Electroweak physics at HERA

Juraj Bracinik
MPI for Physics Munich
for H1 and ZEUS collaborations

• Introduction
• NC/CC cross section
• Effect of polarization
• Combined QCD/EW analysis of the data
• Conclusions and outlook
HERA collider at DESY

Circumference ~ 6.3km

\[ P \rightarrow e^+ e^- \]

920 GeV \quad 27.5 GeV

Central mass energy $\sqrt{s} = 318$ GeV
Available data sets

**HERA I:** (1993-2000)
~ 130 \(1/pb\)
mainly e+p data

**HERA II:** (since 2003)
~ 50 \(1/pb\) e+p data
~ 100 \(1/pb\) e-p data
Kinematics of ep interactions:

Four momentum transfer:

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

Bjorken \( x \): (in LO the fraction of the proton momentum carried by the parton)

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

Inelasticity: (in the proton rest frame the fraction of the electron energy loss)

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

At fixed center of mass energy only two of them are independent:

\[ Q^2 = sxy \]
Neutral current scattering

\( \gamma \) or \( Z \) are exchanged:

Cross section:

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

In quark-parton model:

\[
F_2 \sim x \sum [q + \bar{q}]
\]
\[
x F_3 \sim 2x \sum [q - \bar{q}]
\]
\[
F_L = 0
\]

Experimental signatures:

- Scattered electron and hadron jet(s)
- Transverse momentum balance

\[ Q^2 = 25030 \text{ GeV}^2, \quad y = 0.50, \quad M = 211 \text{ GeV} \]

See talk by Yujin Ning
Charged current scattering

W-bosons are exchanged:

\[ W(Q^2) \]

\[ e \rightarrow \text{neutrino} \]

\[ p(P) \rightarrow X \]

Cross section:

\[
\frac{d^2 \sigma_{CC}^{\pm \gamma}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_+ W_2 + Y_- x W_3 - y^2 W_L \right]
\]

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

Experimental signatures:
- Neutrino escapes undetected
- Hadron jet(s)
- Missing transverse momentum
NC/CC at high $Q^2$

NC/CC cross sections are similar above $Q^2$ equal to $W$ mass!

$$\frac{d^2 \sigma_{NC}^{\pm p}}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} \text{pdf}$$

$$\frac{d^2 \sigma_{CC}^{\pm p}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \text{pdf}$$

**HERA I data**

\[ M_W^2 = 80.4 \text{GeV}^2 \]
**NC and xF3 at high Q^2**

\[
\frac{d^2 \sigma_{NC}^{\pm \pm p}}{dx dQ^2} = \frac{2 \pi \alpha_e^2}{x Q^4} \left[ \ldots + Y_\perp x \tilde{F}_3 - \ldots \right] 
\]

\[
x \tilde{F}_3 = -a_e \chi Z x F_3^{\gamma Z} + 2 v_e a_e \chi_Z^2 x F_3^{Z} 
\]

↑ **Dominant**  ↓ **Suppressed**

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

\[
x F_3 \sim 2x \sum [q - \bar{q}] 
\]

**HERA Neutral Current**

**The γ-Z interference term clearly visible!**
Longitudinal polarization of lepton beam: new at HERA II.

- The transverse polarization builds up naturally (Sokolov-Ternov effect)
- Typical build-up time $\sim 40$ min
- Spin rotators flip the polarization to longitudinal just before the interaction regions
- Typical level of polarization – 30 – 40 %
**CC cross section with polarization I.**

Polarization affects CC cross section in particularly clean way:

- In SM only left handed particles (right handed antiparticles) interact via CC

- **Level of polarization $P$ is defined as**

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

  $N_R, N_L$ - number of lh (rh) leptons in beam

\[
\frac{d^2 \sigma_{e^\pm p}^{CC}}{dx dQ^2} = [1 \pm P] \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_+ W_2 + Y_- x W_3 - y^2 W_L \right]
\]

*Expect linear dependence of CC cross section on $P$!*
CC cross section with polarization III.

- Data are in good agreement with SM prediction
- Fit by straight line
- Allows to determine the limits on $W_R$ mass (assuming the same coupling)

**H1:** $(Q^2 > 400 \text{ GeV}^2, y < 0.9)$

$e^+ p : \sigma_{CC}(P = -1) = -3.9 \pm 2.3(\text{stat}) \pm 0.7(\text{sys}) \pm 0.8(\text{pol}) \text{ pb}$

$M(W_R) > 208 \text{ GeV} (95\% \text{ CL})$

$e^- p : \sigma_{CC}(P = -1) = 3.9 \pm 2.9(\text{stat}) \pm 1.9(\text{sys}) \pm 2.9(\text{pol}) \text{ pb}$

$M(W_R) > 186 \text{ GeV} (95\% \text{ CL})$

**ZEUS:** $(Q^2 > 200 \text{ GeV}^2)$

$e^+ p : \sigma_{CC}(P = -1) = 7.4 \pm 3.9(\text{stat}) \pm 1.2(\text{sys}) \text{ pb}$

$e^- p : \sigma_{CC}(P = -1) = 0.8 \pm 3.1(\text{stat}) \pm 5(\text{sys}) \text{ pb}$

$M(W_R) > 180 \text{ GeV} (95\% \text{ CL})$

Data are in good agreement with SM
**CC cross section with polarization II.**

\[ e^+ p \]

ZEUS

\[ e^- p \]

ZEUS

Differential cross sections with different polarizations have the same shape, only the normalization is different.
**Polarized NC cross section I.**

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

Generalized structure functions depend on polarization:

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

\[
\tilde{F}_2 \sim F_2 \pm P_e a_e \chi_Z F_2^{\gamma Z}
\]

To first order the same magnitude and opposite sign for two lepton beam charges

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

\[
x \tilde{F}_3 \sim -a_e \chi_Z x F_3^{\gamma Z}
\]

To first order does not depend on \(P\), allows to measure unpolarized \(xF_3\)

\[
a_e = -0.5
\]

\[
v_e \approx -0.04
\]
Polarized NC cross section II.

H1: $e^+ p$

ZEUS: $e^+ p$

H1: $e^- p$

ZEUS: $e^- p$

Polarization effects start to be visible
Corrected for residual polarization effects, most precise $x F_3$ up to now.
The EW/QCD analysis of NC/CC data

Precize data sets allow combined EW+QCD analysis:

- Fit QCD parameters (pdf)
- EW parameters at the same time

Recent results:

- ZEUS HERAI+II preliminary EW+QCD fit (polarization)

CC is sensitive to $M_W$:

$$\frac{d^2\sigma_{CC}^{e^p}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_W W_2 + Y_{-x} W_3 - y^2 W_L \right]$$

NC is sensitive to quark axial and vector couplings to Z:

$$\tilde{F}_2 = F_2 - (v_e \pm P_e a_e) \chi_Z \tilde{F}_2^{\gamma Z} (a_i, v_i) + (v_e^2 + a_e^2 \pm 2P_e v_e a_e) \chi_Z^2 F_2^Z (a_i, v_i)$$
The extraction of quark couplings to $Z$

In QPM:

$$F_2^{\gamma Z} = 2e_i v_i \sum x [q_i + \overline{q_i}]$$

$$F_2^Z = (v_i^2 + a_i^2) \sum x [q_i + \overline{q_i}]$$

$$xF_3^{\gamma Z} = 2e_i a_i \sum x [q_i - \overline{q_i}]$$

$$xF_3^Z = 2v_i a_i \sum x [q_i - \overline{q_i}]$$

• No sign ambiguity (interference terms)
• Sensitive both to $v$ and $a$, different $Q^2$ dependence
• Polarization helps with $v$

Competitive measurement!
**EW/QCD analysis: Right handed isospin**

Introduce right handed isospin, should be zero in SM:

$$a_q = T_{q,L}^3 + T_{q,R}^3$$

$$v_q = T_{q,L}^3 - T_{q,R}^3 - 2e_q \sin^2 \theta_W$$

$T_{q,L}^3, \sin^2 \theta_W$ fixed to SM values

No deviation from SM seen
**EW/QCD analysis: propagator mass**

The mass of the propagator can be determined from the $Q^2$ dependence of the CC cross section:

$$\frac{d^{2}\sigma_{CC}^{e^{\pm}p}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_{prop}^2}{M_{prop}^2 + Q^2} \right]^2 \text{[}]$$

**Fit simultaneously $G$ and $M_{prop}$:**

$G$ fixed to world average:

$$H1: M_{prop} = 82.87 \pm 1.82^{+0.32}_{-0.18} \text{GeV}$$

$$ZEUS: M_{prop} = 79.1 \pm 0.77 (\text{st + uncor}) \pm 0.99 (\text{cor.syst.}) \text{GeV}$$

In good agreement with mass of $W$
Conclusions and Outlook

- HERA experiments collected interesting data sets with lepton polarization for both lepton beam charges
- Direct sensitivity to RH CC (unique) – data in agreement with SM
- Effects of Z exchange seen in NC:
  - Beam charge asymmetry
  - Polarization effects
- Competitive determination of EW parameters from combined EW+QCD fits

More data to come soon