Inclusive Deep-Inelastic Scattering at HERA

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on behalf of the H1 and ZEUS Collaborations

Completion of the HERA inclusive DIS cross section measurements:

1. NC at $E_p = 460, 575$ GeV and model independent $F_L$ measurements

2. NC measurements at highest $x \to 1$

3. Combination of all HERA I+II NC&CC inclusive measurements (HERAPDF2.0)
Deep-Inelastic Scattering (DIS)

**Neutral Current (NC):** \(e^+p \rightarrow e^+X\)

**Charged Current (CC):** \(e^+p \rightarrow \nu X\)

\[Q^2 = -q^2 = -(k-k')^2\] virtuality of \(\gamma^*, Z^0, W\)

\[x = Q^2/2(Pq)\] Bjorken \(x\)

\[y = (Pq)/(Pk)\] inelasticity

\[Q^2 = sxy\] \(s=(k+P)^2\)

H1+ZEUS in total 1 fb\(^{-1}\)
- about equally shared between \(e^+\) and \(e^-\), positive and negative \(P_e\)
- special running at low proton energy for \(F_L\)

ICHEP 2014
Valencia 4.07.2014
1. NC cross section measurements at high $y$ and low $E_p=460, 575$ (and 920) GeV

<table>
<thead>
<tr>
<th>Data Set</th>
<th>$x$ Grid from</th>
<th>to</th>
<th>$Q^2$/GeV$^2$ Grid from</th>
<th>to</th>
<th>$\mathcal{L}$ pb$^{-1}$</th>
<th>$e^+/e^-$</th>
<th>$\sqrt{s}$ GeV</th>
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<tbody>
<tr>
<td>HERA II $E_p=575$ GeV data sets</td>
<td></td>
<td></td>
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<tr>
<td>H1 NC high $Q^2$</td>
<td>0.00065</td>
<td>0.65</td>
<td>35</td>
<td>800</td>
<td>5.4</td>
<td>$e^+p$</td>
<td>252</td>
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<tr>
<td>H1 NC low $Q^2$</td>
<td>0.0000279</td>
<td>0.0148</td>
<td>1.5</td>
<td>90</td>
<td>5.9</td>
<td>$e^+p$</td>
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<tr>
<td>ZEUS NC nominal</td>
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<td>0.013349</td>
<td>7</td>
<td>110</td>
<td>7.1</td>
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<tr>
<td>ZEUS NC satellite</td>
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<td>0.013349</td>
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<td>110</td>
<td>7.1</td>
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<td>HERA II $E_p=460$ GeV data sets</td>
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<td>110</td>
<td>13.9</td>
<td>$e^+p$</td>
<td>225</td>
</tr>
</tbody>
</table>


ZEUS: NC “nominal” and “satellite”: DESY-14-053
measurements at $E_p=460, 575, 920$ GeV
NC at high $y$ for $E_p = 460, 575$ (and 920) GeV

**Experimental challenge:** large $\gamma p$ background at high $y$ (low scattered electron energy)

**H1:**
$E_e$ down to 3 GeV

→ **“soft electron identification”:**
optimal use of information on shower shape in LAr calorimeter, momentum matching with the track, $dE/dx$

→ accept only electron candidates with the **“right electric charge”** and use the **“wrong charge”** events for estimation of remaining background.

**ZEUS:**
$E_e$ down to 6 GeV

→ **“backward tracking”:** use hits in the tracking detectors

→ remaining bkg is subtracted using MC predictions verified from 6m–tagger and $\gamma p$ enriched sample (agreement within 10%)
A model independent measurement of $F_L$ using data at $E_p=460, 575$ and $920$ (820) GeV

$\rightarrow F_L$ and $F_2$ can be determined in a model independent way at each $x$ and $Q^2$

$$\sigma_{NC}(x, Q^2, y) = F_2(x, Q^2) - f(y) F_L(x, Q^2), \quad f(y) = y^2/(1+(1-y)^2)$$

an example: $Q^2=60$ GeV$^2$ and 6 values of $x$

Measurements at $E_p=820$ GeV (ZEUS97) are included in fits

H1: high $Q^2$ 460/575 together with 460/575 data at low $Q^2$ (Spacal) and 920 $e^+p$ data from HERA II
\( F_L \) and \( F_2 \) measurements as a function of \( Q^2 \) and \( x \)

using a \( \chi^2 \) minimisation technique accounting for correlations across all measurements

\( H1 \) Collaboration

\( F_L \) measurements are extended to \( Q^2 = 800 \) GeV\(^2\)
Longitudinal structure function $F_L$

$F_L$ is a pure QCD effect sensitive to gluon density

\[
F_L(x, Q^2) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum_q e_q^2 (1 - \frac{x}{z}) \cdot xg \right]
\]

approximate relation between $F_L$ and gluon (order of $\alpha_s$, with $a=1$)

\[
xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_s(Q^2)} F_L(ax, Q^2)
\]

Consistency of the H1 and ZEUS FL data was checked accounting for corr. errors: $\chi^2/ndf=11/8$ (p-value=20%).

$R = \frac{\sigma_L}{\sigma_T} = F_L/(F_2 - F_L) = 0.23 \pm 0.04$ (H1, $1.5 \leq Q^2 \leq 800$ GeV$^2$)

$R = 0.105 + 0.055 - 0.037$ (ZEUS, $9 \leq Q^2 \leq 110$ GeV$^2$)

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2. Integrated $e^\pm p$ NC cross section at high $x \to 1$

NC events at high $Q^2$ have about 100% acceptance and efficiency for the scattered electron but at highest $x$ the hadronic final state disappears in the beam pipe and there are no means to measure $x$

ZEUS measured the integrated $e^\pm p$ NC cross sections at $x \to 1$ using events without jets at $x$ above $x_{\text{edge}}$.

$$\int_{x_{\text{edge}}}^{1} \frac{d^2\sigma(x, Q^2)}{dx dQ^2} dx$$

NC $e^\pm p$ cross section at highest $x$

$\rightarrow$ there is sensitivity to PDFs at high $x \rightarrow 1$. These integrated measurements are not used so far in the QCD fits (and in the combination below)

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3. Combination of all inclusive NC and CC $e^\pm p$ data from H1 and ZEUS

41 data sets from H1 and ZEUS (1 fb$^{-1}$): $0.045 \leq Q^2 \leq 50000$ GeV$^2$, $6 \times 10^{-7} \leq x \leq 0.65$

21 data sets from HERA I ($E_p=920$ and 820 GeV) and
20 data sets from HERA II (12/4/4 sets for $E_p=920/575/460$ GeV)

Combination of the H1 & ZEUS incl. unpolarized NC and CC data include expert knowledge in the treatment of the correlations between individual data sets.

→ precise, complete and easy in use
→ reduction of stat. and syst. uncertainties

1. HERA I data: JHEP 1001:109,2010 HERAPDF 1.0
2. HERA I and preliminary HERA II data HERAPDF 1.5

HERAverager (wiki-zeuthen.desy.de/HERAverager) is used for the cross section averaging,
162 corr. syst. sources are treated as multiplicative,
the following $\chi^2$ definition is used:

$$
\chi^2_{exp,ds} (m, b) = \sum_{i,d} + \sum_{j,b} = \sum_i \frac{[(m_i - \sum_j m_j b_j - \mu)^2]}{\delta_{i,stat}^2 + (\delta_{i,unco} m_i)^2 + \sum_j b_j^2}
$$

Three additional procedural errors:
- multiplicative vs. additive
- correlation over all data sets of photoproduction bkg and hadronic energy scale uncertainties
Averaging of all NC and CC HERA I+II data

2927 cross sections are combined to 1307 points with 165 correlated systematic errors

$\rightarrow$ up to 6 measurements are combined into one averaged point
$\rightarrow$ good consistency of the input data sets ($\chi^2/\text{ndf} = 1685/1620$)
Pulls for different samples

H1 and ZEUS preliminary

\[ p_{i,k} = \frac{\mu_{i,k} - \mu_{i,\text{ave}}(1 - \sum_j \gamma_{j,i,k} b_{j,\text{ave}})}{\sqrt{\Delta_{i,k}^2 - \Delta_{i,\text{ave}}^2}} \]

→ everywhere consistent with expected one sigma gaussian
Comparison of combinations
HERA I+II vs. HERA I

\[ \sigma^-(x,Q^2) \]

\[ \sigma^{+}(x,Q^2) \]

→ significant improvements in precision at high \( Q^2 \) (especially for e^{-} p NC&CC) and at high \( y \): about 1% precision in the best measured regions

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H1 and ZEUS preliminary

**Combined NC and CC data set from HERA (HERAPDF2.0)**

$e^+p$ NC&CC ($E_p = 920$ GeV), $e^+p$ NC ($E_p = 820, 575, 460$ GeV), corresponding to $1$ fb$^{-1}$

$\rightarrow$ 165 correlated syst. err.; $0.045 \leq Q^2 \leq 50000$ GeV$^2$, $6 \times 10^{-7} \leq x \leq 0.65$

$\sqrt{s} = 318$ GeV

Fixed Target

HERA NC $e^\pm p$ (prel.) $0.4$ fb$^{-1}$

HERA NC $e^\pm p$ (prel.) $0.5$ fb$^{-1}$

$\sqrt{s} = 318$ GeV

NLO, $Q^2_{\text{min}} = 3.5$ GeV$^2$

$e^\pm p$ NC&CC ($E_p = 920$ GeV), $e^\pm p$ NC ($E_p = 820, 575, 460$ GeV), corresponding to $1$ fb$^{-1}$

$\rightarrow$ for QCD analysis of the combined data (HERAPDF2.0) see talk of Katarzyna Wichmann

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Inclusive DIS at HERA
Conclusions

H1 and ZEUS completed inclusive DIS cross section measurements at HERA

- $e^+p$ NC cross sections measurements at low $E_p=460$ and 575 GeV and a model independent determination of $F_L$.
- ZEUS $e^±p$ NC measurements at high $x\rightarrow 1$

All inclusive $e^±p$ NC and CC cross sections at $E_p=920$, 820, 575 and 460 GeV are combined in one coherent HERA data set which is used as a sole input to the HERAPDF 2.0 QCD fits