The LHeC as a Higgs Facility

Max Klein
U Liverpool and CERN
For the LHeC Study Group

ICHEP, Valencia, 3rd of July, 2014
The theory of DIS has developed much further: J.Blümlein Prog.Part.Nucl.Phys. 69(2013)28
DIS is an important part of particle physics: G.Altaarelli, 1303.2842, S.Forte, G.Watt 1301.6754
LHeC Study group and CDR authors (May 13)
60 GeV electron beam energy, $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, $\sqrt{s} = 1.3 \text{ TeV}$: $Q_{\text{max}}^2 = 10^6 \text{ GeV}^2$, $10^{-6} < x < 1$

Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, energy recovery)

Ring-ring as fall back. “SAPHIRE” 4 pass 80 GeV option to do mainly: $\gamma\gamma \rightarrow \text{H}$. CDR
### Accelerator Design: Participating Institutes

![Institute Logos](image)

### Source and Power [MW]

<table>
<thead>
<tr>
<th>Source</th>
<th>Power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenics (linac)</td>
<td>21</td>
</tr>
<tr>
<td>Linac grid power</td>
<td>24</td>
</tr>
<tr>
<td>SR compensation</td>
<td>23</td>
</tr>
<tr>
<td>Extra RF cryopower</td>
<td>2</td>
</tr>
<tr>
<td>Injector</td>
<td>6</td>
</tr>
<tr>
<td>Arc magnets</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>78</strong></td>
</tr>
</tbody>
</table>
**CERN: LHC+FCC: the only realistic opportunity for energy frontier deep inelastic scattering**

Huge step in energy \((Q^2, 1/x)\) and 2-3 orders of magnitude higher luminosity than HERA
2. Remarks on Higgs ep and pp Physics
Higgs Production at the LH(e)C

Higgs production in ep comes uniquely from either CC or NC

Cross section at LHeC ~200fb (about as at the ee colliders).

Pile-up in ep at $10^{34}$ is 0.1, 25ns

Clean(er) bb final state, S/B ~ 1

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

VBF cross section about 200fb (about as at the ep colliders).

Pile-up in ep at $5 \times 10^{34}$ is 150, 25ns

S/B very small for bb
$e^p \rightarrow vH(bb)X$  
charged currents  
$\sigma BR \sim 120$ fb  
$S/B \sim 1-2$ \rightarrow crucial for QCD of H  
Pile up 0.1  
1% coupling precision at 1 $ab^{-1}$

$pp \rightarrow X_1W(l\nu)H(bb)X_2$  
associated VH  
$\sigma BR \sim 130$ fb  
$S/B < \sim 0.01$  
$<\text{Pile up}> \sim 20$

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ep (new) Simulation 100 $fb^{-1}$  
Confirming CDR initial studies  
See Poster U. Klein Higgs in ep – this conference

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ATLAS Preliminary
$s = 7$ TeV $\int L dt = 4.7$ fb$^{-1}$
$s = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

0 lep., 2 jets, 2 tags, 160$<p_T<200$ GeV

pp 2013: Measurement
ATLAS CONF-2013-079
Rates of Higgs Production in $e^-p$

<table>
<thead>
<tr>
<th>Higgs in $e^-p$</th>
<th>CC - LHeC</th>
<th>NC - LHeC</th>
<th>CC - FHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.8</td>
</tr>
<tr>
<td>Luminosity [ab$^{-1}$]</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Cross Section [fb]</td>
<td>196</td>
<td>25</td>
<td>850</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay</th>
<th>BrFraction</th>
<th>$N^H_{CC}$</th>
<th>$N^H_{NC}$</th>
<th>$N^H_{CC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to b\bar{b}$</td>
<td>0.577</td>
<td>113 100</td>
<td>13 900</td>
<td>2 450 000</td>
</tr>
<tr>
<td>$H \to c\bar{c}$</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
<td>123 000</td>
</tr>
<tr>
<td>$H \to \tau^+\tau^-$</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
<td>270 000</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
<td>1 000</td>
</tr>
<tr>
<td>$H \to 4l$</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
<td>550</td>
</tr>
<tr>
<td>$H \to 2l2\nu$</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
<td>45 000</td>
</tr>
<tr>
<td>$H \to gg$</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
<td>365 000</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
<td>915 000</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
<td>110 000</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
<td>10 000</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>0.00154</td>
<td>300</td>
<td>40</td>
<td>6 500</td>
</tr>
</tbody>
</table>

Clean VV production and high S/B in reconstruction are base for unique further program as on CP Biswal et al, PRL109(12)261801 +differential measurements
There is a huge potential for Higgs physics in ep.

High rates for $b\bar{b}$ but also $WW,gg,\tau\tau,cc \rightarrow$ desire for maximum luminosity $O(10^{34})$ cm$^{-2}$s$^{-1}$
Note that $10^{33}$ is 100 times HERA (I) and a huge step more than adequate for DIS
Each of the channels requires dedicated simulation study, as has been done for $b\bar{b}$
Ahead is use of ep detector and its design optimisation for H and general fwd physics.
For the detector design – see poster ‘A New Detector for ep Scattering’ – this conference
Prospects for H at HL-LHC

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \]

- **H → μμ** (comb.)
  - Incl.
  - (ttH-like)
- **H → ττ** (VBF-like)
- **H → ZZ** (comb.)
  - (VH-like)
  - (ttH-like)
  - (VBF-like)
  - (ggF-like)
- **H → WW** (comb.)
  - (VBF-like)
  - (+1j)
  - (+0j)
- **H → Zγ** (incl.)
- **H → γγ** (comb.)
  - (VH-like)
  - (ttH-like)
  - (VBF-like)
  - (+1j)
  - (+0j)

\[ \Delta \mu / \mu \]

Prospects for signal strength measurements at the **LHC** and the **HL-LHC**

Dashed: Theoretical uncertainties from PDFs, strong coupling and scales

To make the LHC a precision Higgs factory, one needs: much better PDFs, much more precise \( \alpha_s \), all determined to a next order pQCD: \( N^3\text{LO} \)

The **LHeC** provides a unique data basis and theoretical framework for H physics in pp while \( N^3\text{LO} \) Higgs calculations have begun (Anastasio et al)

Note we do not know yet the bb prospect as it is notoriously difficult in pp, and there is no cc nor gg prospect for pp either.
Precision Parton Distributions from ep

**Why important:** qg dynamics determines the mass of the visible universe.
Low x: nonlinear evolution?, Medium x: Higgs  High x: d/u... Searches at HL-LHC – hi Mass

**Why ep:** Because it is the only way to measure/derive these and they will be needed for HL-LHC
For testing QCD: Factorisation, Resummation, N^3LO (Higgs), α_s – lattice, HF, intrinsic PDFs, ..

**Why LHeC:** the only base for fully unfolding PDFs, free of symmetry assumptions (need precision CC), bDF, tDF..
Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 → 10%).

LHeC: 0.0002!

Needs $N^3LO$

HQ treatment important ...
3. Recent Machine and Developments
## CDR Parameters - LHeC

<table>
<thead>
<tr>
<th>10^{33} \text{ cm}^{-2} \text{ s}^{-1} \text{ Luminosity reach}</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [10^{33} \text{ cm}^{-2} \text{ s}^{-1}]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \varepsilon_{x,y} [\mu m]$</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Beta Function $\beta^*_{x,y} [m]$</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>rms Beam size $\sigma^*_{x,y} [\mu m]$</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma'_{x,y} [\mu \text{rad}]$</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>430 (860)</td>
<td>6.6</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25 (50)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>1.7*10^{11}</td>
<td>(1<em>10^9) 2</em>10^9</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>27</td>
<td>(0.16) 0.32</td>
</tr>
</tbody>
</table>

“Ultimate” proton beam parameters

100 times HERA Luminosity and 4 times cms Energy
## Advanced Luminosity Parameters*) - LHeC

<table>
<thead>
<tr>
<th>10^{34} cm^{-2} s^{-1} Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [10^{33} cm^{-2}s^{-1}]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Normalized emittance γε_{x,y} [μm]</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Beta Function β_{x,y} [m]</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>rms Beam size σ_{x,y} [μm]</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>rms Beam divergence σ'_{x,y} [μrad]</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>1112</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>2.2*10^{11}</td>
<td>4*10^9</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*) under study now

HL-LHC proton beam parameters

1000 times HERA Luminosity and 4 times cms Energy
Areas of Study Post-CDR *)

More realistic with dedicated tools and evaluation of high luminosity prospect

Choice of RF Frequency – 802 MHz
Optimisation of IR Design \([L^*(e) < L^*(p), \text{inner triplet half? quad…}]\)
Integration of p optics into HL-LHC
Integration of e optics into HL-LHC
Beam-beam effects (phase space deformation)
Multi-bunch beam break up
Wakefield effects on multi-bunch instability at IP
Emittance growth
Coherent synchrotron radiation
Fast beam-ion instability (1/3 gap compensated by 1.3 from pinch effect)
Arc optics  FODO vs FMC (flexible momentum compaction)
Lattice design
Spreader and combiner
Civil engineering
...

So far no showstopper found for \(O(10^{34})\text{cm}^{-2}\text{s}^{-1}\): it requires further serious study and the development of SCRF within a Testfacility

*) Recent presentations by A.Bogacz, O.Bruening, E.Cruz, E.Jensen, D.Schulte, A.Valloni – see Webpage
Work by E.Cruz, M.Korostelev, E.Nissen, J.Osborne, D.Pellegrini, A.Letina, A.Milanese, A.Valloni and others
Optics Design Study

- High luminosity Linac-Ring option – ERL
  - RF power nearly independent of beam current.
- Multi-pass linac Optics in ER mode
  - Choice of linac RF and Optics – 802 MHz SRF and 130° FODO
  - Linear lattice: 3-pass ‘up’ + 3-pass ‘down’
- Arc Optics Choice – Emittance preserving lattices
  - Quasi-isochronous lattices
  - Flexible Momentum Compaction Optics
  - Balanced emittance dilution & momentum compaction
- Complete Arc Architecture
  - Vertical switchyard
  - Matching sections & path-length correcting ‘doglegs’
- Alternative ERL Topology – ‘Dogbone’ Option?
Switchyards

- Two-step-achromat spreaders and mirror symmetric recombiners
- Arcs are separated into 1m high vertical stack
- Very compact switchyard system (~20 m long)
- Horizontal doglegs used for path-length adjustment

A. Bogacz, A. Milanese, A. Valloni
Phase Space Deformation from Beam Beam

Hypersphere phase space is significantly deformed by beam-beam interactions. In the case of the high luminosity configuration, the $(5\sigma)$ tails are folded back.
John Osborne
Tentative
6/14
Goals of a CERN ERL-Test Facility

- Main goal: **Study real SRF Cavities with beam** – not interfering with HEP!
    - All problems will not be experienced until the complete subsystem is tested under realistic conditions. Be prepared to test, with full rf power systems and beam, all of the pre-production prototypes.

- In addition, it would allow to study **beam dynamics & operational aspects** of the advanced concept ERL (recovery of otherwise wasted beam energy)!
- Exploration of the ERL concept with multiple re-circulations and high beam current operation
- Additional goals:
  - Gun and injector studies
  - Test beams for detector R&D,
  - Beam induced quench test of SC magnets
  - ... later possibly user facility: $e^+e^-$ test beams, CW FEL, Compton $\gamma$-ray source ...
- At the same time, it will be fostering international collaboration (JGU Mainz and TJNAF collaborations being formalized)
A.Hutton, B. Rimmer, E.Jensen et al.  
MoU between CERN and Jlab - signed

Frequency 802 MHz  
Design and built of 2 Modules (CERN+Jlab+?)  
Tentative Design of the LTFC – end of 2014:

Collaborations being established on  
Source, Magnets, Operation, Applications

A. Bogazc, A.Valloni et al. presented at IPAC14 at Dresden by Erk Jensen
Testfacility Design

Arc 3 optics

455 MeV

$\beta_x$ $\beta_y$

Disp_x Disp_y

2-step vert. Spreader

8×22.5° sector bends

2-step vert. Combiner

Arc dipoles:
Ldip = 90.58 cm
B = 6.58 kGauss
$\rho = 230.66$ cm

also: multi-pass linac optics
New LHeC International Advisory Committee

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

*) IAC Composition June 2014, and
Oliver Brüning  Max Klein ex officio

The IAC was invited in 12/13 by the DG with the following

Mandate 2014-2017

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.
My clarifying remark:

Any ep/eA project cannot be a major CERN flagship project. Essentially only one experiment cannot satisfy > 8000 users.

not in competition with main projects (HL-LHC, HE-LHC, CLIC, FCC)
complementary (in time, resources)

International collaboration will be essential
- for experiments (detectors, intersections)
- accelerator design (parameters, optimisation)
- preparing necessary technology (SC rf cavities, possibly ERL test facility)

As in the tradition of CERN

Truth is stranger than fiction, but it is because fiction is obliged to stick to possibilities
Mark Twain, cited by Stan Brodsky at Chavannes
Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)
lepton - hadron colliders (LHeC ??)
lepton - lepton colliders (LC (ILC or CLIC) ?)
Outlook and Summary

Following the publication of the CDR and the Higgs boson discovery, there has been a renewed interest in the LHeC, because of the interest in genuine DIS and also for

*Higgs, LHC Upgrade and Use, High Gradient Cavity and the Energy Frontier*

CERN has called for a new phase of the LHeC development and its consideration in the FCC [hh,he,ee] context by appointing a new advisory committee and a coordination group.

The next important steps regard

**Physics:** H, t, BSM, low x, eA, PDF studies especially with regard to the HL LHC

**Detector:** Simulation and optimised design for H and forward physics

**Accelerator:** Study of the prospects and consequences for high luminosity ep

**SCRF:** Development of two cavity-cryo modules with 802 MHz

**Testfacility:** Design and collaboration (tentative by 14 and CDR by 15)

This is indeed a continuation and ‘A New Beginning’ H.Schopper, MK Ccourier 6/14

The ERL electron beam is a very economic option to realise ep (and eA) with FCC (see presentation tomorrow)
backup
Pre-mounting at the surface of a modular detector – independent of LHC
Lowering (7), Installation (2), Connection (6), Field Map (1), Pipe (1) ... min of 15 Month
which would be compliant with LS3 and may be with LS4 – depends on the LHC
NNLO - PDF Uncertainties vs Mass in Drell-Yan

The mass of the visible universe is provided by the gluon selfinteraction and the gg interaction dominates the production of the Higgs boson in pp interactions.
Determination of the Gluon Density at Large x

High(er) precision at $x \sim 0.01$ for Higgs and independent accurate PDF input at $x > 0.4$ for searches at HL-LHC.

MK, V. Radescu, LHeC Note 2013-002 and Workshop on LHeC, Chavannes, January 14
Strong Coupling Constant

$\alpha_s$ least known of coupling constants
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average (?)

LHeC: per mille - independent of BCDMS.

Challenge to experiment and to h.o. QCD $\rightarrow$
A genuine DIS research programme rather than one outstanding measurement only.

<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>$Q^2 &gt; 2.0$</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>$Q^2 &gt; 10.0$</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Two independent QCD analyses using LHeC+HERA/BCDMS
Determination of the Gluon Density at Small $x$

Small $x$ is related to large $x$ in DY production

\[ x = \frac{M}{\sqrt{s}} \exp(\pm y) = 0.009 \ldots 0.015 \ (8 \ldots 13 \text{ TeV}) \]

HERA constraints end at $x \sim 10^{-3}$ in DIS region

DGLAP may break at small $x$ and the conventional gluon determinations, linking also low and large $x$, will then be inadequate.

The LHeC is the only configuration where this can be tested with enough confidence.

Measure $dF_2/d\ln Q^2$ and $F_L$ precisely!

MK, V.Radescu, LHeC Note 2013-002 and Workshop on LHeC, Chavannes, January 14
Possible QCD Developments and Discoveries

AdS/CFT
Instantons
Odderon
Non pQCD
QGP
$N^k\text{LO}$
Resummation
Saturation and BFKL
Non-conventional PDFs ...

Breaking of Factorisation
Free Quarks
Unconfined Color
New kind of coloured matter
Quark substructure
New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background.