Probing QCD at HERA
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DESY
On behalf of H1 and ZEUS Collaborations

- Inclusive DIS
- Charm and beauty
- Multijet production
**ZEUS and H1 experiments**

**HERA** is the world's only $e^\pm p$ collider:
- operated during 1992 — 2007;
- $e^\pm$ energy 27.5 GeV;
- $p$ energies 920, 820, 575 and 460 GeV.

**H1 and ZEUS** — two collider experiments at HERA:
- $\sim 0.5$ fb$^{-1}$ of luminosity recorded by each experiment.

HERA data provides unique opportunity to study the structure of the proton.
HERA data and the LHC

\[ Q^2 = -(k - k') \]
\[ x = \frac{Q^2}{2P \cdot q} \]
\[ y = \frac{P \cdot q}{P \cdot k} \]

**HERA data** covers a large part of the LHC x range.

Evolution in \( Q^2 \) via **DGLAP** allows to extrapolate **HERA** PDFs into LHC region.
Combined Inclusive DIS

H1 and ZEUS published all inclusive DIS data. 
H1prelim-14-041, ZEUS-prel-14-005 \(\Rightarrow\) Combine the separate data.

All data points are swum to common \(Q^2 - x\) grids:

\[
\chi^2 / \text{ndf} = 1685 / 1620
\]
Combined Inclusive DIS

H1 and ZEUS preliminary

- 2927 data points combined to 1307
- up to 8 data points combined to 1
- data consistent between two experiments and data taking periods
Combined Inclusive DIS

H1 and ZEUS

- Significant increase of statistics
- Significant reduction of systematic uncertainties

H1prelim-14-041, ZEUS-prel-14-005
QCD analysis of combined DJS data

Neutral Current:

$$\frac{d^2 \sigma_{NC}^{e+\bar{p}}}{dx dQ^2} = \frac{2 \pi \alpha^2 \cdot Y_+}{x Q^4} \cdot \left( F_2(x, Q^2) \pm \frac{Y_-}{Y_+} \cdot x \cdot F_3(x, Q^2) - \frac{y^2}{Y_+} \cdot F_1(x, Q^2) \right)$$

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

$$F_2 = \frac{4}{9} (xU + x\bar{U}) + \frac{1}{9} (xD + x\bar{D})$$

$$x \cdot F_3 \sim xu_v + xd_v$$

Charged Current:

$$\frac{d^2 \sigma_{CC}^{e+\bar{p}}}{dx dQ^2} = \frac{G_F^2}{4 \pi \kappa} \cdot \kappa^2 \cdot \left( Y_+ \cdot W_2^- \pm Y_- \cdot x \cdot W_3^- - y^2 \cdot W_1^+ \right)$$

$$\kappa = \frac{M_w^2}{M_w^2 + Q^2}$$

$$W_2^- = x(U + \bar{D}) \quad W_2^+ = x(D + \bar{U})$$

$$x W_3^- = x(U - \bar{D}) \quad x W_3^+ = x(D - \bar{U})$$

Parton Density Functions parametrization at starting scale $Q^2 = 1.9$ GeV$^2$:

- $xg(x)$
- $xu_v(x)$
- $xd_v(x)$
- $x\bar{U}(x)$
- $x\bar{D}(x)$

- fixed or calculated by sum-rules
- set equal

- Evolve to any $Q^2$ with DGLAP at NLO or NNLO.
- Use Thorne-Roberts GMVFN scheme for Heavy quarks.
HERAPDF 2.0 (prel.)

H1 and ZEUS preliminary

\[ \sigma_{r, NC}(\lambda, Q^2) \]

Q^2 = 2 GeV^2
Q^2 = 2.7 GeV^2
Q^2 = 3.5 GeV^2
Q^2 = 4.5 GeV^2
Q^2 = 6.5 GeV^2
Q^2 = 8.5 GeV^2
Q^2 = 10 GeV^2
Q^2 = 12 GeV^2
Q^2 = 15 GeV^2
Q^2 = 18 GeV^2
Q^2 = 22 GeV^2
Q^2 = 27 GeV^2
Q^2 = 35 GeV^2
Q^2 = 45 GeV^2
Q^2 = 60 GeV^2
Q^2 = 70 GeV^2
Q^2 = 90 GeV^2
Q^2 = 120 GeV^2

\[ \sigma_{r, CC}(\lambda, Q^2) \]

Q^2 = 300 GeV^2
Q^2 = 500 GeV^2
Q^2 = 1000 GeV^2
Q^2 = 1500 GeV^2
Q^2 = 2000 GeV^2
Q^2 = 3000 GeV^2
Q^2 = 5000 GeV^2
Q^2 = 8000 GeV^2

\[ \frac{d^2 \sigma_{NC}}{dxdQ^2} \]

\[ \frac{d^2 \sigma_{CC}}{dxdQ^2} \]

\[ \sqrt{s} = 318 \text{ GeV} \]

\[ \text{HERA } \text{e}^+p \text{ (prel.) } 0.5 \text{ fb}^{-1} \]

\[ \text{HERAPDF2.0 (prel.)} \]

\[ \text{NNLO, } Q^2_{\min} = 3.5 \text{ GeV}^2 \]

Reasonable description of NC and CC by NLO and NNLO.
**HERAPDF 2.0 (prel.)** : $Q^2_{\text{min}} = 3.5 \text{ GeV}^2$

**NLO**

- H1 and ZEUS preliminary
- $\mu_r^2 = 10 \text{ GeV}^2$
- HERAPDF2.0 (prel.) NLO $Q^2_{\text{min}} = 3.5 \text{ GeV}^2$
- exp. uncert.
- model uncert.
- parametrisation uncert.

**NNLO**

- H1 and ZEUS preliminary
- $\mu_r^2 = 10 \text{ GeV}^2$
- HERAPDF2.0 (prel.) NNLO $Q^2_{\text{min}} = 3.5 \text{ GeV}^2$
- exp. uncert.
- model uncert.
- parametrisation uncert.

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**Experimental unc.** - estimated using Hessian method at 68% CL.

**Model unc.** - from variation of quark masses, $\alpha_s$, etc.

**Parametrisation unc.** - extra fit parameters and starting scale variation.
HERAPDF 2.0 (prel.) : $Q^2_{\text{min}}$ variation

H1 and ZEUS preliminary

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

NLO : $\chi^2 / \text{ndf} = 1385 / 1130$
NNLO : $\chi^2 / \text{ndf} = 1414 / 1130$

for $Q^2_{\text{min}} = 10$ GeV$^2$

NLO : $\chi^2 / \text{ndf} = 1156 / 1001$
NNLO : $\chi^2 / \text{ndf} = 1150 / 1001$

$\chi^2$ appears to saturate for $Q^2_{\text{min}} = 10$ GeV$^2$. 
\textbf{HERAPDF 2.0 (prel.) : } \textbf{Q}^2_{\text{min}} = 10 \text{ GeV}^2

\textbf{NLO}

H1 and ZEUS preliminary

\mu_f^2 = 10 \text{ GeV}^2

\begin{itemize}
  \item PDFs in good agreement for \textit{x} > 10^{-3}
  \item Higher \textit{Q}^2_{\text{min}} cut increases low \textit{x} gluon uncertainty.
\end{itemize}

\textbf{NNLO}

H1 and ZEUS preliminary

\mu_f^2 = 10 \text{ GeV}^2
\( F_2^{cc} \) and \( F_2^{bb} \)

\[
\frac{d^2 \sigma_{NC}^{e+p}}{dx dQ^2} = \frac{2\pi \alpha^2 \cdot Y_+}{xQ^4} \cdot (F_2(x, Q^2) \pm \frac{Y_-}{Y_+} \cdot x \cdot F_3(x, Q^2) - \frac{Y^2}{Y_+} \cdot F_L(x, Q^2))
\]

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

\( F_2^{cc} \) and \( F_2^{bb} \) are contributions to \( F_2 \) from events with \( \bar{c}c \) and \( \bar{b}b \) in the final state.
9 different H1 and ZEUS charm cross sections measurements were combined: H1 and ZEUS studies. And used together with HERA I inclusive data in FFN scheme QCD fit for extracting running charm mass:

\[ F_{2}^{cc} \]

DESY-12-172 [E.P.J.C 73(2013)2311], ZEUS-prel-14-006

Running of \( m_{c}(\mu_{r}) \) observed.
ZEUS prepared beauty structure functions measurements combination:

Extracted beauty mass:

\[ m_b = 4.07 \pm 0.14 \text{(fit)} + 0.01 \text{(mod.)} + 0.05 \text{(param.)} + 0.08 \text{(theo.)} \text{GeV} \]

And compared to PDG and LEP running beauty mass:

Consistent with running expected from PDG.
Multijet production at high $Q^2$

- H1 recently measured double differential inclusive jet, dijet and trijet cross sections.

- Measured absolute cross sections are normalized to NC DIS cross sections to benefit from cancelation of correlated systematic uncertainties.
Multijet production at high $Q^2$

Simultaneous $\chi^2$-fit to inclusive jet, dijet and trijet cross sections extracts:

$$\alpha_s (M_Z) = 0.1165 \pm 0.0008 \text{ (exp.)} \pm 0.0038 \text{ (theo.)}$$

most precise value of $\alpha_s (M_Z)$ from jet cross sections, theory available at NLO only and gives dominant uncertainty.

The running of the strong coupling $\alpha_s$ as a function of scale $\mu_r$ shows good consistency with other jet data measurements.
Jet data is used in QCD fit with inclusive combined data for estimation of optimal strong coupling $\alpha_s$:
Summary

- Combination of all final inclusive DIS measurements by the H1 and ZEUS collaborations provides cross sections of very high precision.

- Clean determination of proton’s PDFs based solely on HERA ep collider data.

- Combined HERA DIS charm data is sensitive to charm mass: running of charm quark mass $m_c$ observed.

- ZEUS DIS beauty data made possible first measurement of beauty mass at hadron collider.

- H1 measurement of jet production in DIS allows a precise determination of the strong coupling constant $\alpha_s$. 