Precision PDFs at Future Colliders

Claire Gwenlan, Oxford
on behalf of the LHeC and FCC-eh WGs
outline

• **pdfs from future ep high energy colliders, LHeC and FCC-eh**
  summary of ongoing studies towards update of LHeC CDR (arXiv:1206.2913);
  FCC-eh pdf studies from FCC CDR, volume 1 (EPJ C79 (2019), no.6, 474),
  plus some ongoing studies on a lower energy FCC configuration

• **pdfs from the HL-LHC**
  summary of Khalek et al., arXiv:1810.03639;
  contribution to CERN yellow report on Standard Model Physics at the HL-LHC and HE-LHC,
  arXiv:1902.04070
pdfs: the situation today

\[ xg(x,Q), \text{NNLO, } Q^2=100 \text{ GeV}^2, \alpha_s(M_Z)=0.118 \]

Higgs production in gluon fusion

c, b, low mass DY, soft QCD, MC tuning

gluinos, KK gravitons, boosted top quarks, …

current data above \( x = 5 \times 10^{-5} \), and below \( x = 0.6 - 0.7 \)

pdfs poorly known at large and small \( x \)

higher precision needed also for H, W, t

pdf luminosities (LHC@14TeV)

\( \text{qqbar} \)

\( \text{gg} \)

\( \text{W,Z,VH} \)

\( \text{H,t} \)

\( \text{BSM} \)
improving knowledge: LHeC and FCC-eh

energy recovery LINAC
e beam: up to 60 GeV
Lint → 1 ab⁻¹ (1000× HERA ; per 10 yrs)

operating synchronously:

• with HL-LHC (or HE-LHC)
p: 7 (14) TeV, √s ≈ 1.3 (1.8) TeV
• and/or later with an FCC (A)
p: 50 (20) TeV, √s ≈ 3.5 (2.2) TeV

† FCC (A): a lower energy configuration that could operate earlier in an FCC tunnel, using current magnet technology
kinematic coverage

opportunity for unprecedented increase in DIS kinematic reach; ×1000 increase in lumi.
no higher twist, no nuclear corrections, free of symmetry assumptions, N3LO theory possible, ...
precision pdfs, and exploration of low x regime; plus extensive physics program in its own right

×15/120 extension in $Q^2, 1/x$ reach vs HERA
HL-LHC pdfs

BUT can’t we get precision pdfs from the LHC itself?

HL-LHC projections suggest it can go quite some way!

arXiv:1810.03639

BUT projections are in an ideal world, where many different types of LHC measurements have well understood systematics, correlations, and no data inconsistencies.

single, consistent DIS data set is a tried and tested reliable way to achieve precision.
also, possible issues of timing …
LHeC 1st run, Lint approx. 50 fb⁻¹
total Lint → 1 ab⁻¹

F. Bordry, arXiv: 1810.13022

50 fb⁻¹ could be achieved in 3 years before LS5 and long before the end of HL-LHC running
pdfs from ep colliders

Low Q^2 NC
(\(\gamma\) exchange)

\[ F_2 \sim \sum x (q+q\bar{q}) \]
\[ dF_2/d\ln Q^2 \sim \alpha_s \cdot g \]

Final States:
(Jets, Charm, ...)

\[ \sigma \sim \alpha_s \cdot g \]

High Q^2 NC

\[ \times 15/120 \text{ extension in } Q^2, 1/x \text{ reach vs HERA} \]
LHeC pdf programme

completely resolve all **proton pdfs**, and $\alpha_s$ to permille precision

→ $\bar{u}v, u\bar{v}, d\bar{b}, d\bar{v}, s, c, b, t, xg$ and $\alpha_s$

**NEW LHeC simulations (e: 50 GeV, p: 7TeV)**

<table>
<thead>
<tr>
<th>dataset</th>
<th>e charge</th>
<th>e pol.</th>
<th>lumi (fb-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC/CC</td>
<td>–</td>
<td>−0.8</td>
<td>5,50,1000</td>
</tr>
<tr>
<td>NC/CC</td>
<td>+</td>
<td>0</td>
<td>1,10</td>
</tr>
<tr>
<td>NC/CC</td>
<td>–</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>NC/CC</td>
<td>–</td>
<td>+0.8</td>
<td>10,50</td>
</tr>
</tbody>
</table>

**luminosity**

**positron**

**polarisation**

(important for EW physics)

**simul. assumptions:**

- elec. scale: 0.1%
- hadr. scale: 0.5%
- radcor: 0.3%
- yp at high y: 1%
- uncorrelated extra eff.: 0.5%
- CC syst: 1.5%
- luminosity: 0.5%

**NB, I will frequently refer to the following:**

- LHeC 1st Run ($e^-, 50$ fb-1, $P=-0.8$)
- LHeC full inclusive ($e^-, 1000$ fb-1, $P=-0.8$) + ($e^-, 50$ fb-1, $P=+0.8$) + ($e^+, 10$ fb-1)

**QCD analysis a la HERAPDF**, BUT no constraint that $d\bar{b}=\bar{u}v$ at small $x$;

$4+1 xuv, xdv, xUbar, xDbar$ and $xg$
gluon at large $x$

**gluon at large $x$**

is small and currently very poorly known;

**crucial for new physics searches**

**LHeC** sensitivity at large $x$ comes as part of overall package

- high luminosity ($\times 50$–$1000$ HERA);
- fully constrained quark pdfs; small $x$;
- momentum sum rule

gluon and sea intimately related

**LHeC** can disentangle sea from

valence quarks at large $x$, with precision measurements of $CC$ and $NC$ $F_2^{\gamma Z}$, $xF_3^{\gamma Z}$
impact of luminosity on LHeC pdfs

**small and medium x** quickly constrained (5 fb-1 ≡ ×5 HERA ≡ 1st year LHeC)

**large x** (≡ large Q2), gain from increased Lint
impact of positrons on LHeC pdfs

CC: e+ sensitive to d; NC: e± asymmetry gives $xF_3^{yz}$, sensitive to valence
collider configurations

FCC-eh (A): new preliminary simulation with 2 ab⁻¹ polarised e⁻ (NB, NO e⁺ yet; impact especially in dv)
FCC-eh: CDR, volume 1, EPJ C79 (2019), no.6, 474
empowering LHC searches

external, reliable pdfs needed for range extension and interpretation

gluons
SUSY (RPC, RPV), LQs, ...

quarks
exotic and extra boson searches at high mass

arXiv:1211.5102
gluon at small $x$

no current data much below $x=5 \times 10^{-5}$

**LHeC** provides single, precise and unambiguous dataset down to $x=10^{-6}$

**FCC-eh** probes to even smaller $x=10^{-7}$

explore low $x$ QCD:
DGLAP vs BFKL; non-linear evolution; gluon saturation; implications for ultra high energy neutrino cross sections
effect of small $x$ resummation

- recent evidence for onset of BFKL dynamics in HERA inclusive data
  arXiv:1710.05935; confirmed in xFitter study, arXiv:1802.00064
- impact for LHC and most certainly at ultra low $x$ values probed at FCC
gluon at small x

F2 and FL predictions for simulated kinematics of LHeC and FCC-eh

ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play

see also M. Klein, arXiv:1802.04317
c, b quarks

LHeC: enormously extended range and much improved precision c.f. HERA

- $\delta M_c = 50$ (HERA) to 3 MeV: impacts on $\alpha_s$, regulates ratio of charm to light, crucial for precision $t, H$
- $\delta M_b$ to 10 MeV; MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$
strange

strange pdf poorly known; suppressed cf. other light quarks? strange valence?

**LHeC**: direct sensitivity to strange via $W+s \rightarrow c$

$(x,Q^2)$ mapping of (anti) strange for first time

**also top PDF**

top quark becomes light at large $Q^2$: new field of research opens for top PDFs!


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strange

**LHeC**: direct sensitivity to strange via $W+s \rightarrow c$

$(x,Q^2)$ mapping of (anti) strange for first time

**also top PDF**

top quark becomes light at large $Q^2$: new field of research opens for top PDFs!

impact of HQ data on LHeC pdfs

more flexible parameterisation (5+1): \(x_{uv}, x_{dv}, \bar{x}_U, x_d, x_s\) and \(x_g\)
summary of pdfs from ep

PDF4LHC15

LHeC 1\textsuperscript{st} Run
50 fb-1 e–, P=−0.8

\( \sqrt{s} = 14 \text{ TeV} \)

gg luminosity

\( \sqrt{s} = 14 \text{ TeV} \)

qq luminosity
HL-LHC pdfs

study pdf constraints expected from LHC measurements by end of HL-LHC phase

ATLAS+CMS $3 \text{ ab}^{-1}$
LHCb $0.3 \text{ ab}^{-1}$


concentrate on datasets sensitive to mid-to-high-$x$; and not already systematics dominated

$$\text{sys}(14 \text{ TeV}) \sim f_{\text{corr}} \times f_{\text{red}} \times \text{sys}(8/13 \text{ TeV})$$

Hessian profiling of PDF4LHC15

with tolerance $T=3$

- systematic uncertainties taken from existing data;
- treated as uncorrelated, with factor $f_{\text{corr}}=0.5$, chosen to approximately reproduce effect of syst. correlations in existing measurements;
- variable factor $f_{\text{red}}$ to estimate improvement to systs.
HL-LHC pdfs

PDFs at the HL-LHC (Q = 10 GeV)

- PDF4LHC15
- + HL-LHC (scen A)
- + HL-LHC (scen C)

**gluon**

**down**

**ubar**

**strange**

\[
\begin{align*}
\text{scenario A:} & \quad \text{conservative} \\
\text{scenario C:} & \quad \text{optimistic}
\end{align*}
\]

\[
f_{red} = \begin{cases} 
1/0.5 \ (8/13) \text{TeV} \\
0.4/0.2 \ (8/13) \text{TeV}
\end{cases}
\]

(together with intermediate scenario B, all are available in lhapdf format)
parton luminosities

arXiv:1810.03639
impact on LHC phenomenology

summary

precision determination of quark and gluon structure of proton and $\alpha_s$
of fundamental importance for future hadron collider physics programme (Higgs, BSM, …)

NEW ep pdf studies presented (work in progress)
all critical pdf information can be obtained early with LHeC
(~50 fb-1 $\equiv$×50 HERA), in parallel with HL-LHC operation
major new summary paper later this year;

HL-LHC pdf studies indicate significant constraints;
complementarity between HL-LHC and LHeC (see also arXiv:1906.10127)

caveats: ignored issues relating to correlation models; incompatible data sets; …
not all possible data sets included in either study (EG. LHeC jet data, for further constraints on gluon
at large $x$; HL-LHC data probing lower $x$; …)

electron-proton colliders essential for full exploitation of hadron machines
external precision pdf input; complete q,g unfolding, high luminosity $x \rightarrow 1, s, c, b, (t)$;
N3LO; small $x$; strong coupling to permille precision; …
extras
**ep colliders**

**HERA**: world’s first and still only ep collider ($\sqrt{s} \approx 300$ GeV)

**LHeC**: future ep (eA) collider, proposed to run concurrently with HL/HE-LHC; CDR arXiv:1206.2913 (complementary to LHC; extra discovery channels; Higgs; precision pdfs and $\alpha_s$)

**FCC-eh**: further future ep (eA) collider, integrated with FCC; CDR, volume 1, *EPJ C79 (2019)*, no.6, 474 (further kinematic extension wrt LHeC)
strong coupling, $\alpha_s$

$\alpha_s$ is least known coupling constant

PDG2018:  
$\alpha_s = 0.1174 \pm 0.0016$  
(w/o lattice QCD, 1.5% uncertainty)

precise $\alpha_s$ needed:  
to constrain GUT scenarios; for cross section predictions, including Higgs; …

LHeC: permille precision possible in combined QCD fit for pdfs+$\alpha_s$

arXiv:1206.2913, 1211.5102, new studies underway
strong coupling $\alpha_s$

<table>
<thead>
<tr>
<th>case</th>
<th>cut $[Q^2$ in GeV$^2$]</th>
<th>relative precision in $%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA only (14p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>1.94</td>
</tr>
<tr>
<td>HERA+jets (14p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.82</td>
</tr>
<tr>
<td>LHeC only (14p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.15</td>
</tr>
<tr>
<td>LHeC only (10p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.17</td>
</tr>
<tr>
<td>LHeC only (14p)</td>
<td>$Q^2 &gt; 20$</td>
<td>0.25</td>
</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>
<td>0.20</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>$Q^2 &gt; 10.$</td>
<td>0.26</td>
</tr>
</tbody>
</table>

**LHeC**: NC+CC inclusive; total exp. uncertainties; independent of BCDMS
<table>
<thead>
<tr>
<th>Method</th>
<th>Current $\delta a(m_Z^2)/\alpha(m_Z^2)$ uncertainty (theory &amp; experiment state-of-the-art)</th>
<th>Future $\delta a(m_Z^2)/\alpha(m_Z^2)$ uncertainty (theory &amp; experiment progress)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lattice</td>
<td>$\approx 1%$ (latt. stats/spacing, $N^3$LO pQCD)</td>
<td>$\approx 0.1%$ ($\sim 10$ yrs)</td>
</tr>
<tr>
<td>$\pi$ decay factor</td>
<td>$1.5%<em>{\text{th}}^{} \oplus 0.05%</em>{\text{exp}}^{} \approx 1.5%$ ($N^3$LO RGOP)</td>
<td>$1%<em>{\text{th}}^{} \oplus 0.05%</em>{\text{exp}}^{} \approx 1%$ (few yrs)</td>
</tr>
<tr>
<td>$\tau$ decays</td>
<td>$1.4%<em>{\text{th}}^{} \oplus 1.4%</em>{\text{exp}}^{} \approx 2%$ ($N^3$LO CIPT vs. FOPT)</td>
<td>$0.7%<em>{\text{th}}^{} \oplus 0.7%</em>{\text{exp}}^{} \approx 1%$ (+B-factories), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>$Q\bar{Q}$ decays</td>
<td>$4%<em>{\text{th}}^{} \oplus 4%</em>{\text{exp}}^{} \approx 6%$ (NLO only, $\tau$ only)</td>
<td>$1.4%<em>{\text{th}}^{} \oplus 1.4%</em>{\text{exp}}^{} \approx 2%$ (few yrs)</td>
</tr>
<tr>
<td>soft FFs</td>
<td>$1.8%<em>{\text{th}}^{} \oplus 0.7%</em>{\text{exp}}^{} \approx 2%$ (NLO* only (+NNLL), npQCD small)</td>
<td>$0.7%<em>{\text{th}}^{} \oplus 0.7%</em>{\text{exp}}^{} \approx 1%$ (~2 yrs), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>hard FFs</td>
<td>$1%<em>{\text{th}}^{} \oplus 5%</em>{\text{exp}}^{} \approx 5%$ (NLO only, LEP data only)</td>
<td>$0.7%<em>{\text{th}}^{} \oplus 2%</em>{\text{exp}}^{} \approx 2%$ (+B-factories), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>global PDF fits</td>
<td>$1.5%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx 1.7%$ (Diff. NNLO PDF fits. DIS+DY data)</td>
<td>$0.7%<em>{\text{th}}^{} \oplus 0.7%</em>{\text{exp}}^{} \approx 1%$ (few yrs), 0.15% (LHeC/FCC-ee)</td>
</tr>
<tr>
<td>jets in $e^+p$, $\gamma-p$</td>
<td>$2%<em>{\text{th}}^{} \oplus 1.5%</em>{\text{exp}}^{} \approx 2.5%$ (NNLO* only)</td>
<td>$1%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx 1.5%$ (few yrs), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>$F_2$ in $\gamma-\gamma$</td>
<td>$3.5%<em>{\text{th}}^{} \oplus 3%</em>{\text{exp}}^{} \approx 4.5%$ (NLO only)</td>
<td>$1%<em>{\text{th}}^{} \oplus 2%</em>{\text{exp}}^{} \approx 2%$ (~2 yrs), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>$e^+e^-$ evt shapes</td>
<td>$(1.5-4)%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx (1.5-4)%$ (NNLO+N$^3$LL, npQCD significant)</td>
<td>$1%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx 1.5%$ (+B-factories), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>jets in $e^+e^-$</td>
<td>$(2-5)%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx (2-5)%$ (NNLO+N+LL, npQCD moderate)</td>
<td>$1%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx 1.5%$ (few yrs), &lt;1% (FCC-ee)</td>
</tr>
<tr>
<td>$W$ decays</td>
<td>$0.7%<em>{\text{th}}^{} \oplus 37%</em>{\text{exp}}^{} \approx 37%$ (N$^3$LO, npQCD small. Low-stats data)</td>
<td>$(0.7-0.1)%<em>{\text{th}}^{} \oplus (10-0.1)%</em>{\text{exp}}^{} \approx (10-0.15)%$ (LHC-FCC-ee)</td>
</tr>
<tr>
<td>$Z$ decays</td>
<td>$0.7%<em>{\text{th}}^{} \oplus 2.4%</em>{\text{exp}}^{} \approx 2.5%$ (N$^3$LO, npQCD small)</td>
<td>$0.1%<em>{\text{th}}^{} \oplus (0.5-0.1)%</em>{\text{exp}}^{} \approx (0.5-0.15)%$ (ILC-FCC-ee)</td>
</tr>
<tr>
<td>jets in $p-p$, $p-\bar{p}$</td>
<td>$3.5%<em>{\text{th}}^{} \oplus (2-3)%</em>{\text{exp}}^{} \approx (4-5)%$ (NLO only. Combined exp. observables)</td>
<td>$1%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx 1.5%$ (Tevatron+LHC, ~2 yrs)</td>
</tr>
<tr>
<td>$t\bar{t}$ in $p-p$, $p-\bar{p}$</td>
<td>$1.5%<em>{\text{th}}^{} \oplus 2%</em>{\text{exp}}^{} \approx 2.5%$ (NNLO+N+LL, CMS only)</td>
<td>$1%<em>{\text{th}}^{} \oplus 1%</em>{\text{exp}}^{} \approx 1.5%$ (Tevatron+LHC, ~2 yrs)</td>
</tr>
</tbody>
</table>

**lattice QCD**

**ep: per mille level**

(LHeC/FCC-ee combined with HERA)

**ee: order per mille**

with an FCC-ee

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arXiv:1512.05194
valence quarks from LHeC

precision determination; free from higher twist corrections and nuclear uncertainties

large $x$ crucial for HL/HE–LHC and FCC searches; also relevant for DY, MW etc.;
resolve long-standing mystery of d/u ratio; …
d/u at large x

No predictive power from current PDFs; conflicting theory pictures; data inconclusive, large nuclear uncerts.

resolve long-standing mystery of d/u ratio at large x
impact of polarisation on LHeC pdfs

(impact of polarisation on pdfs generally small (but pol. important for ew)
(CC: \(\sigma(e\pm)\) scales as \((1\pm P)\); NC: effects subtle; pol. asym. gives access to \(F_2^{\gamma Z}\), new quark combinations)

LHeC studies: fit parameterisation

QCD fit ansatz based on HERAPDF2.0, with following differences
much more relaxed sea ie. no requirement that $u_\bar{u} = d_{\bar{d}}$ at small $x$
no negative gluon term (simply for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

4+1 pdf fit (above) has 14 free parameters
5+1 pdf fit for HQ studies parameterises $d_{\bar{d}}$ and $s_{\bar{s}}$ separately, and has 17 free parameters
## HL-LHC pdfs

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$f_{\text{red}}$ (8 TeV)</th>
<th>$f_{\text{red}}$ (13 TeV)</th>
<th>LHAPDF set</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>0.5</td>
<td>PDF4LHC.nnlo_hllhc_scen1</td>
<td>Conservative</td>
</tr>
<tr>
<td>B</td>
<td>0.7</td>
<td>0.36</td>
<td>PDF4LHC.nnlo_hllhc_scen2</td>
<td>Intermediate</td>
</tr>
<tr>
<td>C</td>
<td>0.4</td>
<td>0.2</td>
<td>PDF4LHC.nnlo_hllhc_scen3</td>
<td>Optimistic</td>
</tr>
</tbody>
</table>

Table 4.1. The three scenarios for the systematic uncertainties of the HL-LHC pseudo-data that we assume in the present study. These scenarios, ranging from conservative to optimistic, differ among them in the reduction factor $f_{\text{red}}$, Eq. (2.2), applied to the systematic errors of the reference 8 TeV or 13 TeV measurements. We also indicate in each case the name of the corresponding LHAPDF grid.
PDF4LHC15 profiled with (previous iteration of) LHeC inclusive+HQ simulated data
Figure 4.3: Same as Fig. 4.1, now comparing the impact of the LHeC pseudo–data with that of the HL–LHC projections and to their combination.

Some clear trends are evident from this comparison, consistent with the results from the individual PDFs shown in Figs. 4.3 and 4.4. We can in particular observe that at low mass the LHeC places the dominant constraint, while at intermediate masses the LHeC and HL–LHC constraints are comparable in size, and at high mass the stronger constraint on the gluon–gluon and quark–gluon luminosities comes from the HL–LHC, with the LHeC dominating for the quark–quark and quark–antiquark luminosities.

As in the case of the PDFs, for the partonic luminosities the combination of the HL–LHC and LHeC constraints leads to a clear reduction in the PDF uncertainties in comparison to the individual cases, by up to an order of magnitude over a wide range of invariant masses, $M_X$, of the produced final state. It is also worth emphasising that the LHeC and HL–LHC will have...
PDF4LHC15 profiled with LHeC inclusive+HQ and HL-LHC simulated data
PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data
PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data
PDF4LHC15 and HERAPDF (total uncerts) profiled with LHeC inclusive+HQ simulated data
impact on LHC phenomenology

arXiv:1810.03639,
and CERN yellow report, arXiv:1902.04070
Kinematical coverage

$(x, M_X)$ plane of a $p_s = 100$ TeV hadron collider (solid blue line), compared with the corresponding coverage of the LHC at $p_s = 14$ TeV (dot-dashed red line). The dotted lines indicate regions of constant rapidity $y$ at the FCC. We also indicate the relevant $M_X$ regions for phenomenologically important processes, from low masses (Drell-Yan, low $p_T$ jets), electroweak scale processes (Higgs, $W$, $Z$, top), and possible new high-mass particles (such as a 2 TeV squark or a 20 TeV $Z'$).

In the low-mass region, for $M_X \leq 10$ GeV, PDFs would be probed down to $x' = 5 \cdot 10^{-5}$ in the central region, $y' = 0$, and down to $x' = 5 \cdot 10^{-7}$ at forward rapidities, $y' = 5$. At even forward rapidities, for example those that can be probed by using dedicated detectors down the beam pipe, PDFs could be probed down to $x' = 10^{-8}$. While these extreme regions of very low $x$ are not relevant for neither electroweak scale physics nor for high-mass New Physics searches, they are crucial for the tuning of soft and semi-hard physics in Monte Carlo event generators and therefore it is important to ensure that the PDFs exhibit a sensible behaviour in this region. Moreover, forward instrumentation would also be.

large $x$ relevant in searches for new, very high mass states

small $x$ becomes relevant even for “common” physics (EG. W, Z, H, t)
impact of LHC on today’s pdfs

NNPDF3.1 NNLO, $Q = 100$ GeV

- Global
- no jets
- no top
- no Z $p_T$
Figure 14: Simulations of $F_L$ measurements with the LHeC (red circles) compared with measurements at H1 (blue squares), see text.

With more Silicon detector planes of higher acceptance and resolution and a hadronic backward calorimeter which was basically absent on H1; iii) the increased electron beam energy implies that high $y$ may be achieved at larger scattered electron energy $E_0$. Both the improved detector and the enlarged $E_\text{e}$ will enable to reach highest $y$ values at much reduced background.

A simulation had been performed for the LHeC CDR [5] which is illustrated in Fig. 14. In order to be conceptually independent of the LHC operation, for the LHeC the electron beam energy is lowered as opposed to HERA. The point-by-point precision is impressively improved, from at best $F_L' = \pm 0.1$ with H1 to typically a $0.02$ total uncertainty for the LHeC. Based on the invaluable experience gained with H1 at HERA and on the design prospects for the LHeC and its ep experiment, one can indeed be optimistic that Guido Altarelli’s wish for a precise determination of $F_L$ will eventually be fulfilled. The simulated data, with their exceptional determinations of $F_2$ and $F_L$, were used in a study, presented in the CDR, to illustrate the unique potential in discriminating theory at small $x$.

References


