PDFs and hard QCD at HERA

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V. Chekelian, PDFs and hard QCD at HERA

electrons & positrons of $E_e = 27.5$ GeV collided with protons of $E_p = 920, 820, 575$ and 460 GeV. Two multi-purpose collider experiments H1 & ZEUS collected in total 1 fb$^{-1}$.

- Combination of all inclusive NC&CC data from H1&ZEUS at HERA
  - $F_2, xF_3 \gamma Z, (F_2 \gamma Z, F_L, \sigma_{CC}^{\text{tot}}, ...)$
  - HERAPDF 2.0 PDF set and its variants
  - charm production and combination of $D^*$
  - jet production and $\alpha_s$; multi-jets at low $Q^2$
  - prompt photon & jet production in DIS
NC and CC inclusive data sets at HERA

41 NC and CC data sets from H1 and ZEUS corresponding to 1 fb⁻¹
0.045 ≤ Q² ≤ 50000 GeV², 6 × 10⁻⁷ ≤ x ≤ 0.65

21 data sets from HERA I
NC & CC at E_p = 920 and 820 GeV
and 20 data sets from HERA II (2003-2007)
12 NC & CC sets at E_p = 920 GeV
4 NC sets at E_p = 575 GeV
4 NC sets at E_p = 460 GeV

These data are collected over 15 years with changing beams and detectors conditions and different focus. It is important to handle them properly, e.g. in view of possible correlations

→ combine them into one coherent data set as it was done for HERA I before (JHEP 1001:109, 2010 and HERAPDF 1.0)
Averaging of all NC and CC data at HERA

2927 cross sections are combined to 1307 points with 169 correlated systematic errors and $\chi^2$/d.o.f. = 1685/1620

H1 and ZEUS

Coherent set of unpolarised $e^\pm p$ NC&CC at four $\sqrt{s} = 318, 300, 251, 225$ GeV:
- www.desy.de/h1zeus/herapdf20/
- precise, complete and easy in use
- with reduced stat. and syst. errors

$\sigma^+_r, NC$

$Q^2/\text{GeV}^2$

$0.045 \leq Q^2 \leq 50000 \text{ GeV}^2$, $6 \times 10^{-7} \leq x_Bj \leq 0.65$
total unc. < 1.5% for $Q^2$ up to 500 GeV$^2$

→ up to 6 measurements are combined into one averaged point
→ correlated shifts are propogated to all points (even measured by single experim.)
Combined NC and CC $e^\pm p$ data

- single differential cross sections are obtained by integration over $x$ of the combined NC and CC $e^\pm p$ data at $\sqrt{s}=318$ GeV and $y<0.9$

- $e^+p$ NC and $e^-p$ NC are the same in the $\gamma$-exchange domain at low $Q^2$ and start to differ at high $Q^2$ due to $\gamma Z$ interference.

- CC is two orders of magnitude smaller than NC at $Q^2=200$ GeV$^2$ and about the same at $Q^2$ around $M_Z^2$, $M_W^2$, demonstrating electroweak unification.

- remaining differences in CC are related to $u$, $d$ content of the proton and to helicity factors.
Proton structure function $F_2$

$$\sigma_{r,NC}^{\pm} = \frac{d^2\sigma_{NC}^{\pm}}{dx dQ^2} \frac{xQ^4}{2\pi\alpha_s^2} \frac{1}{Y_+} = \tilde{F}_2 - \frac{y^2}{Y_+} \tilde{F}_L + \frac{Y_-}{Y_+} x \tilde{F}_3 \quad Y_\pm = 1 \pm (1-y)^2$$

### H1 and ZEUS

- HERA NC $e^p$ 0.4 fb$^{-1}$
- HERA NC $e^p$ 0.5 fb$^{-1}$
- Fixed Target
- HERAPDF2.0 $e^p$ NNLO
- HERAPDF2.0 $e^p$ NNLO

$Q^2 = 12$ GeV$^2$

$Q^2 = 6.5$ GeV$^2$

$Q^2 = 120$ GeV$^2$

$Q^2 = 1200$ GeV$^2$

F$_2$ scaling (independence of $Q^2$) at moderate $x$ and scaling violations at high $x_{Bj}$ and low $x_{Bj}$ due to gluon emission and gluon splitting.
\( e^\pm p \) NC: lepton charge dependence and \( xF_3 \)

\[
x \tilde{F}_3 = \frac{Y_+}{2Y_-} (\sigma_{r,NC}^- - \sigma_{r,NC}^+) \quad \text{charge asymmetry of } e^\pm p \text{ NC cross sections is mostly due to } \gamma Z \text{ interference}
\]

\[
xF_3^{\gamma Z} = -x \tilde{F}_3 \left( Q^2 + M_Z^2 \right) / (a_e k Q^2)
\]

\[
\kappa^{-1} = 4 \frac{M_W^2}{M_Z^2} \left( 1 - \frac{M_W^2}{M_Z^2} \right)
\]

transform the \( xF_3^{\gamma Z}(x,Q^2) \) measurements to \( Q^2 = 1000 \text{ GeV}^2 \) and average them to get \( xF_3^{\gamma Z}(x) \) at \( Q^2 = 1000 \text{ GeV}^2 \)

→ related to valence quark:

\[
F_3^{\gamma Z} \approx (2u_v + d_v) / 3
\]

→ integration over the measured range \( 0.016 < x_{Bj} < 0.725 \) gives

\( 1.165 \pm 0.042 - 0.053 \) for data and

\( 1.314 \pm 0.057(\text{stat}) \pm 0.057(\text{syst}) \) using HERAPDF2.0.
$e^\pm p$ CC probe u/d composition of proton

$$\sigma_{r,\text{CC}}^{\pm} = \frac{2\pi x}{G_F^2} \left[ \frac{M_W^2 + Q^2}{M_W^2} \right]^2 \frac{d^2\sigma_{\text{CC}}^{e^\pm p}}{dx dQ^2}$$

$$\sigma_{r,\text{CC}}^+ \sim (x\bar{u} + x\bar{c}) + (1 - y)^2(xd + xs)$$

$$\sigma_{r,\text{CC}}^- \sim (xu + xc) + (1 - y)^2(x\bar{d} + x\bar{s})$$

$\sigma_{r,\text{CC}}^{e^\pm p}$ is related to $d$-quark ($Q^2$ dependence is due to helicity factor $(1-y)^2$).

$e^-p$ CC is dominated by $u$-quark and depends weakly on $Q^2$ at given $x$.
HERAPDF2.0 QCD Fit

The combined $e^p$ NC/CC HERA data set is the only input

- no nuclear, heavy target or HT corrections; consistency of data, $\Delta \chi^2 = 1$ criterion
- parametrisation of PDFs at starting scale $Q^2_o=1.9$ GeV$^2$ with 14 free parameters

\[
\begin{align*}
  xg(x) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g}, \\
xu_\nu(x) &= A_{u\nu} x^{B_{u\nu}} (1-x)^{C_{u\nu}} (1 + E_{u\nu} x^2), \\
xd_\nu(x) &= A_{d\nu} x^{B_{d\nu}} (1-x)^{C_{d\nu}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x), \\
x\bar{D}(x) &= A_{D} x^{B_{D}} (1-x)^{C_{D}}.
\end{align*}
\]

- QCD evolution of PDFs using DGLAP equations at NLO and NNLO
- Thorne-Roberts general mass variable-flavor-number scheme RTOPT (as used in MMHT)
- default $Q_{\text{min}}^2=3.5$ GeV$^2$, $f_s=0.40$ ($xs = f_s x\bar{D}$ at $Q^2_o$)
- $M_c$ and $M_b$ values are optimized using HERA charm and beauty production data
- $\alpha_s(M^2_Z)=0.118$ is consistent with HERA jet data

→ available at www.desy.de/h1zeus/herapdf20/ and on LHAPDF:

HERAPDF2.0 at NLO and NNLO

also with a scan of $\alpha_s(M^2_Z)$ from 0.110 to 0.130 in steps of 0.001

additional PDF sets:

HERAPDF2.0HiQ2 at NLO and NNLO - $Q_{\text{min}}^2=10$ GeV$^2$
HERAPDF2.0AG at LO, NLO and NNLO - alternative gluon parameterisation (strictly positive)
HERAPDF2.0FF3A and FF3B - fixed flavor number schemes at NLO
Uncertainties of HERAPDF2.0

Three types of PDF uncertainties are considered:

**Experimental uncertainty band**
- Hessian method with $\Delta \chi^2 = 1$
  - verified by MC method - replicas of data

**Model uncertainty band**
- variation of model assumptions

**Parameterisation uncertainty band**
- variation of the starting scale $Q^2_0$ and
  - form of parameterisation (number of free parameters)
  - valid in the $x$-range covered by the QCD fit to HERA data

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**Table**

<table>
<thead>
<tr>
<th>Variation</th>
<th>Standard Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{min}}^2$ [GeV$^2$]</td>
<td>3.5</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>$Q_{\text{min}}^2$ [GeV$^2$] HiQ2</td>
<td>10.0</td>
<td>7.5</td>
<td>12.5</td>
</tr>
<tr>
<td>$M_t$ (NLO) [GeV]</td>
<td>1.47</td>
<td>1.41</td>
<td>1.53</td>
</tr>
<tr>
<td>$M_c$ (NNLO) [GeV]</td>
<td>1.43</td>
<td>1.37</td>
<td>1.49</td>
</tr>
<tr>
<td>$M_b$ [GeV]</td>
<td>4.5</td>
<td>4.25</td>
<td>4.75</td>
</tr>
<tr>
<td>$f_s$</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Comparison with modern PDFs from global fits

vs. PDFs using variable-flavor-number scheme: MMHT2014, CT10, NNPDF3.0

vs. PDFs using fixed-flavor-number scheme: ABM11 FF, NNPDF3.0FF(3N)

→ differences in valence quarks at high x: new HERA data

→ sea and gluon are consistent
**Charm production in DIS**

**Charm mass parameter in HERAPDF2.0**

$M_c$ and $M_b$, charm and bottom mass parameters, are determined in $\chi^2$ scans of the HERA charm and bottom data together with combined inclusive data.

\[
\begin{align*}
\chi^2 &\rightarrow \chi^2_{\text{min}} \\
M_c &\rightarrow (1.47 \pm 0.03) \text{ GeV at NLO (NNLO)}
\end{align*}
\]

\[
\begin{align*}
\text{incl. + charm data} &\rightarrow \text{reduction of the } M_c \text{ and } M_b \text{ uncertainties in HERAPDF fits} \\
M_c &\rightarrow (1.47 \pm 0.03) \text{ GeV at NLO (NNLO)}
\end{align*}
\]

**Combination of all D* at HERA**

in the visible phase space, including latest D* cross section measurements by ZEUS. No need for extrapolation to the full phase space as in the former combination of available charm data obtained using different techniques: D* and D± reconstruction, vertex fitting, leptons in the final state.

\[
\rightarrow \text{single diff.: } P_T, \eta, z, Q^2, y \text{ and double diff. } Q^2-y
\]

NLO QCD customised:

\[
\begin{align*}
\pm m_c &\rightarrow 1.4 \text{ GeV}
\end{align*}
\]

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Combined H1 & ZEUS visible D* cross sections

single differential: \(d\sigma(D^\ast)/dP_T\), \(d\sigma/d\eta\), \(d\sigma/dz\), \(d\sigma/dQ^2\), \(d\sigma/dy\)

double differential: \(d^2\sigma/dQ^2 dy\)
Jet production and the strong coupling constant

HERAPDF2.0Jets NLO

include also HERA combined charm and selected jet production data:

$\alpha_s$ from a simultaneous fit with PDFs:

$\alpha_s(M_{Z}^2) = 0.1183 \pm 0.0009^{\text{exp}} \pm 0.0005^{\text{model}} \pm 0.0012^{\text{hadronisation}} +^{37}_{-30}^{\text{scale}}$

PDFs and the error bands are very close to HERAPDF2.0 obtained using inclusive data and $M_c$ and $M_b$ already optimized using charm and bottom HERA data and $\alpha_s=0.118$, consistent with the HERA multi-jet data. (slight increase of err. band is due to hadronisation).
Multijet cross sections in DIS compared to NNLO

New predictions
- NNLO \(\otimes\) hadr. corr.
- aNNLO \(\otimes\) hadr. corr.

Inclusive jet, dijet and trijet cross sections, absolute and normalised to NC (with partial cancellation of systematics) are measured in \(Q^2\) and \(P_T^{\text{jet}}\) bins 5.5 < \(Q^2\) < 80 \(\text{GeV}^2\) and 4.5 < \(P_T^{\text{jet}}\) < 50 \(\text{GeV}\)

For the first time normalised jet cross sections are compared to predictions at NNLO:
- full NNLO
- approximate NNLO

\(\rightarrow\) estimated experimental precision of \(a_s(M_Z)\) in fit to the H1 normalised jet cross sections at low and high \(Q^2\) is 0.4%
Prompt photon accompanied by jets in ep DIS

- Fine segmentation of BCAL in Z direction

**QQ - photons**

\[ \pi^0 \rightarrow \gamma\gamma \]
\[ \eta \rightarrow \gamma\gamma \]

**LL - photons**

\[ \gamma^* \]
\[ \gamma \]
\[ q \]
\[ q' \]

\( \gamma \) is emitted from quark as part of hard process

\( \gamma \) is radiated from incoming or outgoing lepton

\( \gamma \) is theoretically well determined
Prompt photon cross section is measured as function of

\[ x_\gamma (x_p) \] - fractions of incoming photon (proton) energy taken by \( \gamma + \text{jet} \) (parton)

\[ \Delta \phi_{e,\gamma}, \Delta \eta_{e,\gamma} \] - between \( \gamma \) and scattered electron

\[ \Delta \phi, \Delta \eta \] - between \( \gamma \) and jet

LL (Djangoh) + QQ (Pythya) scaled by 1.6

Comparison with BLZ model

Conclusions

H1 and ZEUS continue to deliver the HERA legacy results:

H1 and ZEUS completed the inclusive DIS program at HERA by combining all inclusive unpolarised measurements into one coherent data set of NC & CC $e^+p$ & $e^-p$ at $\sqrt{s} = 318, 300, 251$ and $225$ GeV.

The combined inclusive HERA data on NC and CC are used as a sole input to the QCD analysis resulting in the set of parton distribution functions HERAPDF2.0 (together with its variants).

All H1 and ZEUS D* production cross section measurements in DIS are combined in the visible phase space in $P_T$, $\eta$, $z$, $Q^2$ and $y$.

Inclusive jets, dijets, trijets cross sections (absolute and normalised to NC) are measured by H1 at low $Q^2$ and compared to predictions at NLO and NNLO → precise experimental input to $\alpha_s$ determinations

Prompt photons accompanied by jets are measured in DIS by ZEUS
Dijets and Trijets in DIS compared to NLO, NNLO

Normalised dijets

Normalised trijets

New predictions

H1 HERA-II (prel.)

Systematic uncertainty

NLO ⊗ hadr. corr.

H1prelim-16-061, H1prelim-16-062