Future High Energy Electron-Hadron scattering: LHeC and FCC-he projects

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http://lhec.web.cern.ch/

- Physics prospects
- Detector and machine considerations
- Outlook

Aspen Center of Physics, January 31st 2015
Deep inelastic electron-proton collider

HERA Hamburg 1992-2007

**HERA Luminosity 2002 - 2007**

- **e (27.5 GeV)**
- **P (920 GeV)**

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

Around 500 pb⁻¹ per experiment
HERA established detailed proton structure: parton density functions.

Increasing role of gluons at small $x$. Proton structure is highly complex due to the QCD radiation (evolution).

Other results: measurement of coupling constant, jets, photon structure, diffractive processes (in about 10% events), charm and bottom structure functions, PDFs essential for interpreting Tevatron and LHC results, limits for new physics (leptoquarks).
Lepton-hadron facilities: luminosity vs energy

China
CEIC1 = Electron-Ion Collider
(“A dilution-free mini-COMPASS”)

U.S.
MEIC1 = EIC@Jlab

Europe
LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

future extensions

http://cerncourier.com/cws/article/cern/57304
Conceptual Design Report for LHeC

LHeC Study Group


193 authors
631 pages
947 references
5 chapters
14 sections
International Advisory Committee + Mandate

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, plus Oliver Brüning Max Klein ex officio

Max Klein ICFA Beijing 10/2014
New domain for ep colliders

HERA established the validity of pQCD (DGLAP) due to a very high lever arm in $Q^2$.

Extensions of both $x$ and $Q^2$ ranges are crucial for new experiments and HEP theory developments!
Physics possibilities at LHeC and FCC-he

Beyond Standard Model

- Leptoquarks
- Contact Interactions
- Excited Fermions
- Higgs in MSSM
- Heavy Leptons
- 4th generation quarks
- Z'
- SUSY
- ???

QCD and EW precision physics

- Structure functions
- Quark distributions from direct measurements
- Strong coupling constant to high accuracy
- Higgs in SM
- Gluon distribution in extended x range to unprecedented accuracy
- Single top and anti-top production
- Electroweak couplings
- Heavy quark fragmentation functions
- Heavy flavor production with high accuracy
- Jets and QCD in photoproduction
- Partonic structure of the photon

Small x and high parton densities

- New regime at low x
- Saturation
- Diffraction
- Vector Mesons
- Deeply Virtual Compton Scattering
- Forward jets and parton dynamics
- DIS on nuclei
- Generalized/unintegrated parton distribution functions
Current PDF Uncertainties at LHC

LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.118$

- NNPDF2.3 NNLO
- CT10 NNLO
- MSTW2008 NNLO

LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.118$

- NNPDF2.3 NNLO
- ABM11 NNLO
- HERAPDF1.5 NNLO

[R. Ball et al., JHEP 1304 (2013) 125]
Mapping the Gluon Distribution

QCD fit analysis (default: NC, CC, LHeC only, following HERAPDF) with full experimental errors

The gluon is unknown at low $x$ and high $x$ – QCD: non-linear evolution, resummation. BSM: hi $M$ – HL-LHC!
Flavor decomposition at the LHeC

- Beauty as a small $x$ observable
- Precision strange measurement through charm tagging in CC interactions

![Graph showing anti-strange density vs $Q^2$ for LHeC e$^-$p scattering with charm tagging.]

- High lumi
- High $Q$
- Charm tagging efficiency 10%
- Closed points acceptance to 10 degrees
- Open points acceptance to 1 degree
**Precision PDFs for Higgs in pp**

**NNLO pp–Higgs Cross Sections at 14 TeV**

- Precision pdfs from LHeC
- Uncertainty can be reduced to 0.25%.
- Leads to Higgs mass sensitivity
- Similar conclusions can be reached for FCC-hh and FCC-he
- Will need NNNLO calculations

\[ \alpha_s = \text{underlying parameter relevant for uncertainty (0.005 \rightarrow 10\%)} \]

@ LHeC: measure to permille accuracy (0.0002)
Gluino pair production at the LHC

- Signal is the excess at large invariant mass.
- But large gluon pdf uncertainties dominate the total uncertainty for both signal and background.
- Unknown for masses beyond 2 TeV.

High precision for this process from pdfs constrained by LHeC

Precision PDFs can only be obtained by the measurements in ep machine like LHeC and FCC-he
SM Higgs in $e p$

$E_e = 60$ GeV

$E_e = 120$ GeV

**LHeC** / **FCC-he**: Sizeable charged current DIS unpolarised $e p$ cross sections

Uta Klein, Future $e p / e A$ Colliders
Study of $H \rightarrow b\bar{b}$ at LHeC

$\mathcal{L} = 100 \text{ fb}^{-1}$

Signal to background ratio is about 1.2

With 10 times more data, 1% precision on the $H bb$ coupling

Ongoing studies on the $H \rightarrow c\bar{c}$ simulation
Higgs production at the LHeC and FCC-he

Event rates for 1ab\(^{-1}\). Note the LHeC WW-H cross section is as large as the Z* → ZH cross section at the ILC or FCC- or CEPC, but it is much larger at the FCC-he

<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(<em>H</em>{CC})</th>
<th>N(<em>H</em>{NC})</th>
<th>N(<em>H</em>{CC})</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → 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 → c(\bar{c})</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
<td>123 000</td>
</tr>
<tr>
<td>H → τ(^+)τ(^-)</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
<td>270 000</td>
</tr>
<tr>
<td>H → μμ</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
<td>1 000</td>
</tr>
<tr>
<td>H → 4l</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
<td>550</td>
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<tr>
<td>H → 2l2ν</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
<td>45 000</td>
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<tr>
<td>H → gg</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
<td>365 000</td>
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<tr>
<td>H → WW</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
<td>915 000</td>
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<tr>
<td>H → ZZ</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
<td>110 000</td>
</tr>
<tr>
<td>H → γγ</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
<td>10 000</td>
</tr>
<tr>
<td>H → Zγ</td>
<td>0.00154</td>
<td>300</td>
<td>40</td>
<td>6 500</td>
</tr>
</tbody>
</table>

Cross section at FCC-he
1pb ep → vHX

Luminosity O(10\(^{34}\)) is crucial for H → HH [0.5 fb] and rare H decays
Precision measurement of strong coupling constant

- Strong coupling is least known of all couplings
- Grand unification predictions suffer from uncertainty
- DIS tends to be lower than the world average

LHeC promises per mille accuracy on alphas!

- Previously (HERA, fixed target) limited by uncertainty of low x, which LHeC can cure;
- full exploitation of this requires pQCD at NNNLO;
- LHeC can provide a new level of predicting grand unification
At small $x$ the linear evolution gives strongly rising gluon density.

Parton evolution needs to be modified to include potentially very large logs, resummation of $\log(1/x)$.

Further increase in the energy could lead to the importance of the recombination effects.

Modification of parton evolution by including non-linear or saturation effects in the parton density.

The boundary between the two regimes needs to be determined experimentally.

Unique feature of the LHeC & FCC-he: can access the dense regime at fixed, semihard scales $Q$, while decreasing $x$. 
Small $x$ and vector mesons

Precision measurement of the elastic diffraction of vector mesons: sensitive to saturation effects. FCC-he extends the kinematic reach up to 4TeV.

More differential measurements can help to map the gluon density in the proton. Shifts in the dips of $t$-distribution, as a signal for parton saturation.
LHeC and FCC-he as an electron-ion collider

Nuclear structure below \(x = 0.01\) is completely unknown.

LHeC and FCC-he will extend the kinematic range by 4-5 orders of magnitude.

Electron-ion collisions are the best precision tools to study partonic structure of cold nuclear matter. Important for initial state for heavy ion collisions.

Pin-down the nuclear effects on the propagation of partons through the nuclear matter.

High parton density enhanced by low \(x\) and nuclear effects.

\[
Q_{sA}^2 \sim A^{1/3} Q_{sp}^2 \sim x^{-\lambda} A^{1/3}
\]
constraints on nuclear PDFs

Nuclear ratio:

\[ R_f^A(x, Q^2) = \frac{f^A(x, Q^2)}{A \times f^N(x, Q^2)} \]

Effects in nPDFs, LHeC

- Huge reduction of the uncertainties after including LHeC pseudodata, particularly for sea and gluon.
- Adding charged current interaction may help to perform the flavor separation.
Energy Recovery Linac (3 pass)

![Diagram of Energy Recovery Linac (3 pass)](image)

Figure 1: Schematic view on the LHeC racetrack configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the collision point with three passes through the opposite linear structures of 60 cavity-cryo modules each. The arc radius is about 1 km, mainly determined by the synchrotron radiation loss of the 60 GeV beam which is returned from the IP and decelerated for recovering the beam power. Comprehensive design studies of the lattice, optics, beam (beam) dynamics, dump, IR and return arc magnets, as well as auxiliary systems such as RF, cryogenics or spin rotators are contained in the CDR [1], which as for physics and detector had been reviewed by 24 referees appointed by CERN.

Ring-Ring option as fall back;
Civil Engineering Footprint

<table>
<thead>
<tr>
<th>LHeC construction planning</th>
<th>YEAR 1</th>
<th>YEAR 2</th>
<th>YEAR 3</th>
<th>YEAR 4</th>
<th>YEAR 5</th>
<th>YEAR 6</th>
<th>YEAR 7</th>
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<tbody>
<tr>
<td>Land negotiations</td>
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<td>Environmental Impact Study</td>
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<td></td>
<td>7 years for 9km</td>
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<tr>
<td>Building permits</td>
<td></td>
<td></td>
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<tr>
<td>Detailed design &amp; tendering</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Civil Engineering

Contributions to cost

- Tunnel
- Linac
- Magnets

MK 6/14

LHeC
Civil Engineering
Different Options
Fraction 1/3-1/4-1/5
Pt2 and Pt8

Max Klein ICFA Beijing 10/2014
Superconducting RF and ERL Test Facility Design at CERN

Frequency 802 MHz
Design and built of 2 Modules (CERN+Jlab+)

Conceptual Design of the LTFC – end of 2015:
SCRF under beam conditions, applications,
high quality, high current, multipass, ERL

Interest for participation expressed by
BINP, BNL, CORNELL, IHEP BJ, JLAB .

Max Klein ICFA Beijing 10/2014

A. Bogazc, A. Valloni, A. Milanese et al.
Figure 13.52: Acceptance for $J/\psi$ with $E_e = 50$ GeV as a function of $W$, the center of mass energy of the $p$ system. A detector with larger coverage both in the forward and in the rear region allows for measurements on a much wider $W$ range.

Figure 13.53: A full view of the baseline detector in the r-z plane with all components shown. The detector dimensions are $14$ m in $z$ with a diameter of $9$ m.

Forward/backward asymmetry in energy deposited and thus in geometry and technology

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

Taggers at $-62$m (e), $100$m ($\gamma$,LR), $-22.4$m ($\gamma$,RR), $+100$m (n), $+420$m (p)
First study of detector for FCC-he

Detector for FCC scales by about \( \ln(50/7) \sim 2 \) in fwd, and \( \sim 1.3 \) in bwd direction. 1000 H \( \rightarrow \) \( \mu \mu \) may call for better muon momentum measurement.
## FCC-he parameters

<table>
<thead>
<tr>
<th>collider parameters</th>
<th>FCC ERL</th>
<th>FCC-ee ring</th>
<th>protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>$e^- (e^+?)$</td>
<td>$e^\pm$</td>
<td>$e^\pm$</td>
</tr>
<tr>
<td>beam energy [GeV]</td>
<td>60</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>bunches / beam</td>
<td>-</td>
<td>10600</td>
<td>1360</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>0.05</td>
<td>0.94</td>
<td>0.46</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>25.6</td>
<td>480</td>
<td>30</td>
</tr>
<tr>
<td>rms bunch length [cm]</td>
<td>0.02</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>rms emittance [nm]</td>
<td>0.17</td>
<td>1.9 (x)</td>
<td>0.94 (x)</td>
</tr>
<tr>
<td>$\beta_{x,y}$ [mm]</td>
<td>94</td>
<td>8, 4</td>
<td>17, 8.5</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ [\mu m]</td>
<td>4.0</td>
<td>4.0, 2.0</td>
<td>equal</td>
</tr>
<tr>
<td>beam-b. parameter $\xi$</td>
<td>(D=2)</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>hourglass reduction</td>
<td>0.92</td>
<td>~0.21</td>
<td>~0.39</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>3.5</td>
<td>3.5</td>
<td>4.9</td>
</tr>
<tr>
<td>luminosity[10^{34}cm^{-2}s^{-1}]</td>
<td><strong>1.0</strong></td>
<td><strong>6.2</strong></td>
<td><strong>0.7</strong></td>
</tr>
</tbody>
</table>

F.Zimmermann
ICHEP14, June
PRELIMINARY
L is 1000*HERA
Summary and outlook I

• Thorough understanding of the particle physics can only proceed through variety of HEP experiments with different energies and probes. Therefore it is essential to perform and study complementary $e^+e^-/pp/e^\pm p$ collisions.

• LHeC and FCC-he projects have an unprecedented potential as a high luminosity, high energy DIS machines. Precision DIS measurements: constraining and unfolding PDFs, heavy flavor physics, precision strong coupling, precision electroweak measurements. Higgs properties. Offering a unique window for small x physics and high parton density regime.

• FCC-he project with new energy frontier can address big questions: structure of visible matter, lepton-quark symmetries and BSM physics.

• $eA$ at high energy essential to untangle the complex nuclear structure at low x and constrain the initial conditions for AA at the LHC. Complementary to $pp/pA/AA$.

• CDR for the LHeC project is complete: arXiv:1206.2913
Summary and outlook II

• New International Advisory Committee and Coordination Group set up by CERN with mandate to further develop LHeC and study prospects at FCC.

• Prospect of higher luminosity at LHeC/FCC-eh $\mathcal{O}(10^{34})$ cm$^{-2}$ s$^{-1}$ calls for reevaluation of the physics possibilities.

• In particular, following Higgs discovery, there is an ongoing effort to study the potential for Higgs precision physics in high luminosity ep machines.

• Physics studies for FCC-he machine, especially the BSM possibilities.

• CDR for the ERL test facility, end of 2015.

More information on both projects can be found:

http://lhec.web.cern.ch/
Klein & Schopper, CERN Courier, June 2014
Bruening & Klein, Mod Phys Lett A28 (2013) 1130011