Probing QCD at HERA

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DESY
On behalf of H1 and ZEUS Collaborations

- Inclusive DIS
- Charm and beauty
- Multijet production

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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:

- ~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

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.
H1 and ZEUS published all inclusive DIS data. 

H1prelim-14-041, ZEUS-prel-14-005 ⇒ Combine the separate data.

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

H1prelim-14-041, ZEUS-prel-14-005

H1 and ZEUS

- Significant increase of statistics
- Significant reduction of systematic uncertainties

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QCD analysis of combined DIS data

**Neutral Current:**

\[
\frac{d^2 \sigma^{e+p}_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2 \cdot Y_+}{x Q^4} \cdot (F_2(x, Q^2) \pm \frac{Y_-}{Y_+} \cdot x \cdot F_3(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)) \\
Y_\pm = 1 \pm (1 - y)^2
\]

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

\[x \cdot F_3 \sim x u_v + x d_v\]

**Charged Current:**

\[
\frac{d^2 \sigma^{e+p}_{CC}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \cdot \kappa^2 \cdot (Y_+ \cdot W_2^\mp \pm Y_- \cdot x \cdot W_3^\mp - y^2 \cdot W_L^\mp)
\]

\[
k = \frac{M_W^2}{M_W^2 + Q^2}
\]

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

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

**Parton Density Functions parametrization at starting scale \(Q^2 = 1.9 \text{ GeV}^2\):**

- \(x g(x) = A_g x^B (1 - x)^C - A'_g x^B' (1 - x)^C'\)
- \(x u_v(x) = A_{u_v} x^B (1 - x)^C (1 + D_{u_v} x + E_{u_v} x^2)\)
- \(x d_v(x) = A_{d_v} x^B (1 - x)^C\)
- \(x \bar{U}(x) = A_{\bar{U}} x^B (1 - x)^C (1 + D_{\bar{U}} x)\)
- \(x \bar{D}(x) = A_{\bar{D}} x^B (1 - x)^C\)

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

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

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

**Parametrization unc.** - extra fit parameters and starting scale variation.

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HERAPDF 2.0 (prel.) : $Q^2_{\text{min}}$ variation

H1 and ZEUS preliminary

$\chi^2$/dof for $Q^2_{\text{min}} = 3.5$ GeV$^2$
- NLO : $\chi^2 / \text{ndf} = 1385 / 1130$
- NNLO : $\chi^2 / \text{ndf} = 1414 / 1130$

$\chi^2$/dof 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$^2$. 

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HERAPDF 2.0 (prel.) : $Q^2_{\text{min}} = 10 \text{ GeV}^2$

**NLO**

H1 and ZEUS preliminary

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

**NNLO**

H1 and ZEUS preliminary
\( F_2^{cc} \) and \( F_2^{bb} \) are contributions to \( F_2 \) from events with \( \bar{c}c \) and \( \bar{b}b \) in the final state.

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

\[
Y_\pm = 1 \pm (1-y)^2
\]
9 different H1 and ZEUS charm cross sections measurements were combined: H1 and ZEUS and used together with HERA I inclusive data in FFN scheme QCD fit for extracting running charm mass.

Running of $m_c(\mu_r)$ observed.
ZEUS prepared beauty structure functions measurements combination:

Extracted beauty mass:

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

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.
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 $\alpha_s$:

Jet data highly increase sensitivity to $\alpha_s$.
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 $m_c(\mu_r)$ 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 $\alpha_s$. 