The LHeC - a Large Hadron-Electron Collider
~50-100 GeV electrons on 7 TeV protons (Linac- Ring).
Designed such that e-p can operate synchronously with p-p in the HL-LHC phase.

Currently uncertainties on the parton distribution functions (PDFs) limit searches for new heavy particles, dominate the theory uncertainty on Higgs production and limit the precision of $M_W$, $\alpha_s$, EW parameters

With higher luminosity and higher energy machines on the horizon we will need higher precision PDFs
Current level of knowledge of PDFs at 13TeV (including Run-I LHC data) still have considerable uncertainty at high scale BUT at future colliders the low scale region will also have large uncertainties...
lepton-proton facilities

LHeC: $\sqrt{s} = 1.3$ TeV
$\times 100$–1000 HERA lumi.

FCC-eh: $\sqrt{s} = 3.5$ TeV

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
The LHeC/FCC-he option represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity.

- This represents a tremendous increase in the precision of Parton Distribution Functions
- And the exploration of a kinematic region at low-x where we learn more about QCD- e.g. is there gluon saturation?
- Precision PDFs are needed for BSM physics
- PDFs in an extended kinematic region will also be needed for any FCC
DIS is the best tool to probe proton structure

Mostly scenario B is presented here

\[ 2 < Q^2 < 100,000 \quad 0.000002 < x < 0.8 \]

Gluon also comes from the scaling violations

Typical uncertainties:

- 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>

\[ Q^2 = -q^2 = -(k - k')^2 \]

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:

\[ e_r(x, Q^2) = \frac{d^2 \sigma(e^+p)}{dxdQ^2} = \frac{Q^4x}{2\pi \alpha^2 \gamma} \cdot F_2(x, Q^2) - \frac{y^2}{\gamma} F_L(x, Q^2) + \frac{\gamma}{\gamma_L} F_3(x, Q^2) \]
The potential for precision parton distributions at the LHeC is assessed using:

- LHeC simulated data (scenario B) on NC, CC $e^+p$ and $e^-p$ cross-sections
- Published HERA-I combined data
- Fixed target data from BCDMS ($W^2>15$)
- ATLAS 2010W, Z data

HERAFitter framework is used, with PDF fit settings as for HERAPDF1.0 NLO.

Valence distributions

NOW

THEN
Gluon and sea at high x

The high x gluon is not well known
Current PDFs differ
The gluon and sea evolution are intimately related.
The LheC can disentangle the sea from the valence at high-x through measurement of CC cross-sections and $F_2^{YZ}$, $xF_3^{YZ}$

THEN

NOW
Why are we interested in the high-x sea? - one example

Current BSM searches in High Mass Drell-Yan are limited by high-x antiquark uncertainties as well as by high-x valence uncertainties.

\[ \text{arXiv:1607.03669} \]
Why are we interested in the high-x gluon? - one example

Many interesting processes at the LHC are gluon-gluon initiated. Top, Higgs… BSM processes like gluon-gluon → gluino-gluino. And the high-scale needed for this involves the high-x gluon. The gluon-gluon luminosity at high-scale is not well-known. This leads to uncertainties on the gluino pair production cross section.

Which could be considerably reduced using LheC data.
Another related uncertainty is the uncertainty on $\alpha_s(M_Z)$

The cross-sections for gluon-gluon initiated processes also depend sensitively on $\alpha_s(M_Z)$, which is also not so well known. DIS data tends to give lower values. Although the world average looks well determined it is a compromise between many differing determinations. It is dominated by lattice QCD rather than by experimental measurement.

A highly accurate $\alpha_s(M_Z)$ is important for GUTS, to know where the couplings unify and under what GUT scenario.

LHeC promises per mille accuracy on alphas!
strong coupling from LHeC

combined fit to PDFs+$\alpha_s$ using LHeC data

\[ \sim 0.3\% \text{ precision from LHeC} \]

M Klein, V Radescu

NC,CC
NC,CC+F2c

LHeC could resolve a > 30-year old puzzle:
$\alpha_s$ consistent in inclusive DIS, versus jets?

expected 0.1% precision when combined with HERA
Gluon and sea at low $x$

**NOW**

HERA sensitivity stops at $x > 5 \times 10^{-4}$
Below that, uncertainties depend on the parametrisation
LHeC goes down to $10^{-6}$
- FL measurement will also contribute
- Explore low-$x$ QCD DGLAP vs BFKL or non-linear evolution
- Important for high energy neutrino cross sections – Auger etc.

**THEN**
Why are we interested in low-x?

Because the HERA data indicated that there may be something new going on at low x

- New in the sense of a new regime of QCD
- Something that DGLAP evolution at NLO or NNLO cannot describe
- Needing $\ln(1/x)$ rather than $\ln Q^2$ resummation (BFKL)
- Or even non-linear evolution (BK, JIMWLK, CGC) and gluon saturation

The rise of the HERA F2 structure function at low x was steeper than expected and continued to lower $Q^2$ than expected. This gave rise to speculation that one might have entered the BFKL domain.

One way to test this is to make DGLAP QCD fits in which this domain is cut out ($Q^2 > A x^{-0.3}$). If physics is the same above and below the cut then these fits will be compatible (although the cut fits will have larger uncertainties).

This is not the case….and **this tendency is reconfirmed in the new HERA-I+II final combination data.**
IN DGLAP based fits to inclusive data at low-$x$, we have
\[ F_2 \sim xq \quad \text{for the sea} \]
\[ dF_2/d\ln Q^2 \sim P_{qg} xg \quad \text{for the gluon} \]

Our deductions about gluon behaviour at low-$x$ come via the DGLAP splitting function $P_{qg}$

If DGLAP is inadequate then so will our deductions about the shape of the gluon be inadequate. We need other ways to probe it, e.g.

$F_L$ is gluon dominated at low-$x$

\[ F_L(x, Q^2) = \frac{\alpha_s}{\pi} \left[ \frac{4}{3} \int_0^1 \frac{dy}{y} z^2 F_2(y, Q^2) + 2 \Sigma x_i^2 \int_0^1 \frac{dy}{y} z^2 (1-z) p_{ig}(y, Q^2) \right] \]

Blue is what we have now averaged over $x$ for each $Q^2$ bin
Red is what we could get from the LHeC (note that $E_e$ rather than $E_p$ is varied to make this measurement so it does not interfere with $p$-$p$)

Compare LHeC pseudo-data predicted by a non-linear saturation based model to the DGLAP predictions.
It is usually assumed that $u_{\text{bar}} = d_{\text{bar}}$ at low-$x$.

If we relax this assumption then PDF errors increase tremendously. But LHeC data can constrain this.

Here we compare uncertainties on the total sea distribution.

And here we compare uncertainties on the $d/u$ ratio.

This would improve more if deuteron target data are used. Deuterons can also give information on neutron structure.
The LHeC would also allow us to improve our knowledge of heavy quarks. Compare the potential for the measurement of $F_2^{c-c\bar{c}}$ and $F_2^{b-b\bar{b}}$ with what is currently available from HERA.

Why are $F_2^{b,c}$ measurements better?
- higher cross section, higher $Q^2$, higher luminosity ($F_2^{b}$)
- smaller envelope of interaction, new generation of Si detectors

Top quarks and strange quarks could also be studied for the first time
- top: $t$PDF, cross section few pb at $E_e=60$GeV, $W_b \rightarrow t$
Top Quarks at LHeC

Top quarks can be studied in DIS (negligible cross section at HERA)

CC: $Wb \rightarrow t$ production  
(cross section $O(10\text{pb})$)

NC: $tt$-bar pair production

$t$ and $tt$-bar physics with LHeC still to be studied: 
precision measurement of top mass, top PDF, ...

A top PDF could be important at FCC
The strange PDF is not well known
Is it suppressed compared to other light quarks?
Is there strange-antistrange asymmetry?

LHeC could give direct sensitivity to strange through charm tagging in CC events.
Results are shown for 10% charm tagging efficiency, 1% light quark background in impact parameter.
This could give the first $x,Q^2$ measurement of the anti-strange PDF
This also assumes an updated scenario from the CDR .....
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>
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<tbody>
<tr>
<td>e+p</td>
<td>0</td>
</tr>
<tr>
<td>e-p</td>
<td>50</td>
</tr>
<tr>
<td>e-p</td>
<td>500</td>
</tr>
</tbody>
</table>

plus, dedicated measurements of strange, anti-strange, F2cc
(not yet F2bb, low Ep data, F1)

more flexible PDF fit:
xg, xuv, xdv, xub, xdb, xstr
xf(x) = A x^B (1-x)^C (1+Dx+Ex^2)
- 14 free parameters

can better constrain all PDFs
Summary

The LHeC represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity.

- This represents a tremendous increase in the precision of Parton Distribution Functions
- And the exploration of a kinematic region at low-x where we learn more about QCD beyond linear DGLAP evolution
- Precision PDFs are needed for BSM physics
- The higher luminosity can also provide a precision Higgs ‘factory’

This can run parallel with HL-LHC and the results fed into HL_LHC physics
Backup
primary measurements – simulated – high $Q^2$

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

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

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 gluon via scaling violation (and F1)
Electroweak studies

Improvement in the precision of the measurements

Improvement in the deduced electroweak parameters
Including \( \sin^2 \theta_W \) from polarisation asymmetry
Master formulae for NC DIS

\[
\sigma_{r,NC} = \frac{d^2\sigma_{NC}}{dx dQ^2} \cdot \frac{Q^4 x}{2\pi \alpha^2 Y_+} = F_2 + \frac{Y_-}{Y_+} x F_3 - \frac{y^2}{Y_-} F_L
\]

\[
F_2^{\pm} = F_2 + \kappa_Z (-v_e \mp P \alpha_e) \cdot F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z
\]

\[
x F_3^{\pm} = \kappa_Z (\pm a_e + P v_e) \cdot x F_3^{\gamma Z} + \kappa_Z^2 (\pm 2v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z
\]

\[
(F_2, F_2^{\gamma Z}, F_2^Z) = x \sum (e_q^2, 2e_q v_q, v_q^2 + a_q^2) (q + \bar{q})
\]

\[
(x F_3^{\gamma Z}, x F_3^Z) = 2x \sum (e_q a_q, v_q a_q) (q - \bar{q})
\]

\[
F_L(x) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \cdot \left[ \frac{16}{3} F_2(z) + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right]
\]

Vary charge and polarisation and beam energy to disentangle contributions.
**Charged Currents**

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

\[
\sigma_{r,CC}^\pm = \frac{1 \pm P}{2} \left( W_2^\pm + \frac{Y_-}{Y_+} x W_3^\pm - \frac{y^2}{Y_+} W_L^\pm \right)
\]

\[W_2^+ = x(\bar{U} + D), \ xW_3^+ = x(D - \bar{U}), \ W_2^- = x(U + \bar{D}), \ xW_3^- = x(U - \bar{D})\]

\[U = u + c \quad \bar{U} = \bar{u} + \bar{c} \quad D = d + s \quad \bar{D} = \bar{d} + \bar{s}\]

\[\sigma_{r,CC}^+ \sim x\bar{U} + (1 - y)^2 x\bar{D}, \]

\[\sigma_{r,CC}^- \sim xU + (1 - y)^2 xD\]

\[\sigma_{r,NC}^\pm \sim [c_u(U + \bar{U}) + c_d(D + \bar{D})] + \kappa_Z [d_u(U - \bar{U}) + d_d(D - \bar{D})]\]

with \(c_{u,d} = e^{2}_{u,d} + \kappa_{Z}(-\nu_e + Pa_e)\)\(\nu_{u,d} + \nu_{u,d}\) and \(d_{u,d} = \pm a_d a_{u,d} e_{u,d}\).

**Complete unfolding of all parton distributions to unprecedented accuracy**
Compare the valence distributions also at low $x$ (maybe cut this)
LHeC deuteron data

3.5 TeV $\times$ 60 GeV, e-p, $P=-80\%$, 1 fb$^{-1}$, 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
**Intrinsic Charm**

*Intrinsic charm*: existence of $c\bar{c}$ pair as non-perturbative component in the bouncy state nucleon ($|uudc\bar{c}\rangle$)

→ may explain certain aspects of the charm data and dominate in some regions of the phase space

for large $x$ very good forward tag acceptance needed (possible with reduced $E_p$)

simulated measurement of the charm structure function ($E_p=1$ TeV, $L=1$ fb$^{-1}$, CTEQ66)

→ reliable detection of an intrinsic heavy charm component challenging but possible
LHeC and Higgs

The dominant Higgs production mechanism at LHC is $g\,g\rightarrow H$

Thus the extra precision on the gluon PDF and $\alpha_s(M_Z)$ which can be obtained at the LHeC improves the precision of SM Higgs cross section predictions-

and their dependence on Higgs mass

LHeC at high luminosity is also a Higgs factory, Higgs can be produced by WW, ZZ fusion and $H\rightarrow b\bar{b}$-bar decay is easily identified
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