Probing proton structure in high-energy ep collisions

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Deep inelastic scattering at HERA

- Probing the proton at small distance scales

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

\[ x = \frac{Q^2}{2p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k} \]

\[ s = (p + k)^2 \quad Q^2 = x \cdot y \cdot s \]

- \( Q^2 \) is the “probing power”
- \( x \) is the Bjorken scaling variable
- \( y \) is related to the scattering angle in CMS (=\( \sin^2(\theta^*/2) \))
HERA I operation

\[ e^+/e^- \rightarrow 27.5 \text{ GeV} \quad 820 \text{ GeV} \quad 920 \text{ GeV} \quad 1994-97 \quad 1998-00 \]

<table>
<thead>
<tr>
<th></th>
<th>e^+p</th>
<th>e^-p</th>
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<tbody>
<tr>
<td><strong>H1</strong></td>
<td>~100 pb(^{-1})</td>
<td>~16 pb(^{-1})</td>
</tr>
<tr>
<td><strong>ZEUS</strong></td>
<td>~110 pb(^{-1})</td>
<td>~16 pb(^{-1})</td>
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**HERA luminosity 1994 – 2000**

Integrated Luminosity (pb\(^{-1}\))

Days of running
The H1 detector

- Liquid argon calorimeter
- 45000 cells
- EM:
  - Systematic 0.3-3%
- HAD:
  - Systematic 1.4-2%

Isolated electromagnetic cluster with matching track

\[
\frac{\sigma(E)}{E} = \frac{12\%}{\sqrt{E}} \oplus 1\%
\]

\[
\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 1\%
\]
The ZEUS detector

- Compensating depleted uranium calorimeter
- 6000 cells
- EM:
  - Systematic 1-2%
- HAD:
  - Systematic 1%

\[
\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E}}
\]

\[
\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}}
\]

Missing transverse momentum from the neutrino
**DIS cross sections**

**NC Cross Section:**

NC Reduced cross section: \( \tilde{\sigma}_{NC}(x, Q^2) \)

\[
\frac{d^2 \sigma^{NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} Y_+ \left[ F_2 - \frac{y^2}{Y_+} F_L \frac{m_Y}{Y_+} xF_3 \right] \quad Y_\pm = 1 \pm (1 - y)^2
\]

Dominant contribution

Sizeable only at high \( y \)

**CC Cross Section:**

CC Reduced cross section: \( \tilde{\sigma}_{CC}(x, Q^2) \)

\[
\frac{d^2 \sigma^{CC}(e^\pm p)}{dx dQ^2} = \frac{G_F^2}{4\pi x} \frac{M_W^4}{(Q^2 + M_W^2)^2} \left[ Y_+ F_2^{CC} - y^2 F_L^{CC} m_Y xF_3^{CC} \right]
\]

CC Cross Section:

Contribution only important at high \( Q^2 \)
Kinematic range of HERA data

- Overlap with fixed target data at low $Q^2$ and high $x$
- Gluon distn at low $x$
- Valence quarks at high $x$
- Access to non-perturbative region
- Measurements extend fixed target data to higher $Q^2$ and higher $y$
- Probe distances down to $1/1000$ proton

Non-perturbative region
The structure function $F_2$

Wide range of predictions before HERA

Vast progress since the beginning of HERA
The structure function $F_2$

- $F_2$ dominates cross section
- Measured with precision of ~2-3%
- Systematics limited at low $Q^2$
- Statistics limited above $Q^2 \sim 1000$ GeV$^2$
- Directly sensitive to sum of quarks and antiquarks

\[ F_2 \propto \sum_q e_q^2 x(q + \bar{q}) \]
The structure function $F_2$

- $F_2$ sensitive to gluon density via QCD radiation
- Scaling violations
  - Largest at low $x$
  - Driven by gluon density
- Well described by QCD
The longitudinal structure function $F_L$

- At leading order in QCD $F_L = 0$
- Appears in NLO QCD
- Direct access to gluon distribution
- Important test of QCD

- Two methods from H1
  - “Derivative” method
  - “Shape” method
  - Will discuss new low $Q^2$ extractions

- ZEUS
  - ISR events to vary CMS energy
\[ \left( \frac{\partial \sigma}{\partial \ln y} \right)_{Q^2} = \left( \frac{\partial F_2}{\partial \ln y} \right)_{Q^2} - F_L \cdot y^2 \cdot \frac{2 - y}{Y_+^2} - \frac{\partial F_L}{\partial \ln y} \cdot \frac{y^2}{Y_+} \]

- At a fixed \( Q^2 \)
  - \( F_2 \sim x^{-\lambda} \sim e^{\lambda \ln y} \sim 1 + \lambda \ln y + \ldots \)
- Fit \( \partial \sigma / \partial \ln y \) with a straight line at low \( y \) (<0.2)
- Extrapolate line to high \( y \)
- Difference between extrapolated line and measured points gives FL \((y>0.4)\)
- Assumption that \( \partial F_2 / \partial \ln y \) linear in \( \ln y \)
FL from the shape method

\[ \sigma_{\text{FIT}} = c \cdot x^{-\lambda} \frac{y^2}{1+(1-y)^2} F_L \]

- Fit for one \( F_L \) point per \( Q^2 \) bin at \( <y> \)
- \( c, \lambda \) and \( F_L \) free parameters
- Shape driven by \( y^2/Y_+ \) factor
- Constant \( F_L \) over small \( x \) range
- Fits describe the data well
The structure function $F_L$

- Extractions consistent
- Shape method gives smaller uncertainties
FL from ISR events

- NC events with initial state radiation
- Hard photon detected in tagger
- Variation in $\sqrt{s}$ gives access to a range of $y$ values at a fixed $x$ and $Q^2$
- Use shape of cross section as a function of $y$ to measure $F_L$
**Define:**

\[ \delta_{F_L} = \frac{\sigma(F_L \neq 0)}{\sigma(F_L = 0)} = \frac{F_2 - (1-\varepsilon)F_L}{F_2} \]

\[ \varepsilon = \frac{2(1-y)}{1+(1-y)^2} \]

**Fit:**

\[ \frac{N_{\text{data}}}{N_{\text{MC} (F_L=0)}} = N \cdot \delta_{F_L} \]

**Fit as a function of y**

- N and \( F_L \) free parameters
- \( F_2 \) measured

**F_L from ISR events**
The structure function $F_L$

- Direct measurement of $F_L$
- Currently not statistically precise, but…
  - Consistent with NLO QCD
  - Proof that ISR method can work
- For precise measurement of $F_L$ at HERA in the future need to vary beam energy
High $Q^2$ cross sections & $xF_3$

- Current knowledge comes from fixed target data
- Data very precise but subject to theoretical uncertainties
  - Nuclear binding effects
  - Non-perturbative effects at low $Q^2$
- HERA data free from these uncertainties
- Data at high $Q^2$ and high $x$ constrain the valence quark distributions
- Low statistics
  - Cross sections are low
- Sensitive to EW effects through exchange of $Z^0$ in neutral current and $W$ in charged current
High $Q^2$ cross sections & $x F_3$

- Difference between $e^+p$ and $e^-p$ cross sections gives $x F_3$

$$x F_3 \propto \sum_q x (q - \bar{q})$$

- $F_L$ is small contribution
- $x F_3$ comes from interference between gamma and $Z^0$ exchange processes
High $Q^2$ cross sections & $xF_3$

- HERA data confirm valence quark structure
- Uncertainties dominated by statistical uncertainty of $e^-$p data sample
- Clear need for high luminosity
Charged current cross sections

- Different for $e^+p$ and $e^-p$
  \[\sigma \propto [u + c + (1-y)^2(d + s)]\]
  - $e^-p$ sensitive to $u(x,Q^2)$
  - $e^+p$ sensitive to $d(x,Q^2)$
  - $e^+p$ suppressed by $(1-y)^2$ helicity factor
- Sensitive to $M_W$ through propagator

![HERA I high $Q^2$ Charged Current](image-url)
Charged current cross sections

- $e^+p$ scattering sensitive to $d(x,Q^2)$
- Current measurements limited by statistics
- In agreement with global PDFs
Charged current cross sections

- $e^-p$ scattering sensitive to $u(x,Q^2)$
- Current measurements limited by statistics
- In agreement with global PDFs
Parton distributions

• PDFs cannot be calculated by pQCD
  – Measured at a $Q^2$ value
  – Parameterise as a function of $x$
  – Evolve using DGLAP to all $Q^2$ where pQCD is valid

• Accurate determination of PDFs allow accurate SM predictions

• QCD fits have many choices, should be reflected in the PDF uncertainty:
  – Starting scale, min $Q^2$, data sets, perturbative phase space? choice of
densities to parameterise, treatment of heavy quarks, functional form
of parameterisation, treatment of experimental systematic
uncertainties, renorm/factorisation scale…

• H1 & ZEUS make different choices…
ZEUS 2002 fit

- Essentially a global analysis
  - ZEUS 96/97 NC e^+p
  - p and d F_2 NMC
  - p and d F_2 E665
  - F_2 p BCDMS
  - CCFR xF_3
- 2.5 GeV^2 < Q^2 < 30000 GeV^2
- W^2 > 20 GeV^2
- Q_o^2 = 7 GeV^2
- Fit xg, xu_ν, xd_ν, xSea, x(db-ub)
- Thorne-Roberts VFNS
ZEUS 2002 fit

- Agreement with CTEQ and MRST
- $\Delta g \sim 10\% \, Q^2 > 20 \, \text{GeV}^2$
- Gluon negative for $Q^2 \sim 1 \, \text{GeV}^2$
- Can free $\alpha_s$

$\alpha_s = 0.1166 \pm 0.0008\, \text{(uncorr.)} \pm 0.0032\, \text{(corr.)} \pm 0.0036\, \text{(norm.)} \pm 0.0018\, \text{(model)}$
H1 2000 fit

- Minimum number of data sets
  - H1 only
  - BCDMS $F_2 p$ as a cross check
- $3.5\,\text{GeV}^2 < Q^2 < 30000\,\text{GeV}^2$
- $Q_o^2 = 4\,\text{GeV}^2$
- Fit tuned combinations of PDFs to cross sections
  - $xg, xU (= u+c), xD (= d+s), xUb, xDb$
- Zero mass variable flavour number scheme
H1 2000 fit

- In agreement with CTEQ and MRST
- $\Delta x_U \sim 3\% \ x=0.4$
- $\Delta x_D \sim 10\% \ x=0.4$
- Uncertainties on valences PDFs factor ~2 larger with only HERA data
Summary

- Many interesting results from HERA I
- Analysis of structure function data is (almost) complete
- Precision of 2-3% for $F_2$
- HERA provide consistent picture of NC/CC/$F_2$/$F_L$/xF$_3$
- Measurements cover 5 orders of magnitude in $Q^2$ and $x$
- Probe structure of the proton at $10^{-18}m$
- Fits allow HERA data to constrain PDFs
Future prospects for HERA II

- H1 and ZEUS detectors upgraded
  - New detector components commissioned
- Design specific luminosity achieved
- 50% $e^+$ longitudinal polarisation achieved
- Beam currents limited by backgrounds in detectors
  - Remedied during current shutdown
- Improved precision at high $Q^2$
- $F_L$ measurement from lower beam energy runs
- Measure polarisation dependence of charged and neutral current cross sections
- HERA III?