Future High Energy Electron Proton Scattering: The LHeC Project

Paul Newman
Birmingham University, (for LHeC study group)

Cambridge Seminar
30 October 2012

A second generation lepton-hadron collider in the 2020s, based on the high luminosity phase of the LHC

http://cern.ch/lhec
Material from recently published Conceptual Design Report

630 pages, summarising a 5 year workshop commissioned by CERN, ECFA and NuPECC

~200 participants from 69 institutes


LHeC is the latest & most promising idea to take ep physics to the TeV centre-of-mass scale ... ... at high luminosity

Contents

- A brief history of ep Physics
- How to build an ep Collider based on the LHC
- Detector considerations
- Physics motivation
  - Proton structure / Impact on the LHC
  - QCD at high parton densities
  - Electron - ion collisions
  - BSM physics
- Timeline and outlook
Electron Scattering Experiments

“It would be of great scientific interest if it were possible to have a supply of electrons ... of which the individual energy of motion is greater even than that of the alpha particle.”
[Ernest Rutherford, Royal Society, London, (as PRS) 30 Nov 1927]

1950s
Hoffstadter

First observation of finite proton size using 2 MeV e beam

Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.
Proposal:
“A general survey of the basic cross sections which will be useful for future proposals”
First Observation Of Proton Structure

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)

... and so on ...
Basic Deep Inelastic Scattering Processes

\[ Q^2 = -q^2 \] : resolving power of interaction

\[ x = \frac{Q^2}{2q.p} \] : fraction of struck quark / proton momentum
DESY, Hamburg

HERA (1992-2007)

... the only ever collider of electron beams with proton beams

Equivalent to a 50 TeV beam on a fixed target proton
~2500 times more than SLAC!

Around 500 pb\(^{-1}\) per experiment
Proton “Structure”?

Proton constituents ...
2 up and 1 down valence quarks ...
... and some gluons ...
... and some sea quarks ...
... and lots more gluons and sea quarks ...
→ strong interactions induce rich and complex ‘structure’ of high energy proton interactions!

Scattering electrons from protons at $\sqrt{s} > 300\text{GeV}$ at HERA established detailed proton structure & provided a testing ground for QCD over a huge kinematic range ...

... parton density functions
**HERA’s greatest legacy**

Proton parton densities in x range well matched to LHC rapidity plateau

*Some limitations:*
- Insufficient lumi for high x precision
- Lack of $Q^2$ lever-arm for low x gluon
- Assumptions on quark flavour decomposition
- No deuterons ...
- u and d not separated
- No heavy ions

- **H1/ZEUS publications still coming**
- Further progress requires higher energy and luminosity ...

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**H1 and ZEUS HERA I+II PDF Fit**

$Q^2 = 10 \text{ GeV}^2$

- HERAPDF1.5 NNLO (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.

**HERAPDF Structure Function Working Group March 2011**
Currently Approved Future of High Energy DIS
How Could ep be Done using LHC?

... whilst allowing simultaneous ep and pp running ...

- First considered (as LEPxLHC) in 1984 ECFA workshop
- Main advantages: high peak lumi, tunnelling (mostly) exists
- Main difficulties: building round existing LHC, e beam energy and lifetime limited by synchrotron radiation

- Previously considered as `QCD explorer’ (also THERA)
- Main advantages: low interference with LHC, high and stageable $E_e$, high lepton polarisation, LC relation?
- Main difficulties: obtaining high positron intensities, no previous experience exists
Baseline Design (Electron “Linac”) 

Design constraint: power < 100 MW → $E_e = 60$ GeV @ $10^{33}$ cm$^{-2}$ s$^{-1}$

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures
  [CERN plans energy recovery prototype]

- ep Lumi ~ $10^{33}$ cm$^{-2}$ s$^{-1}$ corresponds to ~10 fb$^{-1}$ per year (~ 100 fb$^{-1}$ total)
- eD and eA collisions have always been integral to programme
- e-nucleon Lumi estimates ~ $10^{31}$ ($10^{32}$) cm$^{-2}$ s$^{-1}$ for eD (ePb)

# Alternative designs based on electron ring and on higher energy, lower luminosity linac also exist
Civil Engineering Studies for Major Projects after LHC
## Design Parameter Summary

**RR** = Ring - Ring  
**LR** = Linac - Ring

<table>
<thead>
<tr>
<th>electron beam</th>
<th>RR</th>
<th>LR</th>
<th>LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>e- energy at IP[GeV]</td>
<td>60</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>luminosity $[10^{32} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>17</td>
<td>10</td>
<td>0.44</td>
</tr>
<tr>
<td>polarization [%]</td>
<td>40</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>bunch population $[10^9]$</td>
<td>26</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>e- bunch length [mm]</td>
<td>10</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>bunch interval [ns]</td>
<td>25</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>transv. emit. $\gamma\varepsilon_{x,y}$ [mm]</td>
<td>0.58, 0.29</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>rms IP beam size $\sigma_{x,y}$ [$\mu$m]</td>
<td>30, 16</td>
<td>7</td>
<td>7</td>
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<tr>
<td>e- IP beta funct. $\beta^*_{x,y}$ [m]</td>
<td>0.18, 0.10</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>full crossing angle [mrad]</td>
<td>0.93</td>
<td>0</td>
<td>0</td>
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<tr>
<td>geometric reduction $H_{hg}$</td>
<td>0.77</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>repetition rate [Hz]</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
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<td>beam pulse length [ms]</td>
<td>N/A</td>
<td>N/A</td>
<td>5</td>
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<tr>
<td>ER efficiency</td>
<td>N/A</td>
<td>94%</td>
<td>N/A</td>
</tr>
<tr>
<td>average current [mA]</td>
<td>131</td>
<td>6.6</td>
<td>5.4</td>
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<tr>
<td>tot. wall plug power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>proton beam</th>
<th>RR</th>
<th>LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch pop. $[10^{11}]$</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>tr.emit. $\gamma\varepsilon_{x,y}$ [$\mu$m]</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>spot size $\sigma_{x,y}$ [$\mu$m]</td>
<td>30, 16</td>
<td>7</td>
</tr>
<tr>
<td>$\beta^*_{x,y}$ [m]</td>
<td>1.8, 0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Include deuterons (new) and lead (exists)  
10 fb$^{-1}$ per year looks possible  
... ~ 100 fb$^{-1}$ total
Access to $Q^2=1$ GeV$^2$ in $ep$ mode for all $x > 5 \times 10^{-7}$ requires scattered electron acceptance to $179^\circ$.

Similarly, need $1^\circ$ acceptance in outgoing proton direction to contain hadrons at high $x$ (essential for good kinematic reconstruction).
Forward/backward asymmetry in energy deposited and thus in geometry and technology

Present dimensions: $L \times D = 14 \times 9 \, \text{m}^2$ [CMS $21 \times 15 \, \text{m}^2$, ATLAS $45 \times 25 \, \text{m}^2$]

Taggers at -62m (e),100m ($\gamma$ LR), -22.4m ($\gamma$ RR), +100m (n), +420m (p)
• Full angular coverage, long tracking region $\Rightarrow 1^\circ$ acceptance
• Several technologies under discussion
Liquid Argon EM Calorimeter [accordion geometry, inside coil]
Barrel: Pb, 20 $X_0$, 11m$^3$  
FEC: Si -W, 30 $X_0$  
BEC: Si -Pb, 25 $X$

Hadronic Tile Calorimeter [modular, outside coil: flux return]
A GEANT4 Simulated High $x$ Event
In the absence of a detailed simulation set-up, simulated `pseudo-data' produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

<table>
<thead>
<tr>
<th></th>
<th>LHeC</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (\text{cm}^{-2}\text{s}^{-1})</td>
<td>(10^{33})</td>
<td>(1-5\times10^{31})</td>
</tr>
<tr>
<td>Acceptance [°]</td>
<td>1-179</td>
<td>7-177</td>
</tr>
<tr>
<td>Tracking to</td>
<td>0.1 mrad</td>
<td>0.2-1 mrad</td>
</tr>
<tr>
<td>EM calorimetry to</td>
<td>0.1%</td>
<td>0.2-0.5%</td>
</tr>
<tr>
<td>Hadronic calorimetry</td>
<td>0.5%</td>
<td>1-2%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Measuring $\alpha_s$

- Least constrained fundamental coupling by far (known to ~1%)
- Do coupling constants unify (with a little help from SUSY)?
- (Why) is DIS result historically low?

- Simulated LHeC precision from fitting inclusive data

→ per-mille (experimental)
→ also requires improved theory
PDF Constraints at LHeC

Full simulation of inclusive NC and CC DIS data, including systematics $\rightarrow$ NLO DGLAP fit using HERA technology...

... impact at low $x$ (kinematic range) and high $x$ (luminosity)

... precise light quark vector, axial couplings, weak mixing angle

... full flavour decomposition
Cross Sections and Rates for Heavy Flavours

LHeC total cross sections (MC simulated)

<table>
<thead>
<tr>
<th>Process</th>
<th>HERA</th>
<th>Charm [10^{10} / 10 fb^{-1}]</th>
<th>Beauty [10^{8} / 10 fb^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>charm γp</td>
<td>[7.5 × 10^{20}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>charm DIS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>beauty γp</td>
<td>[10^{3}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>beauty DIS</td>
<td>[10^{4}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC e+p</td>
<td>[10^{2}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC e+p DIS</td>
<td>[10]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sW → c</td>
<td>[4.10^{5}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sW → cbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bW → t</td>
<td>[10^{5}]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttbar</td>
<td>[10^{3}]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

c.f. luminosity of ~10 fb^{-1} per year ...
Flavour Decomposition

Precision c, b measurements (modern Si trackers, beam spot 15 * 35 \( \mu \text{m}^2 \), increased HF rates at higher scales).

Systematics at 10% level

\[ \rightarrow \text{beauty is a low } x \text{ observable!} \]

\[ \rightarrow s, \overline{s} \text{ from charged current} \]

(Assumes 1 fb\(^{-1}\) and
- 50% beauty, 10% charm efficiency
- 1% uds \( \rightarrow c \) mistag probability.
- 10% c \( \rightarrow b \) mistag)
Current uncertainties due to PDFs for particles on LHC rapidity plateau (NLO):
- Most precise for quark initiated processes around EW scale
- Gluon initiated processes less well known
- All uncertainties explode for largest masses
Do we need to Care?

Ancient history (HERA, Tevatron)

- Apparent excess in large $E_T$ jets at Tevatron turned out to be explained by too low high $x$ gluon density in PDF sets

- Confirmation of (non-resonant) new physics near LHC kinematic limit relies on breakdown of factorisation between $ep$ and $pp$

Searches near LHC kinematic boundary may ultimately be limited by knowledge of PDFs (especially gluon as $x \to 1$)
Executive summary: nothing on scale of 1 TeV ... need to push sensitivity to higher masses (also non-SUSY searches)
e.g. High Mass Gluino Production

- Signature is excess @ large invariant mass
- Expected SM background (e.g. $gg \rightarrow gg$) poorly known for $s\text{-}hat > 1$ TeV.

- Both signal & background uncertainties driven by error on gluon density ... Essentially unknown for masses much beyond 2 TeV.

- Similar conclusions for other non-resonant LHC signals involving high $x$ partons (e.g. contact interactions signal in Drell-Yan)
PDF Uncertainties for Higgs Physics

Theory Cross Section Uncertainties
(125 GeV Higgs J Campbell, ICHEP’12)

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section (pb)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>$19.5$</td>
<td>$14.7$</td>
</tr>
<tr>
<td>VBF</td>
<td>$1.56$</td>
<td>$2.9$</td>
</tr>
<tr>
<td>WH</td>
<td>$0.70$</td>
<td>$3.9$</td>
</tr>
<tr>
<td>ZH</td>
<td>$0.39$</td>
<td>$5.1$</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$0.13$</td>
<td>$14.4$</td>
</tr>
</tbody>
</table>

Projected Experimental Uncertainties

$\sqrt{s} = 14$ TeV: $L dt = 300$ fb$^{-1}$; $L dt = 3000$ fb$^{-1}$

Similarly fermionic modes ($bb\bar{b}$, $cc\bar{c}$)

... tests of Standard Model in Higgs sector may become limited by knowledge of PDFs in HL-LHC era
ep Higgs Production at LHeC

Dominant charged current process probes product of $WW \rightarrow H$ and $H \rightarrow bb\bar{b}$ couplings

Clean separation from (smaller cross section) neutral current process $ZZ \rightarrow H$

Sensitive to anomalous couplings and (via azimuthal degree of freedom) anomalous CP structure
A First Higgs Study

2 b-tags in a simulated `generic LHC detector'
Backgrounds (b & light jets in NC, CC, Z→ bbbar single top) suppressed with cuts on jet multiplicity, b-tags, event kinematics, missing $p_t$

<table>
<thead>
<tr>
<th></th>
<th>$E_e = 150$ GeV (10 fb$^{-1}$)</th>
<th>$E_e = 60$ GeV (100 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H → bb$ signal</td>
<td>84.6</td>
<td>248</td>
</tr>
<tr>
<td>S/N</td>
<td>1.79</td>
<td>1.05</td>
</tr>
<tr>
<td>S/\sqrt{N}</td>
<td>12.3</td>
<td>16.1</td>
</tr>
</tbody>
</table>

$m_H = 120$ GeV, LHeC with 10fb$^{-1}$

90% lepton polarisation enhances signal by factor 1.9
→ ~500 events ... $H→bbbar$ coupling to a few %.
Direct Sensitivity to New Physics

• The (pp) LHC has much better discovery potential than LHeC (unless $E_e$ increases to $\sim 500$ GeV and Lumi to $10^{34}$ cm$^{-2}$ s$^{-1}$)

  e.g. Expected quark compositeness limits below $10^{-19}$ m at LHeC

  ... big improvement on HERA, but already beaten by LHC

• LHeC is competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states
Determining Leptoquark Quantum Numbers

Mass range of LQ sensitivity to ~ 2 TeV ... similar to LHC
Single production gives access to LQ quantum numbers:
- fermion number (below)
- spin (decay angular distributions)
- chiral couplings (beam lepton polarisation asymmetry)
A fundamental QCD problem is looming ... rise of low $x$ parton densities cannot continue

... High energy unitarity issues reminiscent of longitudinal WW scattering in electroweak physics:
- Somewhere & somehow, the low $x$ growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Parton level language $\rightarrow$ recombination $gg \rightarrow g$?

... new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? ...
... gluon dynamics $\rightarrow$ confinement and hadronic mass generation
**Strategy for making the target blacker**

LHeC delivers a 2-pronged approach:

Enhance target ‘blackness’ by:
1) Probing lower x at fixed $Q^2$ in ep
   [evolution of a single source]
2) Increasing target matter in eA
   [overlapping many sources at fixed kinematics ... density $\sim A^{1/3} \sim 6$ for Pb ... worth 2 orders of magnitude in x]
Establishing and Characterising Saturation

With 1 fb\(^{-1}\) (1 month at 10\(^{33}\) cm\(^{-2}\) s\(^{-1}\)), \(F_2\) stat. < 0.1%, syst, 1-3% \(F_L\) measurement to 8% with 1 year of varying \(E_e\) or \(E_p\)

• LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
• Unambiguous observation of saturation will be based on tension between different observables e.g. \(F_2\) v \(F_L\) in \(ep\) or \(F_2\) in \(ep\) v \(eA\)
Exclusive / Diffractive Channels and Saturation

1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?
Simulation of $J/\psi$ Photoproduction

e.g. “b-Sat” Dipole model
- “eikonalised”: with impact-parameter dependent saturation
- “1 Pomeron”: non-saturating

- Significant non-linear effects expected in LHeC kinematic range.

- Data shown are extrapolations of HERA power law fit for $E_e = 150$ GeV...
  $\Rightarrow$ Sat$^n$ smoking gun?
What is Initial State of LHC AA Collisions?

• Very limited x, Q^2 and A range for F_2^A so far (fixed target experiments covered x >~ 10^-2)

• LHeC extends kinematic range by 3-4 orders of magnitude with very large A

[and eA potentially provides control for AA QGP signatures]
**Current Knowledge: Nuclear Parton Densities**

Nuclear parton densities don’t scale with A (Fermi motion, shadowing corrections ...)

\[ R_i = \text{Nuclear PDF } i / (A^*\text{proton PDF } i) \]

Early LHC data (e.g. inclusive \(J/\Psi\)) suggest low \(x\) assumptions inadequate
Impact of eA F₂ LHeC data

- Simulated LHeC ePb F₂ measurement has huge impact on uncertainties
- Most striking effect for sea & gluons
- High x gluon uncertainty still large

[Example pseudo-data from single Q² Value]

[Effects on EPS09 nPDF fit]
Current mandate from CERN is to aim for TDR by ~ 2015.  
... requires detailed further study and prototyping of accelerator components (including CERN ERL LHeC test facility), but also an experimental collaboration to develop the detector concept.
Summary

- LHC is a totally new world of energy and luminosity, already making discoveries. LHeC proposal aims to exploit it for lepton-hadron scattering ...
  ... ep complementing LHC and next generation ee facility for full Terascale exploration

- ECFA/CERN/NuPECC workshop gathered many accelerator, theory & experimental colleagues

→ Conceptual Design Report published. Moving to TDR phase
→ Awaiting outcome of European strategy exercise
→ Build collaboration for detector development

[More at http://cern.ch/lhec]
... with thanks to many colleagues working on LHeC ...

http://cern.ch/lhec

LHeC Study Group

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