The LHeC as a Higgs Facility

Max Klein
U Liverpool and CERN
For the LHeC Study Group

ICHEP, Valencia, 3\textsuperscript{rd} of July, 2014

http://lhec.web.cern.ch
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.Altarelli, 1303.2842, S.Forte, G.Watt 1301:6754
LHeC Study group and CDR authors (May 13)
60 GeV electron beam energy, \(L = 10^{33} \text{ cm}^{-2} \text{s}^{-1}\), \(\sqrt{s}=1.3\) TeV: \(Q^2_{\text{max}} = 10^6 \text{ GeV}^2\), \(10^{-6} < x < 1\)
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

<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 \( \sim 200 \text{fb} \) (about as at the ee colliders).

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

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

Higgs production in pp comes predominantly from \( gg \to H \)

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
$ep \rightarrow vH(bb)X$
charged currents
$\sigma BR \sim 120 \text{ fb}$
$S/B \sim 1-2 \rightarrow$ crucial for QCD of $H$
Pile up 0.1

1% coupling precision at 1 ab$^{-1}$

$pp \rightarrow X_1 W(lv)H(bb)X_2$
associated VH
$\sigma BR \sim 130 \text{ fb}$
$S/B \sim 0.01$
$<\text{Pile up}> \sim 20$

**ATLAS Preliminary**

$\sqrt{s} = 7 \text{ TeV} \int \text{Ldt} = 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV} \int \text{Ldt} = 20.3 \text{ fb}^{-1}$

0 lep., 2 jets, 2 tags, $160<p_T<200 \text{ GeV}$

**H → bbar**

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

**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>
<tr>
<td>Decay</td>
<td>BrFraction</td>
<td>N_H^{CC}</td>
<td>N_H^{NC}</td>
</tr>
<tr>
<td>H → b\bar{b}</td>
<td>0.577</td>
<td>113 100</td>
<td>13 900</td>
</tr>
<tr>
<td>H → c\bar{c}</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
</tr>
<tr>
<td>H → τ⁺τ⁻</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
</tr>
<tr>
<td>H → μμ</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>H → 4l</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>H → 2l2ν</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
</tr>
<tr>
<td>H → gg</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
</tr>
<tr>
<td>H → WW</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
</tr>
<tr>
<td>H → ZZ</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
</tr>
<tr>
<td>H → γγ</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
</tr>
<tr>
<td>H → Zγ</td>
<td>0.00154</td>
<td>300</td>
<td>40</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 bb but also WW,gg,ττ,cc → desire for maximum luminosity O(10³⁴) cm⁻²s⁻¹

Note that 10³³ 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 bb

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

<table>
<thead>
<tr>
<th>( H \rightarrow \mu \mu )</th>
<th>(comb.)</th>
<th>(incl.)</th>
<th>(ttH-like)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \tau \tau ) (VBF-like)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow ZZ ) (comb.)</td>
<td>(VH-like)</td>
<td>(ttH-like)</td>
<td>(VBF-like)</td>
</tr>
<tr>
<td>( H \rightarrow WW ) (comb.)</td>
<td>(VBF-like)</td>
<td>(+1j)</td>
<td>(+0j)</td>
</tr>
<tr>
<td>( H \rightarrow Z \gamma ) (incl.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \gamma \gamma ) (comb.)</td>
<td>(VH-like)</td>
<td>(ttH-like)</td>
<td>(VBF-like)</td>
</tr>
</tbody>
</table>

\( \Delta \mu / \mu \) vs. \( \mu \)

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: \( N^3LO \)

The LHeC provides a unique data basis and theoretical framework for \( H \) physics in pp while \( N^3LO \) 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.

ATLAS-PHYS-PUB-2013-014 (10/13) - see also CMS prospects with two assumptions on theory uncertainties
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), \( \alpha_s \) – 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></th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$10^{33}$ cm$^{-2}$ s$^{-1}$ Luminosity reach</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity [$10^{33}$ cm$^{-2}$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 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>$1.7\times10^{11}$</td>
<td>$(1\times10^{9})$ $2\times10^{9}$</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} \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>16</td>
<td>16</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \varepsilon_{x,y} [\mu\text{m}]$</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Beta Function $\beta^*_{x,y} [\text{m}]$</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>rms Beam size $\sigma^*_{x,y} [\mu\text{m}]$</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma'_{x,y} [\mu\text{rad}]$</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>$2.2\times10^{11}$</td>
<td>$4\times10^9$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*) under study now

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) \), 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
Hypersphere phase space is significantly deformed by beam-beam interactions. In the case of the high luminosity configuration, the (5σ) tails are folded back.
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^+ - 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)
SCRF and LTFC
superconducting RF and ERL Test Facility at CERN

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. Hutton, B. Rimmer, E. Jensen et al.
MoU between CERN and Jlab - signed

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

Arc 3 optics

455 MeV

\[ \beta_x, \beta_y, \text{Disp}_x, \text{Disp}_y \]

2-step vert. Spreader
8×22.5° sector bends
2-step vert. Combiner

Arc dipoles:
\[ L_{\text{dip}} = 90.58 \text{ cm} \]
\[ B = 6.58 \text{ kGauss} \]
\[ \rho = 230.66 \text{ cm} \]

9.8° bends
(1 rec. + 3 sec.)

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)

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.

*) IAC Composition June 2014, and Oliver Brüning Max Klein ex officio
Workshop at Chavannes 20/21.1.2014

Herwig Schopper (Chair IAC) at Chavannes in the Panel Discussion with the CERN Directorate

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
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 Courier 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.

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

<table>
<thead>
<tr>
<th>AdS/CFT</th>
<th>Breaking of Factorisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantons</td>
<td>Free Quarks</td>
</tr>
<tr>
<td>Odderons</td>
<td>Unconfined Color</td>
</tr>
<tr>
<td>Non pQCD</td>
<td>New kind of coloured matter</td>
</tr>
<tr>
<td>QGP</td>
<td>Quark substructure</td>
</tr>
<tr>
<td>$N^k$LO</td>
<td>New symmetry embedding QCD</td>
</tr>
<tr>
<td>Resummation</td>
<td></td>
</tr>
<tr>
<td>Saturation and BFKL</td>
<td></td>
</tr>
<tr>
<td>Non-conventional PDFs ...</td>
<td>QCD may break .. (Quigg DIS13)</td>
</tr>
</tbody>
</table>

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.