Proton structure functions and parton distribution functions at the HERA ep collider

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Outline

- HERA luminosities and kinematics
- The ZEUS and H1 detectors
- Deep inelastic scattering
- $F_2$, $xF_3$ and $F_L$ structure functions and high $Q^2$ cross sections
- Parton distributions from QCD fits
- High $Q^2$ cross sections with polarised leptons
- Summary and future prospects
HERA

- ep collider in Hamburg, Germany
- Centre of mass energy of 320 (300) GeV
- In 2000-2002 HERA I upgraded to HERA II
  - Increased luminosity
  - Polarised leptons

<table>
<thead>
<tr>
<th>HERA luminosity (pb⁻¹)</th>
<th>HERA I (92-00)</th>
<th>HERA II (02-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻p</td>
<td>27</td>
<td>&gt; 80</td>
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<tr>
<td>e⁺p</td>
<td>165</td>
<td>90</td>
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The ZEUS and H1 detectors

**ZEUS**
- General-purpose detector
- Depleted uranium calorimeter
  - $\sigma(E_{\text{EM}})/E_{\text{EM}} = 0.18/\sqrt{E_{\text{EM}}}$
  - $\sigma(E_{\text{HAD}})/E_{\text{HAD}} = 0.35/\sqrt{E_{\text{HAD}}}$
  - Systematics 1-2 %

**H1**
- General-purpose detector
- Liquid argon calorimeter
  - $\sigma(E_{\text{EM}})/E_{\text{EM}} = 0.12/\sqrt{E_{\text{EM}}} \pm 0.01$
  - $\sigma(E_{\text{HAD}})/E_{\text{HAD}} = 0.50/\sqrt{E_{\text{HAD}}} \pm 0.01$
  - Systematics 0.3-3 %
Deep inelastic scattering kinematics

- $Q^2$ is a measure of the probing power
  - High $Q^2$ $\Rightarrow$ small distance scale
  - Can probe $1/1000$ proton
- $x$ is Bjorken scaling variable
  - Fraction of proton’s momentum carried by struck parton
- $y$ related to $\theta$ in CoM frame
  - Fraction of lepton’s energy transferred to the proton

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

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

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

\[
s = (p + k)^2
\]

\[
Q^2 = xys
\]
HERA kinematic range

- $x$ dependence must be determined empirically from fits to cross sections
- HERA covers very large $x$ range
- At low $x$ measure gluon PDFs
- At high $x$ measure $x F_3$ and valence quark PDFs
- Then extrapolate using pQCD to other $Q^2$ values
- LHC requires precise knowledge of PDFs from HERA to extrapolate into region of LHC new physics
Deep inelastic scattering cross sections

- Neutral current - exchange $Z^0 / \gamma$

$$
\frac{d^2\sigma^\pm}{dx \, dQ^2} = \frac{2\pi \alpha^2}{x Q^4} Y_+ \left( F_2 - \frac{y^2}{Y_+} F_L + \frac{Y_-}{Y_+} x F_3 \right)
$$

$$
\bar{\sigma}_{NC}(x, Q^2)
$$

- Charged current - exchange $W^\pm$

$$
\frac{d^2\sigma^\pm}{dx \, dQ^2} = \frac{G_F^2}{4\pi x} \frac{M_W^4}{(Q^2 + M_W^2)} \left( Y_+ F_2^{CC} - y^2 F_L^{CC} + Y_- x F_3^{CC} \right)
$$

$$
\bar{\sigma}_{CC}(x, Q^2)
$$
The structure functions

\[ F_2 \propto \sum x (q + \bar{q}) \quad x F_3 \propto \sum x (q - \bar{q}) \quad F_L \propto \alpha_s x g(x, Q^2) \]

- \( F_2 \) is dominant contribution to cross sections
- \( x F_3 \) becomes significant at high \( Q^2 \)
- \( F_L \) is only important at low \( Q^2 \) and high \( y \)
- At HERA can study sea and valence quarks
- Also gluons via scaling violations and jet data
- CC with \( e^-p \) (\( e^+p \)) most sensitive to u (d) valence quark

\[
\frac{d^2 \sigma_{CC}^-}{dxdQ^2} \propto \left( (u + c) + (1 - y)^2 (\bar{d} + \bar{s}) \right) \\
\frac{d^2 \sigma_{CC}^+}{dxdQ^2} \propto \left( (\bar{u} + \bar{c}) + (1 - y)^2 (d + s) \right)
\]
$F_2$ measurement

$F_2 \propto \sum x (q + \bar{q})$

- Sensitive to sum of quark and anti-quark
- Measured to 2-3 % precision
- Low $Q^2 \Rightarrow$ systematic error dominates
- High $Q^2$ (beyond 1000 GeV$^2$) $\Rightarrow$ statistical error dominates
**F₂ measurement**

- Measure over huge range
  - $1 < Q^2 < 30,000 \text{ GeV}^2$
  - $10^{-5} < x < 1$
- F₂ sensitive to gluon density by QCD radiation
  - scaling violation
  - F₂ not constant with Q²
- ZEUS and H1 data in agreement and well-described by QCD
Low $Q^2 F_2$ measurement

- $F_2$ well measured in bulk region
- Now extend HERA’s range
  - $0.5 < Q^2 < 7$ GeV$^2$
  - $0.001 < x < 0.06$
- Based on analysis of QED Compton events
  - Cross section depends on $F_2$ and $F_L$, but $y$ small so $F_L \sim 0$
- Overlap with fixed target data in good agreement
High $Q^2$ neutral current cross sections

- At high $Q^2$ $\sigma_{NC}$ different for $e^-$ and $e^+$
- Small cross sections so need high luminosity
- Can measure difference between cross sections and extract $xF_3$
\( xF_3 \) measurements

- \( xF_3 \) comes from \( \gamma-Z^0 \) interference and \( Z^0 \) exchange
- Confirm valence quark structure of proton
- Large statistical uncertainty
  - Using small HERA I e\( -p \) sample
  - Now collecting more e\( -p \) data at HERA II…
High x neutral current cross sections

- Hard to measure PDFs at high x
  - Low statistics
  - High migration
- New reconstruction method at high x
  - Use $E_{jet}$ and $\theta_{jet}$
  - Better x resolution at high x
- Cross section measurements in good agreement with theory
- Will be used as input to fits to measure PDFs at high x more accurately

![Graphs showing cross section measurements for various values of $x$ and $Q^2$.](Image)
The longitudinal structure function $F_L$

\[ F_L \propto \alpha_s x g(x, Q^2) \]

- Important only at high $y$ and low $Q^2$
- Zero in LO QCD
- Appears in NLO QCD
  - directly sensitive to gluon distribution
- Test QCD
- ZEUS and H1 use different methods to measure $F_L$
  - ZEUS - events with initial state radiation for varying $\sqrt{s}$
  - H1 - ‘shape method’
F_L measurement: ZEUS

- NC with initial state radiation
- For fixed x and Q^2 can measure at range of y values by varying \( \sqrt{s} \)
- Measure

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

where

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

- Fit

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

with N and F_L as free parameters
- Consistent with NLO QCD \( \Rightarrow \) method works
- Would have to vary beam energy for greater precision
**$F_L$ measurement:**

**H1**

- Fit
  
  $\tilde{\sigma} = F_2 - \frac{y^2}{Y_+} F_L$

  with $F_2 = cx^{-\lambda}$

  and $F_L(x, Q^2) = F_L(Q^2)$

  in bins of $Q^2$ at $<y>$

  - $c$, $\lambda$ and $F_L$ free
  - $F_L$ constant over small $x$ range
  - Fits match data well
$F_L$ measurement: $H1$

- $F_L$ measurement and predictions consistent
Charged current cross sections

\[ \frac{d^2\sigma^{CC}}{dx dQ^2} \propto \left( (u + c) + (1 - y)^2 (d + s) \right) \]

\[ \frac{d^2\sigma^{+}}{dx dQ^2} \propto \left( (\bar{u} + \bar{c}) + (1 - y)^2 (d + s) \right) \]

- e^-p most sensitive to u(x,Q^2)
- e^+p most sensitive to d(x,Q^2)
- e^+p cross section suppressed by factor (1-y)^2
- Small cross sections
  - Large statistical errors
- H1 and ZEUS agree
- Agree with global PDFs
Parton distributions

● Want high precision e.g. for high-x gluon PDFs at LHC
● Perturbative QCD (pQCD) cannot calculate PDFs
● Measure them at some $Q^2$ and fit as a function of $x$
● Evolve to higher $Q^2$ with pQCD
● HERA fits previously used
  ● Heavy target data to constrain valence quarks
  ● World $F_2$ data
  ● Inclusive cross sections to parameterise gluon by scaling violations
● Many experiments, each with own systematics
● Now use HERA-only data
  ● High $Q^2$ CC and NC constrain valence and low-x sea and gluon
  ● Jet data to constrain mid to high-x gluon directly
Jet data

- QCD Compton and boson-gluon fusion processes
  - Distinct jets in final state
- QCDC depends on $\alpha_s$ and $q_i(x,Q^2)$
- Constrain $q_i$ with NC and CC data
- BGF depends on $g(x,Q^2)$
  - Constrain gluon directly

ZEUS

$\frac{d\sigma}{dE_{T,\text{jet}}^B} \text{ (pb/GeV)}$

- ZEUS-JETS
  - tot. uncert.
  - ZEUS incl. jet DIS 96-97
  - Jet energy scale uncert.

- $125 < Q^2 < 250 \text{ GeV}^2$ ($\times 10^5$)
- $250 < Q^2 < 500 \text{ GeV}^2$ ($\times 10^4$)
- $500 < Q^2 < 1000 \text{ GeV}^2$ ($\times 10^3$)
- $1000 < Q^2 < 2000 \text{ GeV}^2$ ($\times 100$)
- $2000 < Q^2 < 5000 \text{ GeV}^2$ ($\times 10$)
- $Q^2 > 5000 \text{ GeV}^2$ ($\times 1$)

$E_{T,\text{jet}}^B$ (GeV)

$E_{T,\text{jet}}^B$ (GeV)
Parton distributions with jet data

- ZEUS and H1 PDFs consistent
- PDFs with jet data consistent with MRST and CTEQ
Gluon PDFs with jet data

- Precision of mid to high-\(x\) gluon PDF improves with inclusion of jet data.
\( \alpha_s \) determination from QCD fits

- **Jet shapes in NC DIS**
  - ZEUS (DESY 04-072 - hep-ex/0405065)
- **Multi-jets in NC DIS**
  - ZEUS prel. (contributed paper to ICHEP04)
- **Inclusive jet cross sections in \( \gamma p \)**
- **Subjet multiplicity in CC DIS**
  - ZEUS (Eur Phys Jour C 31 (2003) 149)
- **Subjet multiplicity in NC DIS**
- **NLO QCD fit**
- **NLO QCD fit**
  - ZEUS prel. (contributed paper to ICHEP04)

\[ \alpha_s(M_Z) = 0.1183 \pm 0.0028 \text{(exp)} \pm 0.0008 \text{(model)} \pm 0.0030 \text{(scale)} \]

- Jet data significantly improves precision of \( \alpha_s \) determination
- \( \alpha_s(M_Z) = 0.1183 \pm 0.0028 \) (exp) \pm 0.0008 (model) \pm 0.0030 (scale)
- Large uncertainty from scale
  - Would improve with NNLO fits

- Compatible with world average with competitive precision
Spin-dependent CC cross section

- HERA II is delivering polarised leptons
- Charged current cross section
  \[ \sigma^{\pm}(P) = (1 \pm P)\sigma_{0}^{\pm} \]
- No RH CC in SM
  \[ \sigma(P=\pm1) = 0 \]
- Can test spin-dependent part of SM
- Higher cross sections increase statistics and improve precision of structure function and PDF measurements
Spin-dependent CC cross section

- Latest results from $e^-p$ running
- Highest CC cross section from LH $e^-$
- Results in agreement with SM
- Data-taking is continuing with both lepton helicities
Summary and outlook

- HERA provides important measurements of structure functions and PDFs
- Inclusion of jet data in fits to measure PDFs has constrained gluon PDF - especially important for LHC
- HERA luminosity still increasing so will be able to provide even more accurate measurements of structure functions and PDFs
- Combine ZEUS and H1 data for global fits
- NNLO QCD fits