PDFs, QCD and small x physics in energy frontier DIS with the LHeC and FCC-eh

Claire Gwenlan, Oxford

for the LHeC and FCC-eh study groups

special thanks to Max Klein, Uta Klein and Gavin Pownall
LHeC and FCC-eh

**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 (further kinematic extension wrt LHeC)

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

* LHeC: $\sqrt{s} = 1.3$ TeV $\times 100$–1000 HERA lumi.
* FCC-eh: $\sqrt{s} = 3.5$ TeV

LHeC (FCC-eh) complementary to, synchronous with, HL-LHC (FCC)
kinematic coverage

**LHeC:**

\[ Q^2 \to 10^6 \text{ GeV}^2, \quad x: 10^{-6} \to 1 \]

**FCC-eh:**

\[ Q^2 \to 10^7 \text{ GeV}^2, \quad x: 10^{-7} \to 1 \]

\((\times 15/120 \text{ extension in } Q^2, 1/x \text{ reach vs HERA})\)

- **outline of this talk:**
  - proton pdfs
  - \(\alpha_s\), electroweak

- very rich physics programme; see also other talks in this workshop:

  LHeC and FCC-eh machine (D Schulte); BSM (D Britzger); eA (Z Zhang); SM and BSM Higgs (C Zhang)

see also very fruitful LHeC and PERLE workshop, LAL-Orsay, 26 – 29 June 2018
proton pdfs today

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

gluinos, KK gravitons, boosted top quarks, …

Higgs production in gluon fusion

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

current data only 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

df luminosities (LHC@14TeV)

qqbar

W, Z, VH

H, t

BSM
**Why better PDFs?**

- **High-mass BSM cross-sections**
- **Dominant THM uncertainty** for $M_W$ measurements at LHC
- **Higgs coupling measurements**

**Gluon-Fusion Higgs production, LHC 13 TeV**

<table>
<thead>
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<tbody>
<tr>
<td>$W \to e\nu$</td>
<td>-29.7</td>
<td>17.5</td>
<td>0.0</td>
<td>4.9</td>
<td>0.9</td>
<td>5.4</td>
<td>0.5</td>
<td>0.0</td>
<td>24.1</td>
<td>30.7</td>
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<tr>
<td>$W \to \mu\nu$</td>
<td>-28.6</td>
<td>16.3</td>
<td>11.7</td>
<td>0.0</td>
<td>1.1</td>
<td>5.0</td>
<td>0.4</td>
<td>0.0</td>
<td>26.0</td>
<td>33.2</td>
</tr>
<tr>
<td>Combined</td>
<td>-29.2</td>
<td>12.8</td>
<td>3.3</td>
<td>4.1</td>
<td>1.0</td>
<td>4.5</td>
<td>0.4</td>
<td>0.0</td>
<td>23.9</td>
<td>28.0</td>
</tr>
</tbody>
</table>

- **PDF w.r.t. CT14nnlo [%]**
- **$\delta$ PDF (%)**

**LHC (14 TeV)**

**ATLAS today**

- **large x quarks matter**
- **large x gluons matter**

**W± production**

- **with higher luminosity and energy machines on horizon, will need transformation in precision**

**Juan Rojo**

POETIC8, Regensburg, 19/03/2018
HL-LHC ‘ultimate’ pdf projections

LHC measurements are providing useful pdf constraints (e.g. see previous talk); should certainly be exploited; and currently we have nothing else …

**is there a NEED for future ep collider for pdfs?**
will we improve the precision of pdfs sufficiently using LHC data?

HL-LHC ultimate pdf projection studies ongoing:

(L Harland-Lang, HL/HE-LHC WS, CERN, June 2018)
LHeC and FCC-eh pdf programme

<table>
<thead>
<tr>
<th>NC/CC</th>
<th>Ee [GeV]</th>
<th>Ep [TeV]</th>
<th>P(e)</th>
<th>charge</th>
<th>lumi. [fb-1]</th>
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</thead>
<tbody>
<tr>
<td>NC CC</td>
<td>60 (60)</td>
<td>7 (50)</td>
<td>-0.8</td>
<td>-1</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>60 (60)</td>
<td>7 (50)</td>
<td>-0.8</td>
<td>-1</td>
<td>1000</td>
</tr>
<tr>
<td>NC CC</td>
<td>60 (60)</td>
<td>7 (50)</td>
<td>+0.8</td>
<td>-1</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>60 (60)</td>
<td>7 (50)</td>
<td>+0.8</td>
<td>-1</td>
<td>300</td>
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<td>0</td>
<td>+1</td>
<td>100</td>
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<td>-1</td>
<td>100</td>
</tr>
</tbody>
</table>

LHeC (FCC-eh) simulated NC and CC inclusive

**+NEW:** additional LHeC simulation with 1/10th integrated luminosity (no low energy data)

**LHeC (FCC-eh) goals:** completely resolve all proton pdfs, and $\alpha_s$ to permille precision $u, v, d, v, s, c, b, t, xg$ and $\alpha_s$

no higher twist, no nuclear corrs., free of sym. assumptions, factorization proven, N3LO (on the way)

NB, fit studies do not yet include simulated s, c, b, t or FL data

QCD analysis: V Radescu, G Pownall

Simulation: M Klein

All work in progress
valence quarks from LHeC

precision determination, free from higher twist corrections and nuclear uncertainties
large x crucial for searches; relevant for DY, Mw; resolve mystery of d/u at large x; …
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 ($\times 100–1000$ HERA);
- Fully constrained quark PDFs; low $x$;
- Momentum sum rule.

Gluon and sea intimately related:
- LHeC can disentangle sea from valence quarks at large $x$, with precision measurements of $CC$ and $NC$ $F_2^{yz}$, $xF_3^{yz}$.
Some further values demonstrate the phase space extensions at LHeCs. The projected LHeC that they cover a large fraction of the specific values for which HERA results are available. The data are shown as a function of representing their total uncertainties. The combined HERA results from Hx and ZEUS are shown as triangles with error bars. For the grey shaded and black points events are only accepted if at least one charm quark is found with polar angles acceptance is assumed to cover the whole polar angle range. For the open points the detector simulation are shown as points with error bars representing the statistical uncertainties. The dashed lines are interpolating curves between the points. For the open points the detector acceptance is assumed to cover the whole polar angle range. For the grey shaded and black points events are only accepted if at least one beauty quark is found with polar angles. Acceptance is assumed to cover the whole polar angle range. For the grey shaded and black points events are only accepted if at least one charm quark is found with polar angles. Acceptance is assumed to cover the whole polar angle range. For the open points the detector acceptance is assumed to cover the whole polar angle range. For the grey shaded and black points events are only accepted if at least one beauty quark is found with polar angles. Acceptance is assumed to cover the whole polar angle range. For the open points the detector acceptance is assumed to cover the whole polar angle range.

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

- $\delta M_c = 60$ (HERA) to 3 MeV: impacts on $\alpha_s$, regulates ratio of charm to light, crucial for precision t, H
- MSSM: Higgs produced dominantly via $bb \rightarrow A$
strange

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

ATLAS\textsuperscript{\dagger} see large strange fraction at mean $x\approx0.01$

\textsuperscript{\dagger}ATLAS arXiv:1203.4051, confirmed with high stats in 1612.03016; and by global fitters EG. NNPDF 1706.00428, MMHT 1708.00047

\begin{tikzpicture}
  \begin{axis}[title={s+\bar{s} distribution at $Q^2 = 1.9$ GeV$^2$}, xlabel={$x(x, Q^2 = 1.9$ GeV$^2$)}, ylabel={$x(s+\bar{s})(x, Q^2 = 1.9$ GeV$^2$)}, legend entries={\textbf{NNLO PDF (68\% C.L.)}, CT14, NNPDF3.0, MMHT14, CT14, ATLAS-epWZ16, \textbf{ATLAS}}, legend style={at={(0.5,0.05)}, anchor=north, columns=3, nodes={scale=0.8, transform shape}}]
    \addplot+[mark size=1.5pt, only marks, color=green] coordinates {\textbf{(0.0023,1.5)} (0.006,1.4) (0.01,1.3) (0.023,1.2)} node[above left] {ATLAS}
    \addplot+[mark size=1.5pt, only marks, color=red] coordinates {\textbf{(0.0018,1.5)} (0.006,1.4) (0.01,1.3) (0.025,1.2)} node[above left] {ATLAS-epWZ16}
    \addplot+[mark size=1.5pt, only marks, color=blue] coordinates {\textbf{(0.0015,1.5)} (0.006,1.4) (0.01,1.3) (0.023,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=black] coordinates {\textbf{(0.0018,1.5)} (0.006,1.4) (0.01,1.3) (0.025,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=yellow] coordinates {\textbf{(0.0015,1.5)} (0.006,1.4) (0.01,1.3) (0.025,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=orange] coordinates {\textbf{(0.0018,1.5)} (0.006,1.4) (0.01,1.3) (0.025,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=gray] coordinates {\textbf{(0.0015,1.5)} (0.006,1.4) (0.01,1.3) (0.025,1.2)}
  \end{axis}
\end{tikzpicture}

\begin{tikzpicture}
  \begin{axis}[title={anti-strange density}, xlabel={$Q^2/\text{GeV}^2$}, ylabel={$x$}, xmode=log, ymode=log, legend entries={\textbf{LHeC}, $e^+p$ 60*7000 GeV$^2$ 10 fb$^{-1}$}, legend style={at={(0.5,0.05)}, anchor=north, columns=4, nodes={scale=0.8, transform shape}}]
    \addplot+[mark size=1.5pt, only marks, color=blue] coordinates {\textbf{(0.0001,1.5)} (0.0025,1.4) (0.005,1.3) (0.01,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=red] coordinates {\textbf{(0.000025,1.5)} (0.000035,1.4) (0.00005,1.3) (0.0001,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=green] coordinates {\textbf{(0.00001,1.5)} (0.000025,1.4) (0.00005,1.3) (0.0001,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=yellow] coordinates {\textbf{(0.0000025,1.5)} (0.0000035,1.4) (0.000005,1.3) (0.00001,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=gray] coordinates {\textbf{(0.00000025,1.5)} (0.00000035,1.4) (0.0000005,1.3) (0.000001,1.2)}
    \addplot+[mark size=1.5pt, only marks, color=black] coordinates {\textbf{(0.000000025,1.5)} (0.000000035,1.4) (0.00000005,1.3) (0.0000001,1.2)}
  \end{axis}
\end{tikzpicture}

\textbf{LHeC}: direct sensitivity to strange via $W+s \rightarrow c$

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

also top pdf via CC DIS becomes possible!
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
• recent evidence for onset of BFKL dynamics in HERA inclusive data
• impact for LHC and most certainly at ultra low x values probed at FCC

(see also xFitter study, arXiv:1802.00064)
gluon at small $x$

Effect of small $x$ resummation on ggH cross section for LHC, HE-LHC, FCC. Impact on other EW observables could be of similar size.

M. Bonvini and S. Marzani, arXiv:1802.07758
Gluon at small $x$ 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
summary of LHeC pdfs

PDF4LHC15

Gluon-Gluon, luminosity

LHeC pdf
(1/10 lumi.)

Quark-Antiquark, luminosity

100 TeV

gg

qqbar

LHeC

Generated with APFEL 2.7.1 Web

Generated with APFEL 2.7.1 Web

Generated with APFEL 2.7.1 Web

Generated with APFEL 2.7.1 Web
example impact for LHC

- LHeC provides 
- Precision Higgs from LHC
- ~3 MeV uncertainty on MW from LHC
- Using PDF set from LHeC gives a ~3 MeV uncertainty on the W mass measurement (no categories used), very interesting input to LHC/HL-LHC m_W measurements.
diffractive pdfs

$Q^2_{\text{min}} \approx 5 \text{ GeV}^2$

**Simulation**: extrapol. from ZEUS-SJ; 5% Gaussian noise (syst.) assumed

Precision increased by about $\times 10$ (20) at LHeC (FCC-eh)

diffractive dijets could provide further gluon info.

top quark PS also accessible

**HERA**: diffractive processes constitute $\approx 10\%$ of visible DIS cross section

see also talk by A. Stasto, LHeC and PERLE workshop, LAL-Orsay, June 2018
electroweak physics, and $\alpha_s$

**Up-type quarks**

Preliminary

![Diagram](image1)

**Simultaneous pdf and EW fits**

Extraordinarily precise determinations of EW params.: NC vector and axial-vector light quark couplings, $M_Z, M_W$ and $\sin^2 \theta_W$

$\alpha_s$ to permille precision!

EW: see also talk by D. Britzger, LHeC and PERLE workshop, LAL-Orsay, June 2018
much of LHC and FCC programme is or will become pdf or $\alpha_s$ limited
LHC pdf-constraining measurements available; widely exploited in modern pdf fits

nevertheless, pp constrains, it does not precisely determine pdfs
electron-hadron colliders essential for future of high energy physics
LHC-eh and FCC-eh go beyond HERA in energy, luminosity (and eA)
unprecedented kinematic reach;
accesses scales sensitive to BSM and Higgs;
precision electroweak;
precise determination of all pdfs, and $\alpha_s$ to permille precision
more work ongoing…
extras
LHeC and FCC-eh

LHeC and FCC-eh energy recovery LINAC
e-beam: 60 GeV
Lint $\rightarrow 1$ ab$^{-1}$

LHeC (FCC-eh) complementary to, synchronous with, HL-LHC (FCC)

(M Klein, Rencontre du Vietnam, Sept 2017)
strong coupling $\alpha_s$ from LHeC

- $\alpha_s$ is least known coupling constant
- precise $\alpha_s$ needed to constrain GUT scenarios;
  for cross section predictions, including H; …
- measurements not all consistent
- what is true central value and uncertainty?
- $\alpha_s$(DIS) smaller than world average?
- LHeC: permille precision from QCD fit
  of inclusive NC and CC DIS ($\alpha_s$(DIS-jets)?)
- can challenge lattice QCD

<table>
<thead>
<tr>
<th>case</th>
<th>cut $[Q^2 \text{ in GeV}^2]$</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 incl.; total exp. uncerts; independent of BCDMS)

\[ 1/\alpha \]

\[ \log_{10}(Q/\text{GeV}) \]

PDG
LHeC

Higgs XS

Errors in %

scale var.
PDF (TH)
EW
t.b.c
l/mi
trunc
PDF+$\alpha_s$

(G. Zanderighi, Moriond16; from C. Anastasiou et al, arXiv:1602.00695)
PDF+$\alpha_s$ fit using LHeC simulated data

$\sim 0.3\%$ precision from LHeC

LHeC could resolve a > 30-year old puzzle:
$\alpha_s$ consistent in inclusive DIS, versus jets?
<table>
<thead>
<tr>
<th>Method</th>
<th>Current $\delta a(m^2)$/$a(m^2)$ uncertainty (theory &amp; experiment state-of-the-art)</th>
<th>Future $\delta a(m^2)$/$a(m^2)$ 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>$\approx 0.1%$ (~10 yrs) (improved computing power, N$^4$LO pQCD)</td>
</tr>
<tr>
<td>$\pi$ decay factor</td>
<td>$1.9_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.8%</em>{\text{th}}$ (N$^3$LO RGOP)</td>
<td>$1.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.7%</em>{\text{th}}$ (few yrs) (N$^4$LO RGOP, explicit $m_{u,d,s}$)</td>
</tr>
<tr>
<td>$\tau$ decays</td>
<td>$1.4_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.4%</em>{\text{th}}$ (N$^3$LO CIPT vs. FOPT)</td>
<td>$0.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 0.7%</em>{\text{th}}$ (+B-factories), &lt;1% (FCC-ee) (N$^4$LO, ~10 yrs. Improved spectral function data)</td>
</tr>
<tr>
<td>$Q\bar{Q}$ decays</td>
<td>$4_{-2}^{+2}%<em>{\text{exp}} \approx 6%</em>{\text{th}}$ (NLO only. T only)</td>
<td>$1.4_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2%</em>{\text{th}}$ (few yrs) (NNLO. More precise LDME and $R_{\text{exp}}$)</td>
</tr>
<tr>
<td>soft FFs</td>
<td>$1.8_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2%</em>{\text{th}}$ (NNLO$^*$ only (+NNLL, npQCD small)</td>
<td>$0.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 0.7%</em>{\text{th}}$ (NNLO+NNLL More precise $e^+e^-$ data: 90–350 GeV) (NNLO. More precise $e^+e^-$ data)</td>
</tr>
<tr>
<td>hard FFs</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 5%</em>{\text{th}}$ (NLO only. LEP data only)</td>
<td>$0.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2%</em>{\text{th}}$ (+B-factories), &lt;1% (FCC-ee) (NNLO. More precise $e^+e^-$ data)</td>
</tr>
<tr>
<td>global PDF fits</td>
<td>$1.5_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.7%</em>{\text{th}}$ (Diff. NNLO PDF fits. DIS+DY data)</td>
<td>$0.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 0.7%</em>{\text{th}}$ (few yrs), 0.15% (LHeC/FCC-ee) (N$^3$LO. Full DIS+hadronic data fit)</td>
</tr>
<tr>
<td>jets in $e^\pm p, \gamma-p$</td>
<td>$2_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2.5%</em>{\text{th}}$ (NNLO$^*$ only)</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.5%</em>{\text{th}}$ (few yrs), &lt;1% (FCC-ee) (NNLO. Combined DIS + (extra?) $\gamma-p$ data)</td>
</tr>
<tr>
<td>$F_2^T$ in $\gamma-\gamma$</td>
<td>$3_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 4.5%</em>{\text{th}}$ (NLO only)</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2%</em>{\text{th}}$ (~2 yrs), &lt;1% (FCC-ee) (NNLO. More precise new $F_2$ data)</td>
</tr>
<tr>
<td>$e^+e^-$evt shapes</td>
<td>$(1.5-4)<em>{-0.4}^{+0.6}%</em>{\text{exp}} \approx (1.5-4)%_{\text{th}}$ (NNLO+N$^3$LL, npQCD significant)</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.5%</em>{\text{th}}$ (+B-factories), &lt;1% (FCC-ee) (NNLO+N$^3$LL. Improved npQCD via $\sqrt{s}$-dep. New data)</td>
</tr>
<tr>
<td>jets in $e^+e^-$</td>
<td>$(2-5)<em>{-0.4}^{+0.6}%</em>{\text{exp}} \approx (2-5)%_{\text{th}}$ (NNLO+NNLL, npQCD moderate)</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.5%</em>{\text{th}}$ (few yrs), &lt;1% (FCC-ee) (NNLO+NNLL. Improved npQCD. New high-$\sqrt{s}$ data)</td>
</tr>
<tr>
<td>W decays</td>
<td>$0.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 37%</em>{\text{th}}$ (N$^3$LO, npQCD small. Low-stats data)</td>
<td>$(0.7-0.1)<em>{-0.4}^{+0.6}%</em>{\text{exp}} \approx (10-0.1)%_{\text{th}}$ (LHC,FCC-ee) (N$^4$LO, ~10 yrs. High-stats/precise W data)</td>
</tr>
<tr>
<td>Z decays</td>
<td>$0.7_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2.4%</em>{\text{th}}$ (N$^3$LO, npQCD small)</td>
<td>$0.1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx (0.5-0.1)%</em>{\text{th}}$ (ILC,FCC-ee) (N$^4$LO, ~10 yrs. High-stats/precise Z data)</td>
</tr>
<tr>
<td>jets in p-p, p-$\bar{p}$</td>
<td>$3_{-0.4}^{+0.6}%<em>{\text{exp}} \approx (4-5)%</em>{\text{th}}$ (NLO only. Combined exp. observables)</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.5%</em>{\text{th}}$ (Tevatron+LHC, ~2 yrs) (NNLO. Multiple datasets+observables)</td>
</tr>
<tr>
<td>$t\bar{t}$ in p-p, p-$\bar{p}$</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 2.5%</em>{\text{th}}$ (NNLO+NNLL, CMS only)</td>
<td>$1_{-0.4}^{+0.6}%<em>{\text{exp}} \approx 1.5%</em>{\text{th}}$ (Tevatron+LHC, ~2 yrs) (Improved $m_{\text{top}}$ &amp; PDFs. Multiple datasets)</td>
</tr>
</tbody>
</table>
**d/u at large x**

**dv/uv distribution at $Q^2 = 10$ GeV$^2$**

- **CT14**
- **NNPDF3.0**
- **MMHT2014**
- **ABM12**
- **CJ15 (T=10)**
- **CJ15 (T=1.645)**
- **CJ15+EIC (T=1.645)**
- **LHeC**

**d/u essentially unknown at large x**

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

**with precision ep(n) data to v. large x**

- No nuclear corrections; relax assumptions

**resolve long-standing mystery of d/u ratio at large x**
FL at the LHeC

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 $E_e$ 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


diffractive pdfs

\[ Q^2 \geq 1 \text{ GeV}^2 \]

\[ x = \beta \xi \geq 1^\circ \]

\[ \theta > 1^\circ \]

\[ \theta = 10^\circ \]

\[ 0.001 < y < 0.96 \]

\[ \beta < 1 \]

\[ \xi < 0.4 \]

\[ \xi = (x_p) \]

\[ E_e = 60 \text{ GeV} \]

\[ E_p = 7 \text{ TeV vs. HERA} \]

- \( x_{\text{min}} \) down by factor \(~20\)
- \( Q_{\text{max}}^2 \) up by factor \(~100\)

\[ E_p = 50 \text{ TeV vs. 7 TeV} \]

- \( x_{\text{min}} \) down by factor \(~10\)
- \( Q_{\text{max}}^2 \) up by factor \(~10\)
dpdfs: top contribution

Gluon DPDF error bands from the 5% simulations
\( E_p = 50 \text{ TeV} \)

Quark DPDF error bands from the 5% simulations
\( E_p = 50 \text{ TeV} \)

#1735, no top, \( Q^2_{\text{min}} = 4.2 \text{ GeV}^2 \)
#1990, w. top, \( Q^2_{\text{min}} = 4.2 \text{ GeV}^2 \)

#2171, no top, \( Q^2_{\text{min}} = 1.3 \text{ GeV}^2 \)
#2446, w. top, \( Q^2_{\text{min}} = 1.3 \text{ GeV}^2 \)

top quark phase space region does not have a big effect on the dpdf extraction
LHC pdf prospects

Summary: where can we improve in future?

A.M. Cooper-Sarkar
HL/HE-LHC WS, CERN, Nov. 2017

• **W,Z and Drell-Yan distributions** – sensitivity to valence quarks, strangeness, photon PDF
  ATLAS peak W,Z data has already reached systematic uncertainties of ~0.5%, experimental improvement unlikely and this is already challenging NNLO calculations
  The reach to lower x at 13,14,27TeV brings more theoretical challenges- need for ln(1/x) resummation- see arXIV:1710.05935
  Off-peak Drell-Yan can still improve BUT low-mass brings the same low-x challenges.
  This also affects the LHCb data
  And high-mass requires good understanding of the NLO-EW corrections and photon PDF

• **Inclusive, di-jet and tri-jet distributions**------sensitivity to gluon
  Already challenging theoretical understanding -NNLO is needed but scale choice is still an issue
• **Top-antitop distributions** –sensitivity to gluon
  NNLO calculations already required, data can also improve (data consistency?)

*Combinations of types of data and different beam energies* –accounting for their correlations-can help

For all of these below: precision of the data can improve
• **W,Z +jets** --------sensitivity to gluon- so far limited, can improve
• **W,Z/γ +heavy flavour** -sensitivity to strangeness and intrinsic charm- can improve
• **Direct photon**-------sensitivity to gluon—studies needed

... likely to bring incremental rather than dramatic improvements;
more concrete studies underway in context of ongoing HL/HE-LHC workshop