PDFs and QCD with the LHeC

Claire Gwenlan, Oxford
for the LHeC and FCC-eh study groups

POETIC VI

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with special thanks to: Max Klein, Voica Radescu
some introductory words
we are entering an exciting era in high energy physics …

• LHC@13TeV has begun – new opportunities in **searches** and **precision physics**
• new, higher **luminosity** and **energy** machines on the horizon, or being explored
  – HL-LHC, what can we learn from 300 \( \rightarrow \) 3000 fb\(^{-1}\); energy: HE-LHC, FCC@100TeV, …
• **New Physics discovery** and **understanding of known physics** at energy frontier, relies on **QCD** at high orders and **precise knowledge of proton structure** (PDFs)
• **current PDF uncertainties**: limit searches for new, heavy particles; dominate theory uncertainty on Higgs production; limit precision of \( M_W, \alpha_s, EW \) parameters, …

*next Generation priorities*: Higgs exploitation and BSM searches (and characterisation)
limits on current PDF knowledge **will** restrict physics extracted from current and future colliders

**LHeC**: future ep (and eA) collider proposed to run **concurrently** with HL-LHC
**precise extraction of all PDFs**, and wealth of physics opportunities in its own right – BSM, Higgs, top, low x, …

**FCC-eh**: further future ep collider; integrated with FCC-hh
**DIS ep collider**

**HERA, 92–07**
(DESY, Hamburg)

\[ \sqrt{s} \approx 300 \text{ GeV} \]

**HERA delivered**

- **H1 e^–**
- **H1 e^+**

\[
\begin{align*}
\text{H1 e}^- & \quad 562 \text{ pb}^{-1} \quad \text{Nov 02-Mar 07} \\
\text{H1 e}^+ & \quad 193 \text{ pb}^{-1} \quad \text{May 93 – Aug 00}
\end{align*}
\]

**HERA: established detailed proton structure (PDFs)**
– including strong rise of gluons at low \( x \)

- quantitative Tevatron and LHC results of today
  would not be possible without HERA

\[ \mu_f^2 = 10 \text{ GeV}^2 \]

**H1 and ZEUS**

\[
\begin{align*}
x_f & \\
\text{HERAPDF2.0 NNLO uncertainties:} & \\
\text{expermental:} & \\
\text{model:} & \\
\text{parameterisation:} & \\
\text{HERAPDF2.0AG NNLO:} & \\
x_g (\times 0.05) & \quad x_d (\times 0.05) & \quad x_S (\times 0.05)
\end{align*}
\]

\[
\begin{align*}
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\mu_f^2 = 10 \text{ GeV}^2 & \\
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x_g (\times 0.05) & \quad x_d (\times 0.05) & \quad x_S (\times 0.05)
\end{align*}
\]

... and much more: \( \alpha_s \); jets; \( \gamma \) structure; diffraction (10%); c, b; BSM limits (leptoquarks), ...

- C. Gwenlan, PDFs and QCD at the LHeC
- 3
lepton-proton facilities

LHC (and other future machines eg. FCC-pp) is/will be main discovery machine

**LHeC not a competitor to these**; complementary; synchronous with HL-LHC;
transforms them into high precision facilities

... and wealth of other physics in its own right
improving PDFs with the LHeC

- **low-\(x\):** no current data to constrain \(x \leq 10^{-4}\); rely purely on extrapolation onset of BFKL effects, non-linear equations, gluon saturation?
- **mid-\(x\):** need higher precision for Higgs
- **high-\(x\):** very poorly constrained – limits searches for new, heavy particles

**LHeC:** access to much smaller \(x\), larger \(Q^2\) (1000×HERA luminosity); operation with \(ep\), \(eD\), \(eA\) and **FCC-he** extends even further
proton PDFs, today

- need to know PDFs much better than today, for:
  - nucleon structure; q-g dynamics; Higgs; BSM searches;
  - future colliders, FCC-hh; and development of QCD
- LHC will provide further constraints, but cannot
  resolve precisely (shown are latest global PDFs, also
  including available LHC data)

C. Gwenlan, PDFs and QCD at the LHeC
CDR: arXiv:1206.2913

630 pages, summarising 5 year workshop

http://cern.ch/lhec

LHeC Study Group


about 200 experimentalists and theorists from 76 institutes

supported by

CERN, ECFA, NuPECC

since CDR, proposal re-evaluated by CERN:
new mandate, inviting IAC and coordination groups to extend LHeC study; also launched FCC design study in which ep is an integral part

additional material from subsequent updates:
and recent, PDF+αs studies, courtesy Voica Radescu

http://cern.ch/lhec

LHeC

Journal of Physics G: Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075007

LHeC: Compact Linear Hadron Collider

Proposal for a next generation machine for elementary particle physics

IOP Publishing

C. Gwenlan, PDFs and QCD at the LHeC

radescu
NC/CC cross sections to high precision

- structure functions, sensitive to quarks
- access high $x$, free from nuclear corrections (via high $Q^2$, high luminosity)
- different beam charge and polarisation: determination of all quark types

- C. Gwenlan, PDFs and QCD at the LHeC
valence quarks

CDR study: LHeC simulated NC, CC e±p, P=±0.4, including projected systematics
HERAfitter framework with HERAPDF1.0 NLO settings

now...

up valence distribution at Q2 = 1.9 GeV2

NNPDF3.0
HERAPDF1.5
ABM11
MMHT14
CT14
Q = 1.38e+00 GeV

Generated with APFEL 2.4.0 Web

...then

NNPDF3.0
HERAPDF1.5
ABM11
MMHT14
CT14
Q = 1.38e+00 GeV

Generated with APFEL 2.4.0 Web

uval NLO PDFs, 68% CL

uval 2% at x = 0.8

down valence distribution at Q2 = 1.9 GeV2

dval

dval 4% at x = 0.8

precision determination, free from higher twist corrections and nuclear uncertainties
gluon and sea at high $x$

now...

- gluon PDF at high $x$ poorly known
  - gluon and sea evolution intimately related
  - important to disentangle sea from valence at large $x$ – can be done with precise LHeC measurements of CC cross sections and NC $F_2^{\gamma Z}, xF_3^{\gamma Z}$

then...

- gluon 10% at $x = 0.7$
high x PDFs: link to LHC

- large uncertainties in high x PDFs limit searches for new physics at high scales
- many interesting processes at LHC are gluon-gluon initiated: top, Higgs, … and BSM processes, such as gluino pair production

Current BSM search in dilepton final state; uncertainties on high-x (anti)quarks dominate

**ATLAS**

\[ \int L \, dt = 20.3 \, fb^{-1} \]

\[ \sqrt{s} = 8 \, TeV \]

**Gluino Pair Production PDF Uncertainty**

**LHeC PDF**

\[ M_{\tilde{g}} = M_{sq} \, [TeV] \]

**arXiv:1407.2410**

**arXiv:1211.5102**
**LHeC PDFs for Higgs at the LHC**

*ggH is dominant Higgs production mechanism at LHC*

**LHeC PDF**: 0.3% on cross section (experimental stat.+syst.)

sensitivity to Higgs mass

$\alpha_s$ is underlying parameter: 0.005 change $\equiv$ 10% on cross section

LHeC: $\alpha_s$ to per mille (0.0002)!

need N$^3$LO to reduce scale uncertainty: **now available for ggH**

LHeC with high luminosity is in itself a precision Higgs facility

---

C. Gwenlan, PDFs and QCD at the LHeC
now...

then...

**gluon measurement down to \( x = 10^{-5} \); \((F_L \text{ would improve it further})**

explore low \( x \) QCD: DGLAP vs BFKL? non-linear evolution, saturation? \( F_2 \), and precise \( F_L \);

- important for high energy neutrino cross sections

see, also, talk by N. Armesto Perez
flavour decomposition, charm and beauty

**LHeC**: much more precise and kinematically extended measurements
high $Q^2$, high cross section, high luminosity, no pileup, small beam spot, new generation of Si detectors

- $\delta M_c = 60$ (HERA) to 3MeV: impacts on $\alpha_s$, regulates ratio of charm to light, …
- MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$

- C. Gwenlan, PDFs and QCD at the LHeC
strange: largely unknown; suppressed compared to other light quarks? s=sbar?

e.g. ATLAS data suggest SU(3) symmetric sea

\( Q^2 = 1.9 \text{ GeV}^2, x = 0.023 \)

<table>
<thead>
<tr>
<th>Model</th>
<th>( x(s+s\bar{s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABKM09</td>
<td>0.2</td>
</tr>
<tr>
<td>NNPDF2.1</td>
<td>0.4</td>
</tr>
<tr>
<td>MSTW08</td>
<td>0.6</td>
</tr>
<tr>
<td>CT10 (NLO)</td>
<td>0.8</td>
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</tbody>
</table>

\((s+s\bar{s})\) distribution at \( Q^2 = 1.9 \text{ GeV}^2 \)

Generated with APFEL 2.4.0 Web

C. Gwenlan, PDFs and QCD at the LHeC
**strange**

**strange:** largely unknown; suppressed compared to other light quarks? $s=s\bar{s}$?

**LHeC:** direct sensitivity to **strange**, via charm tagging in CC ($W+s\rightarrow c$)

— first ($x,Q^2$) measurement of (anti-) strange density

note, direct sensitivity to top ($tPDF$?) also possible, for first time ($W+b\rightarrow t$)

(initial study (CDR): 10% charm tagging efficiency, 1% light quark background)
new since CDR
ERL scenario; interest in Higgs prefers e-, high polarisation
Ep=7 TeV, E=60 GeV:
NC,CC:

<table>
<thead>
<tr>
<th>P</th>
<th>L (fb-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+p</td>
<td>0</td>
</tr>
<tr>
<td>e-p</td>
<td>+80%</td>
</tr>
<tr>
<td>e-p</td>
<td>-80%</td>
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<tr>
<td></td>
<td>5 50 500</td>
</tr>
</tbody>
</table>

plus, dedicated measurements of strange, anti-strange, F2cc
(no F2bb, low Ep, FL data yet)

more flexible PDF fit:
xg, xuν, xdν, xub, xdb, xstr
xf(x) =Ax B (1-x)C (1+Dx+Ex2)
– 14 free parameters

can better constrain all PDFs
LHeC PDFs with released assumptions

• furthermore, LHeC does not need to rely on ‘usual’ constraint that u=d at low x, which may not be valid
**FCC-eh vs LHeC vs HERA**

**FCC-eh**: $E_p=50$ TeV, $E_e=100$ GeV  
NC and CC: e-p, $P=80\%$, 1000 fb$^{-1}$  
stat: $0.1-30\%$, uncor: $0.7\%$, syst: $1-5\%$  
coverage down to $x=2\times10^{-7}$, up to $Q^2=10^7$ GeV$^2$

**FCC-eh can further improve, and explore low-x phenomenology**

- C. Gwenlan, PDFs and QCD at the LHeC
strong coupling \( \alpha_s \) is fundamental parameter, not given by theory extracted from experimental measurements in e+e−, ep, pp, and from lattice QCD calculations

PDG world ave.: \( \alpha_s(M_Z) = 0.1184 \pm 0.0006 \) without lattice input: \( \alpha_s(M_Z) = 0.1183 \pm 0.0012 \)

but, measurements not all consistent – what is true central value; true uncertainty; role of lattice calculations?

precise \( \alpha_s(M_Z) \) important to constrain GUT scenarios, and for cross section predictions, such as Higgs
strong coupling from LHeC

combined fit to PDFs+αs using LHeC data

~ 0.3% precision from LHeC

LHeC could resolve a > 30-year old puzzle:

αs consistent in inclusive DIS, versus jets?

expected 0.1% precision when combined with HERA

M Klein, V Radescu

NC,CC
NC,CC+F2c

H1 and ZEUS

NLO
• inclusive charm jet data, $Q^2_{\text{min}} = 3.5 \text{ GeV}^2$
• inclusive charm jet data, $Q^2_{\text{min}} = 10 \text{ GeV}^2$
• inclusive charm jet data, $Q^2_{\text{min}} = 20 \text{ GeV}^2$

M Klein, V Radescu

C. Gwenlan, PDFs and QCD at the LHeC
strong coupling


<table>
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<tr>
<th>Method</th>
<th>Current relative precision</th>
<th>Future relative precision</th>
</tr>
</thead>
</table>
| $e^+e^-$ evt shapes | expt $\sim 1\%$ (LEP)  
                 | thry $\sim 1$–$3\%$ (NNLO+up to $N^3$LL, n.p. signif.) [27] | $< 1\%$ possible (ILC/TLEP)  
                 |                                                               | $\sim 1\%$ (control n.p. via $Q^2$-dep.) |
| $e^+e^-$ jet rates | expt $\sim 2\%$ (LEP)  
                 | thry $\sim 1\%$ (NNLO, n.p. moderate) [28]               | $< 1\%$ possible (ILC/TLEP)  
                 |                                                               | $\sim 0.5\%$ (NLL missing) |
| precision EW    | expt $\sim 3\%$ ($R_Z$, LEP)  
                 | thry $\sim 0.5\%$ (N$^3$LO, n.p. small) [9, 29]         | 0.1% (TLEP [10]), 0.5% (ILC [11])  
                 |                                                               | $\sim 0.3\%$ (N$^4$LO feasible, $\sim 10$ yrs) |
| $\tau$ decays   | expt $\sim 0.5\%$ (LEP, B-factories)  
                 | thry $\sim 2\%$ (N$^3$LO, n.p. small) [8]               | $< 0.2\%$ possible (ILC/TLEP)  
                 |                                                               | $\sim 1\%$ (N$^4$LO feasible, $\sim 10$ yrs) |
| ep colliders    | $\sim 1$–$2\%$ (pdf fit dependent)  
                 | (mostly theory, NNLO) [30, 31], [32, 33]                | 0.1% (LHeC + HERA [23])  
                 |                                                               | $\sim 0.5\%$ (at least N$^3$LO required) |
| hadron colliders | $\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $tt$)  
                 | (NLO jets, NNLO $tt$, gluon uncert.) [17, 21, 34]        | $< 1\%$ challenging  
                 |                                                               | (NNLO jets imminent [22]) |
| lattice         | $\sim 0.5\%$ (Wilson loops, correlators, ...)  
                 | (limited by accuracy of pert. th.) [35–37]               | $\sim 0.3\%$  
                 |                                                               | ($\sim 5$ yrs [38]) |

per mille accuracy can challenge QCD lattice calculations
summary

LHeC: enormous increase in kinematic reach of DIS, and in luminosity

- **main goal, PDFs**: precise determination of proton (and nucleon) structure
- specifically, **precise unfolding of all PDFs**, not constrained by standard assumptions
  (not talked about: unintegrated, diffractive, generalised, polarised, photonic, nuclear PDFs – see, also, talk on “Nuclear PDFs in eA collisions at the LHeC’, by M. Klein)
- $\alpha_s$ to per mille level!
- transforms discovery machines (LHC, HL-LHC, ..) to **higher precision facilities** for Higgs, BSM physics, ...
- and exploration of low x; learn more about QCD beyond DGLAP
  (see, also, talk on ‘Small x Physics at the LHeC’, by N. Armesto Perez)

(for further “Overview of the LHeC project”, see also P. Newman’s talk)
LHeC location

C. Gwenlan, PDFs and QCD at the LHeC
LHeC deuteron data

3.5TeV × 60GeV, e-p, P=-80%, 1fb⁻¹, NC and CC, experimental uncertainties

- symmetrised understanding of u-valence and d-valence
- future fits with ep+eD will lead to precise unfolding of u and d

... also neutron structure!

C. Gwenlan, PDFs and QCD at the LHeC
LHeC PDFs c.f. world data

Ref

**HERA**
- NC cross section HERA-I H1-ZEUS combined e-p.
- NC cross section HERA-I H1-ZEUS combined e+p.
- CC cross section HERA-I H1-ZEUS combined e-p.
- CC cross section HERA-I H1-ZEUS combined e+p.
- H1 Low Ep: 460, 575 GeV
- CDF inclusive jets
- CDF Z rapidity 2010
- D0 pp jets
- D0 Z rapidity 2007
- D0 W asymmetry 2013
- D0 W-\mu nu lepton asymmetry pt $\gtrsim$ 35 GeV
- CDF W asymmetry 2009

**Tevat.**
- BCDMS F2p 100GeV
- BCDMS F2p 120GeV
- BCDMS F2p 200GeV
- BCDMS F2p 280GeV

**fixed target**
- ATLAS Jet data 0 \( \frac{y}{x} \) = 0.3
- ATLAS Jet data 0.3 \( \frac{y}{x} \) = 0.8
- ATLAS Jet data 0.8 \( \frac{y}{x} \) = 1.2
- ATLAS Jet data 1.2 \( \frac{y}{x} \) = 2.1
- ATLAS Jet data 2.1 \( \frac{y}{x} \) = 2.8
- ATLAS Jet data 2.8 \( \frac{y}{x} \) = 3.6
- ATLAS Jet data 3.6 \( \frac{y}{x} \) = 4.4
- ATLAS Z rapidity, 2010 data
- ATLAS W+ lepton pseudorapidity, 2010 data
- ATLAS W- lepton pseudorapidity, 2010 data

**LHC**
- ATLAS Jet data 0 \( \frac{y}{x} \) = 0.3
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LHeC can precisely constrain all PDFs

- C. Gwenlan, PDFs and QCD at the LHeC
LHeC PDFs c.f. world data

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<td>Tevat.</td>
<td>CDF inclusive jets</td>
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<td>BCDMS F2p 280GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>ATLAS Jet data 0 (\gamma = -y \leq 0.3)</td>
<td>ATLAS Jet data 0.3 (\gamma = -y \leq 0.8)</td>
<td>ATLAS Jet data 0.8 (\gamma = -y \leq 1.2)</td>
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LHeC can precisely constrain all PDFs

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LHeC PDFs with released assumptions

C. Gwenlan, PDFs and QCD at the LHeC
Figure 1: Total production cross section predictions for various heavy quark processes at the LHeC with \( x \) TeV proton energy as a function of the lepton beam energy. The following processes are covered: charm and beauty production in photoproduction and DIS and DIS. The flavour inclusive charged current total cross section is also shown. All predictions are taken from Monte Carlo simulations, some details can be found in Table 1. For comparison also the predicted cross sections at HERA with \( 93.8 \) GeV proton energy are shown. It was a different estimate by a large pollution from light quark background events due to the limited detector capabilities to separate secondary from primary vertices. At LHeC one can expect a much better secondary vertex identification and thus a very strong background reduction. It is difficult to predict exactly how much background pollution will remain at LHeC, so for the purpose of this simulation study it was completely neglected. Systematic uncertainties were neglected for the illustrations presented here, but an estimate was provided for the subsequent investigation of the determination of the charm mass.
(anti-)strange – new LHeC scenario

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partons at low $x$

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- also see talk of P Newman
NNLO PDFs might also be needed, if scale not dominant uncertainty, and data highly precise.

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PDFs at large $x$
PDFs at low $x$
strange

\[ W^+ \text{ at LHC} \]
Higgs aside

VBF Higgs Production in ep (top) and pp (bottom)

Higgs production in ep comes uniquely from either CC or NC

Pile-up in ep at $10^{34}$ is 0.1, 25ns
Clean(er) bb final state, $S/B \sim 1$

Clean, precise reconstruction and easy distinction of WWZ and WWH

Higgs production in pp comes predominantly from $gg \rightarrow H$

VBF cross section about 200fb (about as large as at the LHeC).

Pile-up in pp at 5 $10^{34}$ is 150, 25ns
$S/B$ very small for bb

Precision needs accurate PDFs
Higgs aside

The \( ep \rightarrow H \) cross section at the LHeC is as large as the \( H \) cross section at ILC or FCC-ee and the VBF cross section at the LHC.

The \( ep \rightarrow H \) cross section at the FCC-he is 5 times larger than at ILC/FCCee. This paves the way to accessing H-HH with the FCC-he.