PDFs from the LHeC

Voica Radescu

(DESY)

Outline
• Current Status on PDFs
• LHC contribution to PDFS
• Impact of the LHeC
Current Status on PDFs

- All available current PDF sets rely mostly on data from HERA (ep collider)

<table>
<thead>
<tr>
<th></th>
<th>MSTW08</th>
<th>CTEQ6.6/CT10</th>
<th>NNPDF2.1/2.3</th>
<th>HERAPDF1.0/1.5</th>
<th>ABKM09/ABM11</th>
<th>GJR08/JR09</th>
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<tr>
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<td>LO, NLO, NNLO</td>
<td>LO, NLO, NNLO</td>
<td>LO, NLO, NNLO</td>
<td>NLO, NNLO</td>
<td>NLO, NNLO</td>
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<td>✔ (old/new)</td>
<td>✔ (new)</td>
<td>✔ (new/newest)</td>
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<td>some</td>
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<td>SACOT GMVFN</td>
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<td>0.118(f)</td>
<td>0.119</td>
<td>0.1176(f)</td>
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<td>0.1176(f)</td>
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<td>0.1124</td>
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The analyses differ in many areas:
- different treatment of heavy quarks
- inclusion of various data sets and account for possible tensions
- different alphas assumption
Current Status on PDFs

- All available current PDF sets rely mostly on data from HERA

| PDF order  | MSTW08    | CTEQ6.6/G 
|------------|-----------|----------
| HERA DIS   | ✓ (old)   | ✓ (old/new)  
| Fixed target DIS | ✓ | ✓  
| Fixed target DY | ✓ | ✓  
| Tevatron W, Z | ✓ | ✓  
| Tevatron jets | ✓ | ✓  
| LHC | - | -  
| HF Scheme | RTGMVF | SACOT GMVFN  
| Alphas (NLO) | 0.120 | 0.118(f)  
| Alphas (NNLO) | 0.1171 | 0.118(f)  

The analyses differ in many areas:

- different treatment of heavy quarks
- inclusion of various data sets and account for possible tensions
- different alphas assumption

The graph shows NNLO gg→H at the LHC ($\sqrt{s} = 7$ TeV) for $M_H = 120$ GeV.
Although at $x \approx 0.02$ there is precise data from HERA, PDFs are one of main TH uncertainties in Higgs production.
Measurements at LHC to constrain PDFs

- **PDFs are essential for precision physics at the LHC:**
  - PDFs one of main theory uncertainties in Higgs production
  - PDF uncertainties affect substantially theory predictions for BSM high mass production

- **Given the crucial role of the gluon for LHC physics, complementary LHC observables directly sensitive the gluon would be beneficial**

- **LHC data is introducing completely new observables to be used for PDF constraints:**
  - **2010-2011 data:**
    - Inclusive jets and dijets, central and forward: high-x quarks and gluons
    - Inclusive W and Z production and asymmetries: quark flavor separation, strangeness
    - Off peak Drell-Yan production at low and high mass: quarks at low and high-x medium-x gluons
    - Isolated photons:
    - W production with charm quarks: direct handle on strangeness (to come)
    - W,Z production with jets: medium and small-x gluon
    - Single top production: gluon and bottom PDFs
    - ttbar production: help to discriminate between different PDF sets - medium x
      - Also a direct handle on the strong coupling
    - Top quark differential distributions: high-x gluon
    - Z+b production sensitive to b-quark

**More stringent constraints are expected with the full 8 TeV and later 13TeV data**
Measurements at LHC to constrain PDFs

- PDFs are essential for precision physics at the LHC:
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  - PDF uncertainties affect substantially theory predictions
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- LHC data is introducing completely new observables to be used for PDF constraints:
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    - W, Z production with jets:
      - medium and small-$x$ gluon
    - Single top production:
      - gluon and box PDFs
    - $X\bar{X}$ production: help to discriminate between different PDF sets
    - Also a direct handle on the strong coupling
  - Top quark differential distributions
  - Z+$b$ production
  - More stringent constraints are expected with the full 8 TeV and later 13 TeV data

ATLAS Preliminary

ATLAS-CONF-2012-159

ATLAS-CONF-2012-128

Voica Radescu

PDF4LHC – April 2013
Current high-x searches are dominated by PDF uncertainties (20%) [ATLAS-CONF-2012-129]

- Dominated by uubar, dbar at high x

→ this uncertainty with LHeC can be reduced
The LHeC program

http://cern.ch/lhec

Present LHeC Study group and CDR authors

About 200 Experimentalists and Theorists from 76 Institutes

Supported by
CERN, ECFA, NuPECC
LHeC ep kinematics

- DIS is best tool to probe structure of the proton:
  - Processes:
    - NC: $e p \rightarrow e' X$
    - CC: $e p \rightarrow \nu_e X$

- Kinematic variables:
  - $Q^2 = -q^2 = -(k - k')^2$ Virtuality of the exchanged boson
  - $x = \frac{Q^2}{2p \cdot q}$ Bjorken scaling parameter
  - $y = \frac{p \cdot q}{p \cdot k}$ Inelasticity parameter
  - $s = (k + p)^2 = \frac{Q^2}{xy}$ Invariant c.o.m.

- Double Differential cross sections:
  $$\sigma_r(x, Q^2) = \frac{d^2\sigma(e^+p)}{dx dQ^2} = \frac{Q^2 x}{2\pi\alpha^2 Y_+} F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) + \frac{Y_+}{X} x F_3(x, Q^2)$$

- Processes:
  - $F_2$ dominates
  - $xF_3$ sensitive to all quarks
  - $xF_L$ sensitive to valence quarks
  - also we have $F2yZ$, sCC+, sCC-
Simulated LHeC Data

Studied scenarios (described in CDR)

**Scenario B:** (Lumi $e^+/p = 50$ fb$^{-1}$) $E_p=7$ TeV, $E_e=50$ GeV, Pol=$\pm0.4$
- Kinematic region: $2 < Q^2 < 500\ 000$ GeV$^2$ and $0.000002 < x < 0.8$

**Scenario H:** (Lumi $e^p = 1$ fb$^{-1}$) $E_p=1$ TeV, $E_e=50$ GeV, Pol=0
- Kinematic region: $2 < Q^2 < 100\ 000$ GeV$^2$ and $0.000002 < x < 0.8$

**Typical uncertainties:**

Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – based on typical best values achieved by H1

- Statistical: it ranges from 0.1\% (low $Q^2$) to ~10\% for $x=0.7$ in CC
- Uncorrelated systematic: 0.7 \%
- Correlated systematic: typically 1-3\% (for CC high $x$ up to 9\%)

<table>
<thead>
<tr>
<th>source of uncertainty</th>
<th>error on the source or cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>scattered electron energy scale $\Delta E'_e/E'_e$</td>
<td>0.1 %</td>
</tr>
<tr>
<td>scattered electron polar angle</td>
<td>0.1 mrad</td>
</tr>
<tr>
<td>hadronic energy scale $\Delta E_h/E_h$</td>
<td>0.5 %</td>
</tr>
<tr>
<td>calorimeter noise (only $y &lt; 0.01$)</td>
<td>1-3 %</td>
</tr>
<tr>
<td>radiative corrections</td>
<td>0.5 %</td>
</tr>
<tr>
<td>photoproduction background (only $y &gt; 0.5$)</td>
<td>1 %</td>
</tr>
<tr>
<td>global efficiency error</td>
<td>0.7 %</td>
</tr>
</tbody>
</table>
Settings for the PDF determination

Data:

- **LHeC simulated data:**
  - NC $e^+p$, NC, $e^-p$, CC $e^+p$, CC $e^-p$ positive and negative polarisations $P=\pm0.4$
  - Published HERA I (NC, CC $e^-p$ data, $P=0$)
    - Kinematics of HERA data: $0.65>x>10^{-4}$, $30\,000>Q^2>3.5\,\text{GeV}^2$

- Fixed target data from BCDMS,
- ATLAS $W$ asymmetry (with adjusted improved uncertainties stat, unc 0.5 and total 1)
  - New ATLAS $W, Z$ 2010 data (with adjusted lumi uncertainty from 3.4 to 1.4)
- $Q^2_{\text{min}}=3.5\,\text{GeV}^2$ (and $W^2>15\,\text{GeV}^2$ for BCDMS data)
- Only experimental Uncertainties

Initial Theory settings:

- Same settings as for HERAPDF1.0 has been used [JHEP 1001:109, 2010]:
  - NLO DGLAP [QCDNUM package], RT scheme
- Fitted PDFs:
  - $u,v,u_\text{bar}=u_\text{bar}+c_\text{bar}$, $D_\text{bar}=d_\text{bar}+s_\text{bar}$
  - $\text{Sea}=U_\text{bar}+D_\text{bar}$
  - $s_\text{bar}=s_\text{f}D_\text{bar}=d_\text{bar}fs/(1-fs)$ with $fs=0.31$ at starting scale
  - Impose the fermion and momentum sum rules
  - One $B$ parameter for sea and one for valence

\[
xg(x) = A_g x^{B_g} (1-x)^{C_g} (1+D_g x),
xu_\nu(x) = A_{u_\nu} x^{B_{u_\nu}} (1-x)^{C_{u_\nu}} (1+E_{u_\nu} x^2),
xd_\nu(x) = A_{d_\nu} x^{B_{d_\nu}} (1-x)^{C_{d_\nu}},
x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}},
x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.\]

=> LHAPDF grid
Valence distribution

Now...

- Current knowledge is limited at high $x$:
  - Lumi barrier
  - Challenging systematic
  - Nuclear effects
  - Effects of higher twists

- LHeC could improve the knowledge of the valence at high $x$ to a precision of:
  - 2% ($u_{val}$) $x=0.8$
  - 4% ($d_{val}$) $x=0.8$

Important for $d/u$ limit clarification
Gluon PDF at low x

- HERA sensitivity stops at $5 \times 10^{-4}$

$\Rightarrow$ The uncertainties are driven by the parametrisation

- LHeC sensitivity extends to $x = 10^{-6}$
  - LHeC sensitivity to gluon can be improved by the $F_L$ data as well (not included in this study):
    $\Rightarrow$ Allows to study BFKL vs DGLAP

$\Rightarrow$ This is where HERA sensitivity stops
Gluon PDF at high x

Currently, high x gluon is quite uncertain due to limited statistics and reduced sensitivity:

• the gluon effects at high x are in the DGLAP formalism from sea

(valence and gluon are evolved independently)

LHeC can reduce this significantly and it is important to disentangle sea from valence at high x to get precise gluon at high x:

• Measurements such CC+, CC-, F2, F2yZ, xF3 help to provide this decoupling
LHeC and the HL-LHC (SUSY searches)

- gg luminosity is a measure of the gluino pair production – one of the interesting SUSY channels with high masses accessible in the HL-LHC phase.

With high energy and luminosity, the LHC search range will be extended to high masses, up to 5 TeV in pair production.
- At correspondingly high $x (>0.5)$ the PDFs are unknown to a considerable extent

The HL-LHC (search) programme requires a much more precise understanding of QCD, which the LHeC provides (strong coupling, gluon, valence, factorisation, saturation, diffraction..).
Higgs at the LHeC

- The preferred channel for low mass Higgs is in the b\bar{b} decay (BR 60%), but at LHC the Hb\bar{b} couplings are challenging

- At the LHeC the Higgs boson is cleanly produced via ZZ or WW fusion and it is complementary to the dominant gg fusion at pp

14 TeV gg → H total cross section at the LHC calculated for a variety of PDFs at 68% CL

- precision from LHeC can add a very significant constraint on the mass of the Higgs

Figure 5.25: Feynman diagrams for CC (left) and NC (right) Higgs production in leading order QCD at the LHeC. Diagrams produced using MadGraph.
Releasing standard assumptions
Unconstrained setting at low x

- Usual assumptions for light quark decomposition at low x may not necessarily hold.
- Relaxing the assumption at low x that \( u = d \), we observe that uncertainties escalate:

- One can see that for HERA data, if we relax the low x constraint on \( u \) and \( d \), the errors are increased tremendously!
- However, when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing with diffraction [see tomorrow LHeC talks]
Impact on d/u ratios

- Constrained decomposition:

- Unconstrained sea decomposition:
Releasing further PDF constraints

- Releasing further the assumptions:

\[
\begin{align*}
  xg(x) &= A_g x^{B_g} (1 - x)^{C_g} (1 + D_g x), \\
  xu_u(x) &= A_{u_u} x^{B_{u_u}} (1 - x)^{C_{u_u}} (1 + E_{u_u} x^2), \\
  xd_d(x) &= A_{d_d} x^{B_{d_d}} (1 - x)^{C_{d_d}}, \\
  x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}}, \\
  x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}. 
\end{align*}
\]

- Removing the correlation that $\bar{u} = \bar{d}$ at low $x$
- Free parameters for the strange quark are introduced

- This study was driven by the recent ATLAS results on strange determination, hence we have repeated the impact of LHeC study under the new conditions.
Releasing assumptions

Inclusive LHeC data leads to very precise determination of all PDFs even after removing large bulk of assumptions:

LHeC ep data constrain better U than D distributions, however deuteron data would symmetrise our understanding.

Determination of the strange can complement the strange determination from the charm data.
Alphas from DIS
Strong coupling from DIS processes still seem to prefer smaller values

- Results from HERA show that even with precise HERA data one has to rely on jet measurements in order to constrain gluon PDFs

The determination of the strong coupling at the LHeC could solve this ambiguity.

(current knowledge is of order 1%, described in CDR, here and in S.~Bethke et al. [arXiv:1110.0016 [hep-ph]])
Expected precision on alphas(Mz) from DIS

- A dedicated study to determine the accuracy of alphas from the LHeC was performed using for the central values the SM prediction smeared within its uncertainties assuming Gauss distribution and taking into account correlations (accuracy reflects the total experimental uncertainty).

<table>
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<th>case</th>
<th>cut [Q^2 in GeV^2]</th>
<th>relative precision in %</th>
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<tr>
<td>HERA only (14p)</td>
<td>Q^2 &gt; 3.5</td>
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<tr>
<td>HERA+jets (14p)</td>
<td>Q^2 &gt; 3.5</td>
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<tr>
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<td>LHeC only (10p)</td>
<td>Q^2 &gt; 3.5</td>
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<tr>
<td>LHeC only (14p)</td>
<td>Q^2 &gt; 20.0</td>
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</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>Q^2 &gt; 3.5</td>
<td>0.11</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>Q^2 &gt; 7.0</td>
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</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>Q^2 &gt; 10.0</td>
<td>0.26</td>
</tr>
</tbody>
</table>

LHeC promises per mille accuracy on alphas!

- Previously (HERA, fixed target) limited by uncertainty of low x, which LHeC can cure;
- full exploitation of this requires pQCD at NNNLO;
- LHeC can provide a new level of predicting grand unification.
Summary

- LHC can provide information on PDF decomposition and additional constraints on anti-quark density.
  - Measurements at high pT, high invariant masses, sensitive to new physics effects, have significant PDF uncertainties.

- LHeC is a challenging but realistic project and can provide:
  - precision measurements of quark distributions
    - resolving the light quark contents at low and high x
  - precision measurement of $x_g$, crucial for:
    - non-linear evolution at low x, searches at high x
  - an order of magnitude improved measurement of $\alpha_s$

⇒ LHeC represents a natural extension to LHC
  - see next talk for continuation (heavy quarks) → Ringaile’s talk
  - and tomorrow’s talks for the machine and related physics (Higgs, BSM, low x and eA)
- **Gluon**

![Gluon Distribution](image1)

**Figure 4.17:** Ratios to MSTW08 of gluon distribution and uncertainty bands, at $Q^2 = 1.9 \text{ GeV}^2$, for most of the available recent PDF determinations. Left: logarithmic $x$, right: linear $x$.

- **Strange**

![Strange Distribution](image2)

**Figure 4.12:** Sum of the strange and anti-strange quark distribution as embedded in the NLO QCD fit sets as noted in the legend. Left: $s + \bar{s}$ versus Bjorken $x$ at $Q^2 = 1.9 \text{ GeV}^2$; right: ratio of $s + \bar{s}$ of various PDF determinations to MSTW08. In the HERAPDF1.0 analysis (green) the strange quark distribution is assumed to be a fixed fraction of the down quark distribution which is conventionally assumed to have the same low $x$ behaviour as the up quark distribution, which results in a small uncertainty of $s + \bar{s}$. 
Gluon-Gluon Luminosity

- Parton parton luminosity functions provide an easy way to assess the uncertainty on cross sections due to uncertainties in the pdfs.

\[
\frac{\partial L_{ab}}{\partial \tau} = \int_{\tau}^{1} \frac{dx}{x} f_a(x, Q^2) f_b(\tau/x, Q^2)
\]

- gg luminosity is a measure of the gluino pair production – one of the interesting SUSY channels with high masses accessible in the HL-LHC phase.
ATLAS recent result on strange:

FIG. 2. Predictions for the ratio \( r_s = 0.5(s + \bar{s})/d \), at \( Q^2 = 1.9 \text{ GeV}^2 \), \( x = 0.023 \). Points: global fit results using the PDF uncertainties as quoted; bands: this analysis; inner band, experimental uncertainty; outer band, total uncertainty.

The result on \( r_s \), Eq. 2, evolves to

\[
 r_s = 1.00 \pm 0.07_{\text{exp}} \pm 0.03_{\text{mod}}^{+0.04}_{-0.06} \text{par} \pm 0.02 \alpha_S \pm 0.03_{\text{th}} \quad (3) 
\]
### LHeC studies scenarios

<table>
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<tr>
<th>Set</th>
<th>$E_e$/GeV</th>
<th>$E_N$/TeV</th>
<th>N</th>
<th>$L^+$/$fb^{-1}$</th>
<th>$L^-$/$fb^{-1}$</th>
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<td>1</td>
<td>7</td>
<td>-</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.2: Conditions for simulated NC and CC data sets for studies on the LHeC physics. Here, A defines a low electron beam energy option which is of interest to reach lowest $Q^2$ because $Q^2_{\text{min}}$ decreases $\propto E_e^{-2}$; B is the standard set, with a total luminosity split between different polarisation and charge states. C is a lower luminosity version which was considered in case there was a need for a dedicated low/large angle acceptance configuration, which according to more recent findings could be avoided since the luminosity in the restricted acceptance configuration is estimated, from the $\beta$ functions obtained in the optics design, to be half of the luminosity in the full acceptance configuration; D is an intermediate energy linac-ring version, while E is the highest energy version considered, with the luminosities as given. It is likely that the assumptions for D and E on the positron luminosity are a bit optimistic. However, even with twenty times lower positron than electron luminosity one would have 0.5 fb$^{-1}$, i.e. the total HERA luminosity equivalent available in option D for example. F is the deuteron and G the lead option; finally H was simulated for a low proton beam energy configuration as is of interest to maximise the acceptance at large $x$.  

Voica Radescu

EIC workshop 2013, Chile
ATLAS Recent Results

- $s/d$
Impact of LHeC on PDFs: zoom on low $x$

* Experimental uncertainties are shown at the starting scale $Q^2=1.9 \text{ GeV}^2$
Impact of LHeC on PDFs: zoom on high x

* Experimental uncertainties are shown at the starting scale $Q^2=1.9$ GeV$^2$