Precision DIS measurements at HERA

Burkard Reisert
Max-Planck-Institut für Physik München
on behalf of the H1 and ZEUS Collaborations

New Measurements:
- Electro Weak Physics
- Longitudinal Structure Function
- Total $\gamma p$ Cross Section
Two colliding beam experiments: H1 and ZEUS
~0.5 fb$^{-1}$ collected per experiment
approximately same amount of collisions with
electrons and positrons of
Left- and right-handed polarisation

$E_e = 27.5\text{GeV}$, $E_p = 920 \text{ GeV}$
dedicated low $E_p$ runs
$E_p = 460\text{GeV}, 575 \text{ GeV}$
Deep Inelastic Scattering (DIS)

**Neutral Current (NC)**

\[ e^\pm(l) \rightarrow e^\pm(l') \]
\[ p(P) \rightarrow \gamma/Z(q) \]
\[ X(P') \]

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

- **Bjorken x**
  \[ x = \frac{Q^2}{2(Pq)} \]

- **Inelasticity**
  \[ y = \frac{(Pq)}{(Pk)} \]

- **Centre-of-mass energy**
  \[ s = (k + P)^2 = \frac{Q^2}{xy} \]

**Charged Current (CC)**

\[ e^\pm(l) \rightarrow \overline{e}^\pm(l') \]
\[ p(P) \rightarrow k, Q^2, W^2(q) \]
\[ k', X(P') \]

Burkard Reisert, Precision DIS at HERA, ICHEP, Paris, July 22 - 28
Neutral Current Cross Section

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

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

\[
\kappa = \frac{1}{4 \sin^2 \theta_w \cos^2 \theta_w} \frac{Q^2}{Q^2 + M_Z^2}
\]

Generalized structure functions:

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

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

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

\[
\begin{bmatrix}
x F_3^{\gamma Z}, x F_3^Z
\end{bmatrix} = \sum_q \begin{bmatrix}
e_q a_q, v_q a_q
\end{bmatrix} 2x (q - \bar{q})
\]
Charged Current Cross Section

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

CC reduced cross section

e^+/e^- sensitive to different quark densities:

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

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

CC gives sensitivity to different combinations of quarks as NC.
Electroweak Unification

EW component of SM:
NC and CC cross sections are similar at $Q^2 \approx M_Z^2, M_W^2$

Data compared with SM
(HERAPDF 1.0 $\rightarrow$ V. Radescu Track04)
Good agreement over full range

difference in $e^+$ and $e^-$ for NC in high $Q^2$ region comes from contribution of $Z$ exchange
Total Charged Current Cross Section

Linear dependence of $\sigma^{CC}$ on $P_e$

$$\sigma^{CC}(e^\pm p) = (1 \pm P_e)\sigma^{CC}_{P_e=0}(e^\pm p)$$

$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$$

SM: weak CC interactions:

- only left handed particles
- (right handed anti-particles)
- interact

ZEUS and H1 in agreement with SM
Polarised CC Cross Sections

Predictions of SM give good description of data
Quark Antiquark Decomposition

Data of the entire HERA II data sets (LH and RH, corrected to $P_e=0$)

H1 Preliminary

$Q^2 = 1000 \text{ GeV}^2$

$\sigma_{CC}$

$\frac{1}{2} (u + c)$

$(1-y)^2 \frac{1}{2} (d + s)$

ZEUS

$Q^2 = 950 \text{ GeV}^2$

$\sigma_{CC}$

$\frac{1}{2} (\bar{u} + \bar{c})$

$(1-y)^2 \frac{1}{2} (d + s)$

H1 + ZEUS Cross Section Combinations → talk by Voica Radescu
Neutral Current: $x F_3$

NC cross section:

$$\tilde{\sigma}^\pm = \frac{d^2 \sigma^{NC}(e^\pm p)}{dxdQ^2} \frac{x Q^4}{2\pi \alpha^2 Y_+} \left( \tilde{F}_2 \mp \frac{Y_-}{Y_+} x \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L \right)$$

$$x \tilde{F}_3 = \frac{Y_+}{2Y_-} [\tilde{\sigma}^- - \tilde{\sigma}^+]$$

dominant contribution to $xF_3$:

$$xF_3^{\gamma Z} \simeq x \tilde{F}_3 \left( \frac{Q^2 + M_Z^2}{\alpha^2 \kappa Q^2} \right)$$

more on NC & CC polarization effects → see talk by V. Chekelian
NC at High $x$: Motivation

H1 and ZEUS have measured NC cross sections up to $x_{\text{max}}=0.65$ (Fixed Target experiments e.g. BCDMS $x_{\text{max}}=0.75$)

- PDFs at $x \rightarrow 1$ largely undetermined
- Variations between various PDF sets larger than uncertainty estimates

We cannot measure $x > x_{\text{limit}}$, however we know $x_{\text{limit}} < x < 1$

$\Rightarrow$ High $x$ constraint by integrated cross section

The fraction difference of $d^2F/dxQ^2$ to the CTEQ6D

$Q^2 = 648 \text{ GeV}^2$

- CTEQ6D
- CTEQ4D
- MRST99
- ZEUS-S
- ZEUS-JET
NC at High $x$: Results

**ZEUS**

\[ \frac{d^2\sigma}{dx dQ^2} \text{ [pb}/\text{GeV}^2] \]

- $Q^2 = 575$ GeV$^2$
- $Q^2 = 725$ GeV$^2$
- $Q^2 = 875$ GeV$^2$
- $Q^2 = 1025$ GeV$^2$
- $Q^2 = 1200$ GeV$^2$
- $Q^2 = 1400$ GeV$^2$
- $Q^2 = 1650$ GeV$^2$
- $Q^2 = 1950$ GeV$^2$
- $Q^2 = 2250$ GeV$^2$
- $Q^2 = 2600$ GeV$^2$
- $Q^2 = 3000$ GeV$^2$
- $Q^2 = 3500$ GeV$^2$
- $Q^2 = 4150$ GeV$^2$
- $Q^2 = 4850$ GeV$^2$
- $Q^2 = 5600$ GeV$^2$
- $Q^2 = 7000$ GeV$^2$

- ZEUS (prel.) $e^- p$ 187 pb$^{-1}$
- ZEUS (prel.) $e^- p$ 187 pb$^{-1}$

(Integrated / Bin Width)

CTEQ6D

Burkard Reisert, Precision DIS at HERA, ICHEP, Paris, July 22 - 28
Measurement of FL

Measure cross sections at same $x$ and $Q^2$ but different $y = Q^2 / x \cdot s \Rightarrow$ vary $s$

\[ \sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \]

- **Change proton beam energy to change cms energy**
  - $E_p = 920$ GeV, High Energy Run (HER)
  - $E_p = 575$ GeV, Medium Energy Run (MER):
  - $E_p = 460$ GeV, Low Energy Run

- **Large lever arm in $y^2/Y_+$**

- **Measure at high $y$ in LER**

- **Extended measurement to high $y$ region**
  \[ y = 1 - E'_e / E_e (1 - \cos \theta) \Rightarrow \text{high } y \text{ means low } E'_e \]
Combined low $E_p$ Cross Sections

H1 Preliminary

$Q^2 = 6.5 \text{ GeV}^2$

Zeus

$Q^2 = 24 \text{ GeV}^2$

H1 and ZEUS

Range of ZEUS measurement
Extracted $F_L$ and $F_2$

- First $F_2$ measurement without assumptions on $F_L$
- Data support a non-zero $F_L$
- Predictions for $F_2$ and $F_L$ are consistent with data
Good agreement between data and predictions for $Q^2 > 10$ GeV$^2$. $F_L$ at low $Q^2$ above prediction using HERAPDF1.0
Variants of Predictions for $F_L$ for H1 and ZEUS

- **Variation of heavy flavour treatment**
- **Higher Order calculation**

Graph showing data points for $F_L$ with different theoretical calculations and their variations.
Extension of \( \sigma @ \) high \( y \) to low \( Q^2 \)

Data agree well with previous ZEUS measurements
Increase overlap with H1 at low \( Q^2 \)
Total Photon-Proton Cross Section

Measurements at 3 proton energies
Slope with $W_{\gamma p}$ locally extracted

\[ \sigma_{tot} = A \cdot W_{\gamma p}^{-2\eta} + B \cdot W_{\gamma p}^{2\varepsilon} \]

DL98: Donnachie Landshoff, Phys Lett. B296, 227

$\varepsilon = 0.110 \pm 0.032$
Summary

- HERA delivered a wealth of $ep$ DIS data
- H1 and ZEUS measurements reach their ultimate precision
- HERA is a unique place to study the structure of the proton
Results to Cover

- NC e\-p: DESY-08-202
- CC e\-p: DESY-08-177
- CC e\+p: ZEUS-pub-10-004
- NC e-p high x
  ZEUS-prel-10-007

- H1+ZEUS comb F2cc:
  ZEUS-prel-09-015
  → Comb. + QCD Fit of F2cc
  Massimo Corradi, track 04

- FL: DESY-09-046
- extension to low Q^2, high y
  ZEUS-prel-10-006

- Total Cross Section
  ZEUS-prel-10-011

- NC at medium Q^2: DESY-09-005
- low Q2, low x: DESY-08-171

- Polarized CC: H1prelim-09-043
- Polarized NC: H1prelim-09-042
  → V. Chekelian, track 02

- Comb. inclusive cross sections
  DESY-09-158
  → combination and QCD analysis
  V. Radescu, track 04

- FL extended Q2
  H1prelim-09-044
- Combined low Ep cross section
  and FL extraction
  H1prelim-10-043
Backup
Polarized NC measurements

The charge dependent polarization asymmetries in neutral currents → direct measure of EW effects

Polarization asymmetries (A) sensitive to ratio of $\gamma Z$ interference term to $F_2$

$A \propto \frac{2}{P_R - P_L} \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \approx \mp \kappa a_e \frac{F_2^{\gamma Z}}{F_2}$

neglecting Z term, the generalized structure function $F_2$ is expressed:

$\tilde{F}_2^{\pm} \approx F_2^\gamma + \kappa (-v e \pm P e a_e) F_2^{\gamma Z}$

At LO: $F_2^{\gamma Z} = x \sum_q 2e_q v_q (q + \bar{q})$

Data well described by SM
New measurement \((L = 22 \text{ pb}^{-1}, 2000)\) combined with published results \((96/97)\)

\[s_r \sim F_2 (12 < Q^2 < 150 \text{ GeV}^2, y < 0.6)\]  

impressive accuracy 1.3 - 2%

Rise compatible with \(F_2 \propto x^{-\lambda}\)

Effect of Gluon dynamics well described by fit
NC Measurement at low $Q^2$

- Measurement presented as effective $\gamma^*p$ cross section
- Precision of combined measurements better than 2%
- Smooth transition from perturbative to non-perturbative regime at $Q^2 \sim 1\text{GeV}^2$