New DIS & Collider Results

• Introduction
• HERA-II Updates
• H1 NC/CC $e^\pm p$
• ZEUS NC $e^+ p$
• HERAPDF Plans
• LHC Constraints

Eram Rizvi

International Workshop on Neutrino-Nucleus Interactions
The New Kinematic Plane

Final H1 & ZEUS structure function data published
New LHC data being rapidly published

Searches for high mass states require precision knowledge at high $x$

For central production $x=x_1=x_2$

$M=x^2\sqrt{s}$

$\rightarrow M > 1$ TeV probes $x > 0.1$

DGLAP evolution allows predictions to be made

High $x$ predictions rely on

- data (DIS / fixed target)
- sum rules
- behaviour of PDFs as $x \rightarrow 1$

Low $x$ region important for high energy cosmic rays

\[ x_{1,2} = \frac{M}{Q \theta^{\pm y}} \]

\[ Q = M \]

$M = 10$ TeV

$M = 1$ TeV

$M = 100$ GeV

$y = 0, 2, 4$

$y = \pm 7$ TeV

$M = 1, 2$}

$Q = M$
Structure Functions

\[
\frac{d\sigma_{NC}^\pm}{dxdQ^2} = \frac{2\pi\alpha^2}{x} \left[ \frac{1}{Q^2} \right]^2 \left[ Y_+ F_2 + Y_+ x F_3 - y^2 F_L \right]
\]

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

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

Dominant contribution

\[
\tilde{F}_2 \propto \sum (xq_i + x\overline{q}_i)
\]

Only sensitive at high \( Q^2 \sim M_Z^2 \)

\[
x\tilde{F}_3 \propto \sum (xq_i - x\overline{q}_i)
\]

Only sensitive at low \( Q^2 \) and high \( y \)

\[
\tilde{F}_L \propto \alpha_s \cdot xg(x, Q^2)
\]

The NC reduced cross section defined as:

\[
\tilde{\sigma}_{NC}^\pm = \frac{Q^2 x}{2\alpha\pi^2} \frac{1}{Y_+} \frac{d^2\sigma^\pm}{dxdQ^2}
\]

\[
\tilde{\sigma}_{NC}^\pm \sim \tilde{F}_2 + \frac{Y}{Y_+} x\tilde{F}_3
\]

The CC reduced cross section defined as:

\[
\sigma_{CC}^\pm = \frac{2\pi x}{G_F^2} \left[ \frac{M_W^2 + Q^2}{M_W^2} \right]^2 \frac{d\sigma_{CC}^\pm}{dxdQ^2}
\]

\[
\frac{d\sigma_{CC}^\pm}{dxdQ^2} = \frac{1}{2} \left[ Y_+ W_2^\pm + Y_+ x W_3^\pm - y^2 W_L^\pm \right]
\]

similarly for pure weak CC analogues:

\( W_2^\pm, xW_3^\pm \) and \( W_L^\pm \)
Neutral current event selection:
High $P_T$ isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways: energy/angle of hadrons & scattered lepton provides excellent tools for sys cross checks

Removal of scattered lepton provides a high stats “pseudo-charged current sample”
Excellent tool to cross check CC analysis

Final selection: $\sim 10^5$ events per sample at high $Q^2$
$\sim 10^7$ events for $10 < Q^2 < 100$ GeV$^2$

Charged current event selection:
Large missing transverse momentum (neutrino)
Suppress huge photo-production background
Topological finders to remove cosmic muons
Kinematics reconstructed from hadrons
Final selection: $\sim 10^3$ events per sample
HERA Operation

**HERA-I operation 1993-2000**
Ee = 27.6 GeV  
Ep = 820 / 920 GeV  
\( \mathcal{L} \sim 110 \text{ pb}^{-1} \) per experiment

**HERA-II operation 2003-2007**
Ee = 27.6 GeV  
Ep = 920 GeV  
\( \mathcal{L} \sim 330 \text{ pb}^{-1} \) per experiment  
Longitudinally polarised leptons

**Low Energy Run 2007**
Ee = 27.6 GeV  
Ep = 575 & 460 GeV  
Dedicated F_L measurement

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>( R )</th>
<th>( L )</th>
</tr>
</thead>
</table>
| \( e^-p \) | \( \mathcal{L} = 47.3 \text{ pb}^{-1} \)  
\( P_e = (+36.0 \pm 1.0)\% \) | \( \mathcal{L} = 104.4 \text{ pb}^{-1} \)  
\( P_e = (-25.8 \pm 0.7)\% \) |
| \( e^+p \) | \( \mathcal{L} = 101.3 \text{ pb}^{-1} \)  
\( P_e = (+32.5 \pm 0.7)\% \) | \( \mathcal{L} = 80.7 \text{ pb}^{-1} \)  
\( P_e = (-37.0 \pm 0.7)\% \) |
HERA Structure Function Data

Up till now HERA-II datasets only partially published

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Signal Type</th>
<th>Data (pb⁻¹)</th>
<th>Reference</th>
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<td>ZEUS CC e⁻p</td>
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</table>

Complete the analyses of HERA high Q² inclusive structure function data

New published data increase $\int L$ by

- ~ factor 3 for e⁺p
- ~ factor 10 for e⁻p

much improved systematic uncertainties

HERA-II datasets Combined in HERAPDF1.5 (except ZEUS NC e⁺p)
Z\(^0\) contribution enhances as \(Q^2\) increases

Final measurement of ZEUS NC e\(^+\)p data

Shown here for \(P=0\)
Polarised measurements also available

Compared to published NC e\(^-\)p data
Combination of high $Q^2$ data HERA-I and HERA-II

Larger HERA-II luminosity → improved precision at high $x / Q^2$

H1 precision 1.5% for $Q^2 < 500$ GeV$^2$

⇒ factor 2 reduction in error wrt HERA-I

Statsitics limited at higher $Q^2$ and high $x$

Extended reach at high $x$ compared to H1 preliminary data

This $x$ region is the ‘sweet spot’

High precision with long $Q^2$ lever arm $x$-range relevant for Higgs production

Combination of high $Q^2$ data HERA-I and HERA-II

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At high $Q^2$ $x F_3$ arises due to $Z^0$ effects enhanced $e^+e^-$ cross section wrt $e^+$
Difference is $x F_3$
Sensitive to valence PDFs

\[
x \tilde{F}_3 = \frac{Y_+}{2Y_-} \left( \tilde{\sigma}_{NC}^- - \tilde{\sigma}_{NC}^+ \right) \approx a_e \chi_Z x F_3^{\gamma Z}
\]
\[
x \tilde{F}_3 \propto \sum (x q_i - x \bar{q}_i)
\]

H1 measure integral of $x F_3^{\gamma Z}$ - validate sumrule:

\[
\int_{0.016}^{0.725} dx \ F_3^{\gamma Z}(x, Q^2 = 1500 \text{ GeV}^2) = 1.22 \pm 0.09 \text{(stat)} \pm 0.07 \text{(syst)}
\]

NLO integral predicted to be $5/3 + O(\alpha_s/\pi) = 1.16$
NC Cross Sections at High $y$

Measurement extension to high $y$ at high $Q^2$
Sensitive to $F_L$ and $x_g$
Difficult measurement:
- low scattered electron energy $E_e > 5$ GeV
- large photo-production background

Total uncertainty reduced by factor 2:
HERA-I ~4%
HERA-II ~2%
High $Q^2$ CC Cross Sections

Electron scattering

\[
\frac{d^2\sigma_{cc}^-}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ (u + c) + (1 - y)^2 (d + s) \right]
\]

Positron scattering

\[
\frac{d^2\sigma_{cc}^+}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ (\bar{u} + \bar{c}) + (1 - y)^2 (d + s) \right]
\]

H1 combination of high $Q^2$ CC data (HERA-I+II)
Improvement of total uncertainty
Dominated by statistical errors
Provide important flavour decomposition information

CC e+ data provide strong $d_v$ constraint at high $x$
Precision limited by statistics: typically 5-10%
HERA-I precision of 10-15% for e+p
Large gain to come after combination with ZEUS
NC Polarisation Asymmetry

NC polarisation asymmetry:

\[ A^\pm = \frac{2}{P_L - P_R} \cdot \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{\sigma^\pm(P_L^\pm) + \sigma^\pm(P_R^\pm)} \]

At large \( x \) \[ A^\pm \propto +\kappa \frac{1 + d_v/u_v}{4 + d_v/u_v} \]
Measuring the difference in NC polarised cross sections gives access to new structure functions:

\[
\frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{P_L^\pm - P_R^\pm} = \frac{\kappa Q^2}{Q^2 + M_Z^2} \left[ \pm a_e F_2^{\gamma Z} \pm Y_+ \frac{v_e x F_3^{\gamma Z}}{Q^2 + M_Z^2} \right]
\]

\(x F_3\) terms eliminated by subtracted e\(^-\)p from e\(^+\)p

Due to different couplings \(F_2^{\gamma Z}\) has different sensitivity to U-type and D-type compared to \(F_2\)
7.1.1 Measurements with polarised lepton beams

Parameters from assumptions in the QCD analysis. The PDF experimental uncertainties are constructed as an envelope built from the maximal deviation. The strange quark fraction is varied between that exceeds the variation range for

The systematic uncertainties for the polarised measurements of the high momentum cross sections are presented in tables according to all HERA I data sets.

For the polarised HERA II data there is an additional source of uncertainty that varies within its uncertainties as follows:

\[
\begin{align*}
xg(x) &= A_g x^B g (1 - x)^C g - A'_g x^{B' g} (1 - x)^{25}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1 - x)^C_{u_v} (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1 - x)^C_{d_v}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^C_{\bar{U}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^C_{\bar{D}}.
\end{align*}
\]

13 parameter fit: additional flexibility given to \( u_v \) and \( d_v \) compared to H1PDF2009 / HERAPDF1.0

Apply momentum/counting sum rules:

\[
\begin{align*}
\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) &= 1 \\
\int_0^1 dx \cdot u_v &= 2 \\
\int_0^1 dx \cdot d_v &= 1
\end{align*}
\]

Parameter constraints:

\[
\begin{align*}
B_{\bar{U}bar} &= B_{\bar{D}bar} \\
sea &= 2 \times (Ubar + Dbar) \\
Ubar &= Dbar at x=0 \\
fs &= \text{sbar/Dbar}
\end{align*}
\]

Experimental uncertainties produced using RMS spread of 400 replica fits

Parameterisation uncertainty determined from envelope of 14 parameter fit & \( Q_0^2 \) variations

Error band is applied to central value fit ⇒ asymmetric errors since mean of replicas ≠ central fit

\[
\chi^2 = \sum_i \frac{\left[ \mu_i - m_i \left( 1 - \sum_j \gamma^i_j b_j \right) \right]^2}{\delta^2_{i,unc} m^2_i + \delta^2_{i,stat} \mu_i m_i} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,unc} \mu^2_i + \delta^2_{i,stat} \mu^2_i}{\delta^2_{i,unc} \mu^2_i + \delta^2_{i,stat} \mu^2_i}
\]

Errors propagate to measured values - avoid stat fluctuations by scaling errors by expectation \( m_i \)

Modified \( \chi^2 \) definition includes \( \ln \) term to account for likelihood transition to \( \chi^2 \) after error scaling
\( \chi^2/\text{ndf} = 1570/1461 = 1.07 \)

Fit with unsuppressed strange sea \( (f_s=0.5) \) is well within error bands
Comparison of PDF uncertainties from H1 fits with and without new HERA-II data

Large improvement in $x_d$ and $x_D$ over wide $x$ range - driven by more precise CC $e^+p$ data

Improvement in $x_u$ from NC at high $x$.
Error reduction at low $x$ arises from sum rules

High $x$ gluon is also improved from scaling violations

$Q^2 = 1.9$ GeV$^2$
Cross section ratio
for Fe : proton target

Fixed Target & Collider Data at High x

At high x strongest constraints on anti-quarks from deuterium Drell-Yan measurements
Also d quark constraints from deuterium DIS

Cross section ratio
for Fe : proton target

Eram Rizvi
HERAPDF philosophy: Fewer data sets → better control of experimental uncertainties
PDF experimental uncertainty defined by $\Delta \chi^2 = 1$ criterion
Compare to MSTW / CTEQ: effectively use $\Delta \chi^2 = 50$ to 100
Avoid complications of data using nuclear targets

HERAPDF2.0
Include final:
HERA-I low/medium $Q^2$ precision $F_2$
HERA-II high $Q^2$ polarised NC/CC data
HERA-II low/medium $E_p = 575/460$ GeV energy NC data
HERA-I+II $F_2^{cc}$ combined data - almost ready
HERA-I+II multijet data - awaiting H1 publication

Expect several fits:
NLO vs NNLO
NLO will be: inclusive NC/CC data & inclusive + $F_2^{cc}$ (+ jets?)
Include fit to $\alpha_s$
MC method for experimental errors will be used

Timescale ~ spring 2013 (DIS workshop?)
the only pre-LHC process that sets direct constraints on the medium and high energy parton densities.

The addition of non-HERA data in the QCD analyses typically leads to a better description of the high energy parton densities. However, there are still significant uncertainties in the description of the medium energy parton densities.

Measurements of multiplicities of strange hadrons, performed at Fermilab, show how the experimental data included in the NNPDF2.0 fit have been corrected for fragmentation effects. However, there are still significant uncertainties in the description of the medium energy parton densities.

Table of datasets generally used in current QCD fits. The kinematic range of each measurement in \( x, Q^2 \) is given. The normalisation of each measurement, and the incident beam energy are also given. The normalisation of each measurement is given as a 1σ uncertainty.

![Diagram showing typical datasets used in global PDF analyses](image)

**Tevatron jets**

**Tevatron W asymmetry**

**Tevatron Z rapidity**

**HERA-II high Q^2 data**

**Drell-Yan fixed target**

**E605 / E772 / E886**

**DIS fixed target**

**NMC / BCDMS**

**HERA-I data**
**Central detector regions for moderate jet particular interest is the region accessed by the LHCb measurement**. Better agreement with MSTW08 is observed albeit within large HERAPDF1.0 and MSTW08 are in reasonable agreement with the data shown. From [some extent with other DIS data (see Thorne, PDF4LHC Workshop, Sept 2012).

The potential sensitivity of measurements of isolated photons (see section 4.3.1 Electroweak measurements)

4.3.1 Electroweak measurements

```
Electron Charge Asymmetry

0.2
0.1

CMS = 7 TeV

35
255

T

840 pb

8

NNPDF2.2 (NLO)

NNPDF collaboration.

The predicted cross sections at NLO (left) and NNLO (right) for H

(labeled = 7 TeV)

sections. Currently this leads to measurement uncertainties of about

which have recently been published [this observable can be as much as a factor of two larger than the

smaller than the spread of different predictions as discussed in

CT10

CTEQ6.6

and in Pb-Pb collisions [hence, the impact of LHC prompt photon observations

30

> 20 GeV

W

production, or through the

l

W

production is large at the LHC (up to

1/TeV

20%)

ATLAS+CMS+LHCb

Preliminary

Top/anti-top differential cross section

At √s=14 TeV dominant contribution 90% is from gg

Constrains high x gluon

Theory/Data

data

NLO (MCFM)

ALPGEN

MC@NLO

0.8

1.2

1.4

300

1000

2000

m_{hf} [GeV]

3.5

3

2.5

2

1.5

1

0.5

0

0

0.1

0.2

0.3

p_T > 20 GeV

ATLAS (extrapolated data, W → lν) 35 pb⁻¹

CMS (W → μν) 36 pb⁻¹

LHCb (W → μν) 36 pb⁻¹

MSTW08 prediction (MC@NLO, 90% C.L.)

CTEQ66 prediction (MC@NLO, 90% C.L.)

HERA1.0 prediction (MC@NLO, 90% C.L.)

1/σ_{hf} \frac{dσ_{hf}}{dm_{hf}} [1/TeV]

√s=7 TeV

L dt = 2.05 fb⁻¹

√s=14 TeV dominant contribution 90% is from gg

Constrains high x gluon

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CTEQ66 prediction (MC@NLO, 90% C.L.)

HERA1.0 prediction (MC@NLO, 90% C.L.)

1/σ_{hf} \frac{dσ_{hf}}{dm_{hf}} [1/TeV]
LHC inclusive jets
Can reach very high $x \sim 0.9$
Constrains $qq$ and $qg$ at high $x$
Large detector uncertainty from energy scale
Reduce error by taking cross section ratio at different $\sqrt{s}$
$\Rightarrow$ correlated systematic errors ~cancel
Atlas published data for $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV

Other LHC constraints
$W^{\pm}c$ & $W^{-}c$ gives access to strange/anti-strange
High mass Drell-Yan $\rightarrow$ anti-quarks at high $x$
Prompt photon production $qg \rightarrow \gamma q$ constrains high $x$ gluon
....
Summary

- H1 / ZEUS completed their final SF measurements
- New HERA-II data provide tighter constraints at high x / Q^2
- HERA data provide some of the most stringent constraints on PDFs
- Stress-test of QCD over 4 orders of mag. in Q^2
- DGLAP evolution works very well
- HERA data provide a self-consistent data set for complete flavour decomposition of the proton
- New combination of HERA data underway
- Combination ⇒ HERAPDF2.0 QCD fit
- Global PDF analyses now start to use LHC data
New High x Constraints from HERA DIS

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Final high x / high $Q^2$

NC and CC cross sections now published from H1 & ZEUS - legacy data sets

CC $e^p$ gives strong clean constraints on $x_d$

High x constraints at high $Q^2$ improve high x PDFs at lowest $Q^2$ via QCD evolution

Compared to relative experimental uncertainties of the new high $x$ measurements.

Better assess the effect of the new high $x$ constraints at high $Q^2$.
New High x Constraints From LHC

Inclusive jets at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV
Constrain $qg$ and $gg$ PDFs

LHC data provide new high x constraints
Yet to be included in QCD fits to PDFs

Top/anti-top differential cross section
First measurement at $\sqrt{s} = 7$ TeV
Large stat error - future $\sqrt{s} = 14$ TeV will give better constraints

Eram Rizvi
Summary of HERA-I datasets
Combined in HERAPDF1.0

Available since 2009

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<thead>
<tr>
<th>Data Set</th>
<th>x Range</th>
<th>$Q^2$ Range</th>
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<td>H1 CC</td>
<td>99-00</td>
<td>0.013</td>
<td>0.40</td>
<td>300</td>
<td>15000</td>
</tr>
<tr>
<td>ZEUS BPC</td>
<td>95</td>
<td>$2 \times 10^{-6}$</td>
<td>$6 \times 10^{-5}$</td>
<td>0.11</td>
<td>0.65</td>
</tr>
<tr>
<td>ZEUS BPT</td>
<td>97</td>
<td>$6 \times 10^{-7}$</td>
<td>0.001</td>
<td>0.045</td>
<td>0.65</td>
</tr>
<tr>
<td>ZEUS SVX</td>
<td>95</td>
<td>$1.2 \times 10^{-5}$</td>
<td>0.0019</td>
<td>0.6</td>
<td>17</td>
</tr>
<tr>
<td>ZEUS NC</td>
<td>96-97</td>
<td>$6 \times 10^{-5}$</td>
<td>0.65</td>
<td>2.7</td>
<td>30000</td>
</tr>
<tr>
<td>ZEUS CC</td>
<td>94-97</td>
<td>0.015</td>
<td>0.42</td>
<td>280</td>
<td>17000</td>
</tr>
<tr>
<td>ZEUS NC</td>
<td>98-99</td>
<td>0.005</td>
<td>0.65</td>
<td>200</td>
<td>30000</td>
</tr>
<tr>
<td>ZEUS CC</td>
<td>98-99</td>
<td>0.015</td>
<td>0.42</td>
<td>280</td>
<td>30000</td>
</tr>
<tr>
<td>ZEUS NC</td>
<td>99-00</td>
<td>0.005</td>
<td>0.65</td>
<td>200</td>
<td>30000</td>
</tr>
<tr>
<td>ZEUS CC</td>
<td>99-00</td>
<td>0.008</td>
<td>0.42</td>
<td>280</td>
<td>17000</td>
</tr>
</tbody>
</table>

High $Q^2$ NC and CC data limited to 100 pb$^{-1}$ $e^+p$
16 pb$^{-1}$ $e^-p$
Polarisation dependence of CC cross section now final from H1 and ZEUS
Polarised NC measurements completed for $e^+p$, $e^-p$, L-handed, R-handed scattering.

Difference in L,R scattering visible at high $Q^2$. 

Figure 8: The $e^+p$ NC DIS reduced cross-section $\tilde{\sigma}$ for positively and negatively polarised beams plotted as a function of $x$ at fixed $Q^2$. The closed (open) circles represent the ZEUS data for negative (positive) polarisation. Other details as in Figure 5.
HERAPDF1.0
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with 10 parameters
\( \alpha_s = 0.1176 \) (fixed in fit)

HERAPDF1.5
Include additional NC and CC HERA-II data
Complete MSbar NLO and NNLO fit
NLO: standard parameterisation with 10 parameters

HERAPDF1.5f
NNLO: extended fit with 14 parameters

HERAPDF1.6
Include additional NC inclusive jet data 5 < \( Q^2 \) < 15000
Complete MSbar NLO fit
NLO: standard parameterisation with 14 parameters
\( \alpha_s = 0.1202 \pm 0.0013 \) (exp) \( \pm 0.004 \) (scales) free in fit

HERAPDF1.7
Include 41 additional \( F_2^{cc} \) data 4 < \( Q^2 \) < 1000
Include 224 combined cross section points \( E_p=575/460 \) GeV
Complete MSbar NLO fit
NLO: standard parameterisation with 14 parameters
New H1 data are combined with all previously published H1 inclusive cross section measurements

854 data points averaged to 413 measurements
\[ \chi^2/\text{ndf} = 412/441 = 0.93 \]

### Normalisation shifts for H1 data after averaging

<table>
<thead>
<tr>
<th>Source</th>
<th>Shift in units of standard deviation</th>
<th>Shift in % of cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta^L_1 ) (BH Theory)</td>
<td>(-0.39)</td>
<td>(-0.19)</td>
</tr>
<tr>
<td>( \delta^L_2 ) ((e^+) 94-97)</td>
<td>(-0.46)</td>
<td>(-0.66)</td>
</tr>
<tr>
<td>( \delta^L_3 ) ((e^-) 98-99)</td>
<td>(-0.69)</td>
<td>(-1.20)</td>
</tr>
<tr>
<td>( \delta^L_4 ) ((e^+) 99-00)</td>
<td>(-0.07)</td>
<td>(-0.10)</td>
</tr>
<tr>
<td>( \delta^L_5 ) (QEDC)</td>
<td>(0.81)</td>
<td>(1.70)</td>
</tr>
<tr>
<td>( \delta^L_6, \delta^L_7 ) ((e^+L+R))</td>
<td>(0.84)</td>
<td>(0.80)</td>
</tr>
<tr>
<td>( \delta^L_8, \delta^L_9 ) ((e^-L+R))</td>
<td>(0.84)</td>
<td>(0.89)</td>
</tr>
</tbody>
</table>

**Precision medium Q^2**

HERA-I data ~unshifted

**New high Q^2 HERA-II**

data shifted by \(~1.7\%\) (less than 1 std.dev)
<table>
<thead>
<tr>
<th>Data set</th>
<th>$\delta_L$</th>
<th>$\delta^E$</th>
<th>$\delta^h$</th>
<th>$\delta^N$</th>
<th>$\delta_B$</th>
<th>$\delta^V$</th>
<th>$\delta^S$</th>
<th>$\delta_{pol}$</th>
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</thead>
<tbody>
<tr>
<td>$e^+ \text{ Combined low } Q^2$</td>
<td>$\delta_L^1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+ \text{ Combined low } E_p$</td>
<td>$\delta_L^1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+ \text{ NC 94-97}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^2$</td>
<td>$\delta^E_1$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^V_1$</td>
<td>$\delta^S_1$</td>
</tr>
<tr>
<td>$e^+ \text{ CC 94-97}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^2$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^V_1$</td>
<td>$\delta^S_1$</td>
<td></td>
</tr>
<tr>
<td>$e^- \text{ NC 98-99}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^3$</td>
<td>$\delta^E_1$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^V_1$</td>
<td>$\delta^S_1$</td>
</tr>
<tr>
<td>$e^- \text{ NC 98-99 high y}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^3$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^V_2$</td>
<td>$\delta^S_1$</td>
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</tr>
<tr>
<td>$e^- \text{ CC 98-99}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^3$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^V_2$</td>
<td>$\delta^S_1$</td>
<td></td>
</tr>
<tr>
<td>$e^+ \text{ NC 99-00}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^4$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^S_1$</td>
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</tr>
<tr>
<td>$e^+ \text{ CC 99-00}$</td>
<td>$\delta_L^1$</td>
<td>$\delta_L^4$</td>
<td>$\delta^h_1$</td>
<td>$\delta^N_1$</td>
<td>$\delta_B^1$</td>
<td>$\delta^V_2$</td>
<td>$\delta^S_1$</td>
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<tr>
<td>$e^+ \text{ NC high y}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^6, \delta_L^7$</td>
<td>$\delta^E_2$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_2$</td>
<td>$\delta^S_2$</td>
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<tr>
<td>$e^- \text{ NC high y}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^8, \delta_L^9$</td>
<td>$\delta^E_2$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_2$</td>
<td>$\delta^S_2$</td>
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</tr>
<tr>
<td>$e^+ \text{ NC L}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^6$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_2$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_1$</td>
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<td></td>
</tr>
<tr>
<td>$e^+ \text{ CC L}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^6$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_3$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+ \text{ NC R}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^7$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_2$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_2$</td>
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</tr>
<tr>
<td>$e^+ \text{ CC R}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^7$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_3$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_2$</td>
<td></td>
<td></td>
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<tr>
<td>$e^- \text{ NC L}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^8$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_2$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_3$</td>
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<td></td>
</tr>
<tr>
<td>$e^- \text{ CC L}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^8$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_3$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_3$</td>
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<td></td>
</tr>
<tr>
<td>$e^- \text{ NC R}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^9$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_2$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_4$</td>
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<td></td>
</tr>
<tr>
<td>$e^- \text{ CC R}$</td>
<td>$\delta_L^5$</td>
<td>$\delta_L^9$</td>
<td>$\delta^h_2$</td>
<td>$\delta^N_3$</td>
<td>$\delta_B^1$</td>
<td>$\delta^P_4$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Correlation of H1 systematic error sources

$\delta_L^1 \rightarrow 0.5\% \text{ BH theoretical error HERA-I}$

$\delta_L^5 \rightarrow 2.3\% \text{ Compton lumi error HERA-II}$

$\delta_L^{6-9} \rightarrow 1.5\% \text{ Compton unc. error HERA-II}$
## Table 10: Results of the H1 PDF 2012 fit. For each data set the number of data points are given, along with the $\chi^2$ contribution determined using uncorrelated errors (unc. err.) of the data points.

<table>
<thead>
<tr>
<th>Data Period</th>
<th>Global Normalisation</th>
<th>Per Period Normalisation</th>
<th>Total Normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ \text{ Combined low } Q^2$</td>
<td>0.993</td>
<td>—</td>
<td>0.993</td>
</tr>
<tr>
<td>$e^+ \text{ Combined low } E_p$</td>
<td>0.993</td>
<td>—</td>
<td>0.993</td>
</tr>
<tr>
<td>HERA I $e^+$ 94-97</td>
<td>0.993</td>
<td>0.999</td>
<td>0.992</td>
</tr>
<tr>
<td>HERA I $e^-$ 98-99</td>
<td>0.993</td>
<td>1.003</td>
<td>0.996</td>
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<tr>
<td>HERA I $e^+$ 99-00</td>
<td>0.993</td>
<td>1.005</td>
<td>0.998</td>
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<tr>
<td>HERA II $e^+ L$</td>
<td>1.029</td>
<td>0.991</td>
<td>1.020</td>
</tr>
<tr>
<td>HERA II $e^+ R$</td>
<td>1.029</td>
<td>1.013</td>
<td>1.042</td>
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<tr>
<td>HERA II $e^- L$</td>
<td>1.029</td>
<td>1.010</td>
<td>1.039</td>
</tr>
<tr>
<td>HERA II $e^- R$</td>
<td>1.029</td>
<td>1.014</td>
<td>1.043</td>
</tr>
</tbody>
</table>

### Table 11: Factor corresponding to the luminosity normalisations ($L_1, L_3, L_5$), the normalisation for each data period ($L_2, L_4$ for HERA I and $L_6, L_7, L_8, L_9$ for HERA II), and the overall combined normalisation of the data sets as determined by the QCD fit.

Normalisations from H1PDF 2012

- Low $Q^2$ data shifted by -0.7%
- HERA-I high $Q^2$ by -0.3%
- HERA-II high $Q^2$ by +2 to +4%

All shifts are <1.3 std.devs
HERAPDF 1.0
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with 10 parameters
\[ \alpha_s = 0.1176 \] (fixed in fit)

HERAPDF 1.5
Include additional NC and CC HERA-II data
Complete MSbar NLO and NNLO fit
NLO: standard parameterisation with 10 parameters
HERAPDF 1.5f
NNLO: extended fit with 14 parameters

\[
xf(x,Q_0^2) = A \cdot x^B \cdot (1 - x)^C \cdot (1 + Dx + Ex^2)
\]

\[
xg(x) = A_g x^{B_g} (1 - x)^{C_g},
\]

\[
xu_v(x) = A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} \left(1 + E_{u_v} x^2\right),
\]

\[
xU(x) = A_{U} x^{B_{U}} (1 - x)^{C_{U}},
\]

\[
xD(x) = A_{D} x^{B_{D}} (1 - x)^{C_{D}}.
\]

\[ x\bar{s} = f_s x\bar{D} \] strange sea is a fixed fraction \( f_s \) of \( \bar{D} \) at \( Q_0^2 \)

Apply momentum/counting sum rules:
\[
1 \int dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1
\]

\[
1 \int dx \cdot u_v = 2 \quad 1 \int dx \cdot d_v = 1
\]

Parameter constraints:
\[
B_{uv} = B_{dv}
\]
\[
B_{Ubar} = B_{Dbar}
\]
\[
\text{sea} = 2 \times (Ubar + Dbar)
\]
\[
Ubar = Dbar \text{ at } x=0
\]

\[
Q_0^2 = 1.9 \text{ GeV}^2 \] (below \( m_c \))
\[
Q^2 > 3.5 \text{ GeV}^2
\]
\[
2 \times 10^{-4} < x < 0.65
\]

Fits performed using RT-VFNS

HERAPDF1.0 central values:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$xg$</td>
<td>6.8</td>
<td>0.22</td>
<td>9.0</td>
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</tr>
<tr>
<td>$xu_0$</td>
<td>3.7</td>
<td>0.67</td>
<td>4.7</td>
<td>9.7</td>
</tr>
<tr>
<td>$xd_v$</td>
<td>2.2</td>
<td>0.67</td>
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<td>4.3</td>
</tr>
<tr>
<td>$x\bar{U}$</td>
<td>0.113</td>
<td>-0.165</td>
<td>2.6</td>
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<tr>
<td>$x\bar{D}$</td>
<td>0.163</td>
<td>-0.165</td>
<td>2.4</td>
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</tr>
</tbody>
</table>

$\chi^2$/ndf = 574/582

Experimental systematic sources of uncertainty allowed to float in fit
Include model assumptions into uncertainty:
$f_s$, $m_c$, $m_b$, $Q^2_0$, $Q^2_{min}$

<table>
<thead>
<tr>
<th>Variation</th>
<th>Standard Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_s$</td>
<td>0.31</td>
<td>0.23</td>
<td>0.38</td>
</tr>
<tr>
<td>$m_c$ [GeV]</td>
<td>1.4</td>
<td>1.35(a)</td>
<td>1.65</td>
</tr>
<tr>
<td>$m_b$ [GeV]</td>
<td>4.75</td>
<td>4.3</td>
<td>5.0</td>
</tr>
<tr>
<td>$Q^2_{min}$ [GeV^2]</td>
<td>3.5</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>$Q^2_0$ [GeV^2]</td>
<td>1.9</td>
<td>1.5(b)</td>
<td>2.5(c,d)</td>
</tr>
</tbody>
</table>

(a) $Q^2_0 = 1.8$
(b) $f_s = 0.29$
(c) $m_c = 1.6$
(d) $f_s = 0.34$

Excellent consistency of input data allow standard statistical error definition:
$\Delta \chi^2 = 1$

Exclusive jet data required for free $\alpha_s$ fit
See talk of Krzysztof Nowak

In 14 parameter fit:
release $B_{uv} = B_{dv}$ constraint
allow more flexible gluon

$xg(x,Q^2_0) = A \cdot x^B \cdot (1-x)^C - A' \cdot x^{B'} \cdot (1-x)^{C'}$

allows for valence-like or negative gluon at $Q^2_0$
Charm Content of the Proton

The inclusive charm content of proton can be measured in several methods: D* decays, impact parameter significance... Combination yields ~5-10% precision.

Data cover wide phase space region including charm threshold region.

Theory predictions have small spread ⇒ use optimised $m_c$ parameter.

Spread of LHC Z/W production predictions is reduced ~4.5% → ~0.7% when using optimal value of $m_c$. 

Eram Rizvi