• Introduction
• High $y$ and $F_L$
• $F_2$ at medium $Q^2$
• High $Q^2$ NC and CC
• Jets and $F_2^{cc}$

Eram Rizvi
PDF4LHC
DESY, Hamburg – 4th July 2011
Where Are We Going?

LHC: largest mass states at large x
For central production $x=x_1=x_2$
$M=x\sqrt{s}$
i.e. $M > 1$ TeV probes $x > 0.1$

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

$Z'$ / quantum gravity / susy searches...

DGLAP evolution allows predictions to be made

High $x$ predictions rely on
• data (DIS / fixed target)
• sum rules
• behaviour of PDFs as $x \to 1$
Structure Functions

\[
\frac{d\sigma_{NC}^\pm}{dx dq^2} = \frac{2\pi\alpha^2}{x} \left[ \frac{1}{q^2} \right]^2 \left[ Y_+ \tilde{F}_2 + Y_+ x\tilde{F}_3 - y^2 \tilde{F}_L \right]
\]

\[
\frac{d\sigma_{CC}^\pm}{dx dq^2} = \frac{G_F^2}{4 \pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_+ \tilde{W}_2^\pm + Y_- x\tilde{W}_3^\pm - y^2 \tilde{W}_L^\pm \right]
\]

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

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

Dominant contribution

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

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

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

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

The NC reduced cross section defined as:

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

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

The CC reduced cross section defined as:

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

\[
\frac{d\sigma_{CC}^\pm}{dx dq^2} = \frac{1}{2} \left[ Y_+ W_2^\pm + Y_- xW_3^\pm - y^2 W_L^\pm \right]
\]

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-I operation 1993-2000
Ee = 27.6 GeV
Ep = 820 / 920 GeV
\[ \int L \sim 110 \text{ pb}^{-1} \] per experiment

HERA-II operation 2003-2007
Ee = 27.6 GeV
Ep = 920 GeV
\[ \int L \sim 330 \text{ pb}^{-1} \] per experiment
Longitudinally polarised leptons

Low Energy Run 2007
Ee = 27.6 GeV
Ep = 575 & 460 GeV
Dedicated \( F_L \) measurement
### HERA Structure Function Data

<table>
<thead>
<tr>
<th>Data Set</th>
<th>x Range</th>
<th>$Q^2$ Range GeV$^2$</th>
<th>$\mathcal{L}$ pb$^{-1}$</th>
<th>$e^+/e^-$</th>
<th>$\sqrt{s}$ GeV</th>
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<tbody>
<tr>
<td>H1 svx-mb</td>
<td>95-00</td>
<td>$5 \times 10^{-6}$</td>
<td>0.2</td>
<td>12</td>
<td>2.1 $e^+p$ 301-319</td>
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<td>H1 low $Q^2$</td>
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<td>94-97</td>
<td>0.0032</td>
<td>0.65</td>
<td>150</td>
<td>35.6 $e^+p$ 301</td>
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<tr>
<td>H1 CC</td>
<td>94-97</td>
<td>0.013</td>
<td>0.40</td>
<td>300</td>
<td>35.6 $e^+p$ 301</td>
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<td>H1 NC</td>
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<td>0.0032</td>
<td>0.65</td>
<td>150</td>
<td>16.4 $e^-p$ 319</td>
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<tr>
<td>H1 CC</td>
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<td>0.013</td>
<td>0.40</td>
<td>300</td>
<td>16.4 $e^-p$ 319</td>
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<tr>
<td>H1 NC HY</td>
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<td>0.01</td>
<td>100</td>
<td>16.4 $e^-p$ 319</td>
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<tr>
<td>H1 NC</td>
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<td>0.0013</td>
<td>0.65</td>
<td>100</td>
<td>65.2 $e^+p$ 319</td>
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<tr>
<td>H1 CC</td>
<td>99-00</td>
<td>0.013</td>
<td>0.40</td>
<td>300</td>
<td>65.2 $e^+p$ 319</td>
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<tr>
<td>ZEUS BPC</td>
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<td>ZEUS SVX</td>
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<tr>
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<td>0.42</td>
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<tr>
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<td>ZEUS CC</td>
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<td>0.65</td>
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<td>60.9 $e^+p$ 319</td>
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**Summary of HERA-I datasets Combined in HERAPDF1.0**

<table>
<thead>
<tr>
<th>Data Set</th>
<th>$\sqrt{s}$ GeV</th>
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<tbody>
<tr>
<td>ZEUS CC $e^-p$</td>
<td>175 pb$^{-1}$</td>
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<tr>
<td>ZEUS CC $e^+p$</td>
<td>132 pb$^{-1}$</td>
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<tr>
<td>ZEUS NC $e^-p$</td>
<td>170 pb$^{-1}$</td>
</tr>
<tr>
<td>ZEUS NC $e^+p$</td>
<td>135 pb$^{-1}$</td>
</tr>
<tr>
<td>H1 CC $e^-p$</td>
<td>149 pb$^{-1}$</td>
</tr>
<tr>
<td>H1 CC $e^+p$</td>
<td>180 pb$^{-1}$</td>
</tr>
<tr>
<td>H1 NC $e^-p$</td>
<td>149 pb$^{-1}$</td>
</tr>
<tr>
<td>H1 NC $e^+p$</td>
<td>180 pb$^{-1}$</td>
</tr>
</tbody>
</table>

**HERA-II datasets Combined in HERAPDF1.5**
(except ZEUS NC $e^+p$)

For details of fits see Mandy’s talk...
Direct Measurement of $F_L$

$$\sigma_{NC} = F_2 - \frac{y^2}{Y_+} F_L$$

$$Y_+ = 1 + (1 - y)^2$$

Since \( y = \frac{Q^2}{sx} \)

then measuring cross section at fixed \( x, Q^2 \) but different \( y \) \( \Rightarrow F_L \)

Use three values of \( \sqrt{s} = 319, 252 \) and 225 GeV

Important and direct method to access \( xg(x, Q^2) \)

Use cross section using low silicon tracker
Allows b/g suppression at low \( E_\gamma \) (high \( y \))
Extend \( Q^2 \) range to 1.5 GeV\(^2\) (previously 12 GeV\(^2\))
\[ \int L \, E_\gamma 20 \text{ GeV} = 103.5 \text{ pb}^{-1} \]
\[ \int L \, E_\gamma 575 \text{ GeV} = 5.9 \text{ pb}^{-1} \]
\[ \int L \, E_\gamma 460 \text{ GeV} = 12.2 \text{ pb}^{-1} \]
Similar stat and uncorrelated sys sources efficiencies: trigger, track, charge, ID
Direct Measurement of $F_L$  

New H1 measurement extends to $F_L$ down to $Q^2 \sim 1.5$ GeV$^2$ 
$F_L$ measured down to $x \sim 3 \times 10^{-5}$ 
Good agreement with ZEUS measurement at higher $Q^2$ 
All model predictions describe data reasonably well 
Data can provide new constraints to NNLO models
Joint publication from H1 & ZEUS
High precision achieved
Total uncertainty ~1% for 20 < $Q^2$ < 100 GeV$^2$
Data give most stringent constraints on PDFs
Well described by NLO QCD
High $Q^2$ NC Cross Sections

**H1 and ZEUS**

- **HERA I+II NC $e^+p$ (prel.)**
- **HERAPDF1.5 $e^+p$**
- **HERA I+II NC $e^-p$ (prel.)**
- **HERAPDF1.5 $e^-p$**

High $Q^2$ is the EW physics regime

Precision $\sim 2\%$ precision for $Q^2 < 500$ GeV$^2$
Statistics limited at higher $Q^2$ and high $x$

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

Larger HERA-II luminosity
$\rightarrow$ improved precision at high $x / Q^2$
At high $Q^2$ $x F_3$ arises due to $Z^0$ effects enhanced $e^-$ cross section wrt $e^+$ Difference is $x F_3$
Sensitive to valence PDFs

$$x F_3 \propto \sum (x q_i - x \bar{q}_i)$$
High x is a very interesting region
PDFs fall rapidly at high x
Experimentally very challenging region
- scattered electron has very poor x resolution
- hadronic final state enters forward beam pipe

Use jets for x reconstruction (not complete hadronic final state)
Use jet angle and pT of electron
Improves x resolution
New for this meeting

\(e^+p\) HERA-II NC measurement at high x

single integrated bin for highest x

e-\(p\) scattering data already released
**High $Q^2$ CC Cross Sections**

### Electron scattering

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

### Positron scattering

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

**Preliminary combination of High $Q^2$ CC data**

**Improvement of total uncertainty**

**Dominated by statistical errors**

**Provide important flavour decomposition information**

**CC e+ data provide strong $d_f$ constraint at high $x$**

**HERA Inclusive Working Group August 2010**

**HERA I+II CC e+p (prel.)**

**HERAPDF1.5**

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Eram Rizvi

PDF4LHC - DESY, Hamburg - July 2011

H1-10-141 / ZEUS-prel-10-017
High $Q^2$ NC Cross Sections

H1 and ZEUS

- Latest H1/ZEUS combination
- Uses complete NC/CC data (not incl. ZEUS NC $e^+p$)
- Excellent agreement over full phase space
- Consistent description of fixed target data
- Strong scaling violations at fixed $x$  
  $\Rightarrow$ large gluon density

$\sigma_{r,NC}(x,Q^2) \times 2^i$ vs $Q^2/\text{GeV}^2$

- HERA I+II NC $e^+p$ (prel.)
- Fixed Target
- HERAPDF1.5

Eram Rizvi
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 $m_c$
Jet data bring significant sensitivity to $\alpha_s$
Disentangles correlation between $xg(x,Q^2)$ and $\alpha_s$

HERAPDF1.6 : Simultaneous NLO QCD fit to
- combined NC inclusive cross section data
- combined CC inclusive cross sections data
- normalised H1/ZEUS inclusive jet data

$$\alpha_s(M_Z) = 0.1202 \pm 0.0013 \ (\text{exp})$$
$$\pm 0.0007 \ (\text{model})$$
$$\pm 0.0012 \ (\text{hadronisation})$$
$$+0.0045$$
$$-0.0036 \ (\text{scales})$$

Only combined PDF / $\alpha_s$ fit on the market
New H1 measurement of inclusive, dijet and trijet rates
First measurement of double diff’l trijet cross section
Significantly reduced systematic errors
1% hadronic scale uncertainty
For now - unnormalised cross sections...

Jets in Breit frame: $5 < P_T < 50$ GeV
$M_{12} > 16$ GeV

Greater sensitivity to $\alpha_s$ with more jets
High $Q^2$ and large jet $P_T \Rightarrow$ multi-scale QCD problem
Good description in NLO
(worse for di-jets at low $<P_T>$ ...)

NLO calculation $\mu_R = \mu_F = \sqrt{\frac{1}{2} (Q^2 + P_T^2)}$
scales varied by factors of 2 for uncertainty
Di-jet rates in reasonable agreement
\sim 10\% discrepancy at low \langle P_T \rangle
Data want smaller \alpha_s or smaller xg ?

Extract \alpha_s independently for each jet data set in NLO
PDF uncertainty from CT10 error propagation

**Inclusive jets:**
\[ \alpha_s(M_Z) = 0.1190 \pm 0.0021 \text{(exp.)} \pm 0.0020 \text{(pdf)} \pm 0.0050 \text{(th.)} \]

**Dijets:**
\[ \alpha_s(M_Z) = 0.1146 \pm 0.0022 \text{(exp.)} \pm 0.0021 \text{(pdf)} \pm 0.0044 \text{(th.)} \]

**Trijets:**
\[ \alpha_s(M_Z) = 0.1196 \pm 0.0016 \text{(exp.)} \pm 0.0010 \text{(pdf)} \pm 0.0055 \text{(th.)} \]

Achieved \sim 1\% experimental precision on \alpha_s
Theoretical uncertainty (scales) dominate \sim 4\%
PDF uncertainty \sim 1\%

To come:
Use of normalised cross sections
cancellation of systematic uncertainties
\rightarrow reduced error for \alpha_s
Compendium for HERAPDF

**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
$\alpha_s = 0.1202 \pm 0.0013 \text{ (exp)} \pm 0.004 \text{ (scales)}$ free in fit

**HERAPDF1.7**
Include 41 additional $F_{2cc}$ data $4 < Q^2 < 1000$
Include 224 combined cross section points $E_p=575/460 \text{ GeV}$
Complete MSbar NLO fit
NLO: standard parameterisation with 14 parameters

**HERAPDF2.0**
Include final:
HERA-II high $Q^2$ polarised NC/CC data
HERA-I+II $F_{2cc}$ data
HERA-I+II multijet data

Details in Mandy’s talk...
Conclusions

- H1 / ZEUS combined data reach ~1% precision
- These 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
- HERA jet data allow $\alpha_s$ extraction
- Precision limited by missing jet NNLO theory
- New combination with HERA-II data provide tighter constraints at high $x / Q^2$

Soon to publish final HERA-II data
Produce last HERA combined data set
Legacy DIS NC and CC data
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

desy-09-158

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

\[
\begin{align*}
\begin{array}{l}
xg \\
xu_v \\
xd_v \\
xU \\
xD \\
\end{array}
\quad \begin{array}{l}
xg \\
xU = xu + xc \\
xD = xd + xs \\
xU = x\bar{u} + x\bar{c} \\
xD = x\bar{d} + x\bar{s}
\end{array}
\quad \begin{array}{l}
xg(x) = A_g x^B (1 - x)^C \cdot (1 + E u_x^2), \\
xu_v(x) = A_w x^B (1 - x)^C \cdot (1 + E u_x^2), \\
xd_v(x) = A_d x^B (1 - x)^C \cdot (1 + E u_x^2), \\
xU(x) = A_U x^B (1 - x)^C, \\
xD(x) = A_D x^B (1 - x)^C.
\end{array}
\]

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

Apply momentum/counting sum rules:

\[
\int_0^1 dx \cdot (xu_v + xd_v + xU + xD + xg) = 1
\]

\[
\int_0^1 dx \cdot u_v = 2, \quad \int_0^1 dx \cdot d_v = 1
\]

Parameter constraints:

\begin{align*}
B_{uv} &= B_{dv} \\
B_{Ubar} &= B_{Dbar} \\
\text{sea} &= 2 \times (\text{Ubar} + \text{Dbar}) \\
\text{Ubar} &= \text{Dbar} \text{ at } x=0
\end{align*}

\( Q_0^2 = 1.9 \text{ GeV}^2 \) (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:

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<thead>
<tr>
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<th>A</th>
<th>B</th>
<th>C</th>
<th>E</th>
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<td>(x\bar{D})</td>
<td>0.163</td>
<td>-0.165</td>
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<td></td>
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</tbody>
</table>

\[\chi^2/\text{ndf} = 574/582\]

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

<table>
<thead>
<tr>
<th>Variation</th>
<th>Standard Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
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<tr>
<td>(f_s)</td>
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<td>0.38</td>
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<tr>
<td>(m_c) [GeV]</td>
<td>1.4</td>
<td>1.35(^{(a)})</td>
<td>1.65</td>
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<td>(m_b) [GeV]</td>
<td>4.75</td>
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<td>(Q^2_{\text{min}}) [GeV(^2)]</td>
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<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
\(x_g(x, Q^2_0) = A \cdot x^B \cdot (1 - x)^C - A' \cdot x^{B'} \cdot (1 - x)^{25}\)
allows for valence-like or negative gluon at \(Q^2_0\)
Combined HERA Data

H1 and ZEUS

Systematic uncertainties are point-to-point correlated
Average H1 / ZEUS data using $\chi^2$ minimisation
Allow sys error sources free in fit
Constraint of equal cross sections cross calibrates expts.
Different exptl. methods yield different sys errors
Reduce sys uncertainties of both experiments

Data moved to common $x,Q^2$ grid for averaging
1402 data points $\rightarrow$ 741 averaged measurements
110 correlated systematic error sources taken into account
All H1/ ZEUS sys treated independently
3 additional procedural uncertainties are included

$$\chi^2/\text{ndf} = 637/656$$

* except 0.5% normalisation uncertainty
High $Q^2$ CC Cross Sections

Significant improvement in measurement precision

Positron scattering

HERA-I \rightarrow \text{HERA-I+II}

HERA I CC $e^+p$

HERAPDF1.0

HERA I+II CC $e^+p$ (prel.)

HERAPDF1.5

Reduced QCD uncertainty at high $x$