}) \cdot (v_q^2 + a_q^2) \\
x\hat{G}_3 &= 2x \sum_q (q - \bar{q}) \cdot a_qqq \\
x\hat{H}_3 &= 2x \sum_q (q - \bar{q}) \cdot a_qvq
\end{align*}
\]
CC DIS measurement: control plots

Kinematics reconstructed from haronic final state (JB)

H1 / ZEUS Detectors are well understood after major upgrade and performing well
H1 CC DIS measurement: cross section

Kinematic region: $Q^2 > 400 \text{ GeV}^2, y < 0.9$

$\sigma_{CC}(P = +33 \pm 2) =$

$34.7 \pm 1.9(\text{stat.}) \pm 1.7(\text{syst.}) \text{ pb}$

$\sigma_{CC}(P = -40.2 \pm 1.5) =$

$13.8 \pm 1.0(\text{stat.}) \pm 1.0(\text{syst.}) \text{ pb}$

Since: $\sigma_{CC}(P) = (1 + P) \cdot \sigma_{CC}(P = 0) \Rightarrow$ linear fit to $\sigma_{CC}(P)$

$\sigma_{CC}(P = -1) = -3.7 \pm 2.4(\text{stat.}) \pm 2.7(\text{syst.}) \text{ pb}$

Consistent with no R.H. W-exchange
**ZEUS CC DIS measurement:** cross section

**Kin. region:** $Q^2 > 200$

\[
\sigma_{CC}(P = +31.8 \pm 0.9) = 46.7 \pm 2.4\text{(stat.)} \pm 1.0\text{(syst.)} \pm 2.3\text{(lumi.)}\text{ pb}
\]

\[
\sigma_{CC}(P = -40.2 \pm 1.1) = 22.5 \pm 1.6\text{(stat.)} \pm 0.5\text{(syst.)} \pm 1.1\text{(lumi.)}\text{ pb}
\]

Consistent with SM using ZEUS-S (no R.H. W-exchange)
NC DIS measurement: control plots

Kinematics reconstructed from electron and hadronic final state

H1 / ZEUS Detectors are well understood after major upgrade and performing well
**ZEUS NC DIS measurement: cross section**

Consistent with SM
NC much less polarisation-dependent

NC challenge for HERA II
Both H1 & ZEUS:
- performing well after upgrade
- measured $e^+p$ CC cross section with long. polarised $e^+$

Longitudinal lepton beam at HERA II starts to be a success!
EW sector of SM confirmed

Right now HERA runs $e^-$
Total HERA I $e^-$ luminosity exceeded
New data coming to complete EW text-book plot