LHeC status and plans

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for the LHeC Study Group

http://cern.ch/lhec
Contents:

1. Introduction.

2. Accelerator.

3. Detector.

4. Physics case (some highlights):
   - Precision QCD.
   - Top and EW.
   - Higgs.
   - BSM.
   - Small $x$ and $eA$.

5. Organisation and plans.

CDR:1206.2913; 1211.4831; 1211.5102; Brüning & Klein,1305.2090;
Klein & Schöpper, CERN Courier, June 2014;
2015 LHeC Workshop http://indico.cern.ch/event/356714/.

N.Armesto, 09.01.2016. - LHeC status and plans.
Legacy from HERA:

- Structure functions in an extended $x$-$Q^2$ range, $xg \propto 1/x^\lambda$, $\lambda > 0$: PDFs for the LHC.
- Large fraction of diffraction $\sigma_{\text{diff}}/\sigma_{\text{tot}} \sim 10\%$.
- But: $eA/eD$, kinematical reach at small $x$, luminosity for high $x$ /for searches (odderon,...), flavour decomposition, GPDs,...
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DIS at the LHC:

- 2006: proposal of the Large Hadron Electron Collider (hep-ex/0603016), taken in 2007 by CERN, ECFA and NuPECC.

- Study group formed in 2008, series of regular workshops.

Guido Altarelli (1941-2015)
The LHeC:

- **LHeC@CERN** → ep/eA experiment using p/A from the LHC: \(E_p=7 \text{ TeV}, E_{Pb}=2.75 \text{ TeV/nucleon},\) and possibly from the FCC (FCC-he): \(E_p=50 \text{ TeV}, E_{Pb}=19.7 \text{ TeV/nucleon}.

- New e\(^+\)/e\(^-\) accelerator: \(E_{cm}\sim 1-2 \ (3-5) \text{ TeV} \ (E_e=50-150 \text{ GeV}).\)

- **Requirements:**
  * Luminosity \(\sim 1-10\times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\).
  * Acceptance: 1-179 degrees (low-x ep/eA, \(Q^2\sim 1 \text{ GeV}^2,\) nominal energy).
  * Tracking to 0.1 mrad.
  * EMCAL calibration to 0.1 %.
  * HCAL calibration to 0.5 %.
  * Luminosity determination to 1 %.
  * Total wall plug power < 100 MW.
  * Compatible with synchronous LHC operation.

The LHeC:

- **LHeC@CERN** → ep/eA experiment using p/A from the LHC: \( E_p = 7 \) TeV, \( E_{Pb} = 2.75 \) TeV/nucleon, and possibly from the FCC (FCC-he): \( E_p = 50 \) TeV, \( E_{Pb} = 19.7 \) TeV/nucleon.
- New \( e^+ / e^- \) accelerator: \( E_{cm} \sim 1-2 \) (3-5) TeV (\( E_e = 50-150 \) GeV).

**Requirements**:

- Luminosity: \( \sim 1-10 \times 10^{33} \) cm\(^{-2}\)s\(^{-1}\).
- Acceptance: 1-179 degrees (low-x ep/eA, \( Q^2 \sim 1 \) GeV\(^2\), nominal energy).
- Tracking to 0.1 mrad.
- EMCAL calibration to 0.1%.
- HCAL calibration to 0.5%.
- Luminosity determination to 1%.
- Total wall plug power < 100 MW.
- Compatible with synchronous LHC operation.

**Erkenntnisse**:

<table>
<thead>
<tr>
<th>Requirements</th>
<th>LHeC</th>
<th>HERA</th>
<th>How?</th>
</tr>
</thead>
<tbody>
<tr>
<td>high lumi for high x and ( Q^2 )</td>
<td>1-10 \times 10^{33}</td>
<td>1-5 \times 10^{31}</td>
<td>ER technique</td>
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<td>large acceptance</td>
<td>1-179 deg.</td>
<td>7-177 deg.</td>
<td>kinematic coverage</td>
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<td>tracking</td>
<td>0.1 mrad</td>
<td>0.2-1 mrad</td>
<td>modern Si</td>
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<tr>
<td>EMcal</td>
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<tr>
<td>Hcal</td>
<td>0.5 %</td>
<td>1 %</td>
<td>tracking + calo e/h</td>
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<tr>
<td>accurate lumi/pol</td>
<td>0.5 %</td>
<td>1 %</td>
<td>demanding</td>
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</table>

The LHeC:

- **LHeC@CERN** → ep/eA experiment using p/A from the LHC: $E_p=7$ TeV, $E_{Pb}=2.75$ TeV/nucleon, and possibly from the FCC (FCC-he): $E_p=50$ TeV, $E_{Pb}=19.7$ TeV/nucleon.

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**How?**

- **LHeC** vs. **HERA**
  - Large acceptance: 7-177 deg.
  - Kinematic coverage: tracking.
  - Modern Si EMcal: 0.1%.
  - HCAL: 1%.

- **Accurate luminosity/pol:**
  - FCC-he: 1%.

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Power constraints and design considerations:

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<th>Ring</th>
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<td>$e^-$ ($e^+$) per bunch $N_e$ [$10^9$]</td>
<td>20 (20)</td>
<td>1 (0.1)</td>
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<tr>
<td>$e^-$ ($e^+$) polarisation [%]</td>
<td>40 (40)</td>
<td>90 (0)</td>
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<td>bunch length [mm]</td>
<td>10</td>
<td>0.6</td>
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<tr>
<td>tr. emittance at IP $\gamma\epsilon_{x,y}$ [mm]</td>
<td>0.58, 0.29</td>
<td>0.05</td>
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<td>IP $\beta$ function $\beta_{x,y}$ [m]</td>
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<td>beam current [mA]</td>
<td>131</td>
<td>6.6</td>
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<tr>
<td>energy recovery intensity gain</td>
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<tr>
<td>total wall plug power [MW]</td>
<td>100</td>
<td>100</td>
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<td>syn rad power [kW]</td>
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<td>49</td>
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<tr>
<td>critical energy [keV]</td>
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<td>718</td>
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proton beam 7 TeV

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<td>protons per bunch $N_p$ [$10^{11}$]</td>
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<td>transverse emittance $\gamma\epsilon_{x,y}$ [$\mu$m]</td>
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<tr>
<td>collider</td>
<td></td>
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<tr>
<td>$L_{e^-p}$ ($e^+p$) [$10^{32}$cm$^{-2}$s$^{-1}$]</td>
<td>9 (9)</td>
<td>10 (1)</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
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<tr>
<td>rms beam spot size $\sigma_{x,y}$ [$\mu$m]</td>
<td>30, 16</td>
<td>7</td>
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<tr>
<td>crossing angle $\theta$ [mrad]</td>
<td>1</td>
<td>0</td>
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<tr>
<td>$L_{eN} = A L_{eA}$ [$10^{32}$cm$^{-2}$s$^{-1}$]</td>
<td>0.3</td>
<td>1</td>
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Large disruption of LHC operation $\Rightarrow$ backup solution. LR option
- Nominal case: 60+7000. Possible to lower the energy of both beams (e.g. for $F_L$).
- $1 \text{ ab}^{-1}$ in ten years within reach.

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<thead>
<tr>
<th>$10^{34} \text{ cm}^{-2} \text{s}^{-1}$ Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
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<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
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<td>60</td>
</tr>
<tr>
<td>Luminosity [$10^{33} \text{cm}^{-2} \text{s}^{-1}$]</td>
<td>16</td>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \epsilon_{x,y} [\mu \text{m}]$</td>
<td>2.5</td>
<td>20</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>$\beta^*_{x,y} [\text{m}]$</td>
<td>0.05</td>
<td>0.10</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>rms Beam size $\sigma^*_{x,y} [\mu \text{m}]$</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma'_{x,y} [\mu \text{rad}]$</td>
<td>80</td>
<td>40</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>1112</td>
<td>25</td>
<td>430 (860)</td>
<td>6.6</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25 (50)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2.2 \times 10^{11}$</td>
<td>$4 \times 10^{9}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$(1 \times 10^{9})$ $2 \times 10^{9}$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
<td>27</td>
<td>(0.16)</td>
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• Nominal case: 60+7000. Possible to lower the energy of both beams (e.g. for $F_L$).
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<td>1</td>
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<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma^*_{x,y}$ [\mu rad]</td>
<td>80</td>
<td>100</td>
<td>50</td>
<td>300</td>
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$L_{eN} = \begin{cases} 
9 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} & \text{(Nominal Pb)} \\
1.6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} & \text{(Ultimate Pb)}
\end{cases}$
- Nominal case: 60+7000. Possible to lower the energy of both beams (e.g. for $F_L$).
- $1 \text{ ab}^{-1}$ in ten years within reach.

**Nominal case:**

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<td>60</td>
</tr>
<tr>
<td>Luminosity [$10^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>16</td>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
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<td>Normalized emittance $\gamma \varepsilon_{x,y}$ [$\mu$m]</td>
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<td>Beta Function $\beta^*_{x,y}$ [m]</td>
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<td>0.12</td>
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<td>RMS Beam size $\sigma_{x,y}^*$ [$\mu$m]</td>
<td>4</td>
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<td>RMS Beam divergence $\sigma_{x,y}^*$ [$\mu$rad]</td>
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\end{cases}$

$eD : L_{eN} = A L_{eA} > \sim 3 \times 10^{31}$
**Some details:**

Return arcs (A. Milanese)

**IR:** crucial point for updated CDR

- **SC RF:** HL-LHC bunch spacing requires bunch spacing with multiples of 25 ns (40.079 MHz).
- Choice of 802 MHz for optimisation and synergies with FCC, CERN-JLab cooperation: two cavities to be built in 2016.

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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<td>6.brown</td>
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John Osborne June 2014
John Osborne June 2014

## LHeC construction planning

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Footprint:

**Footprint:**

- **LHeC**
- **LHC**
- Preyssin Site
- Meyrin Site
- Pt 2
- Pt 1
- Pt 8

**Contributions to cost**

- Tunnel
- Linac
- Magnets

**LHeC Civil Engineering**

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

Forming an international collaboration to study:

- $pp$-collider ($FCC-hh$) defining infrastructure requirements
  - $\sim16\ T \Rightarrow 100\ TeV\ pp\ in\ 100\ km$
  - $\sim20\ T \Rightarrow 100\ TeV\ pp\ in\ 80\ km$

- $e^+e^-$ collider ($FCC-ee$) as potential intermediate step
  - 120-350 GeV

- $p-e$ ($FCC-he$) option

- 80-100 km infrastructure in Geneva area
Forming an international collaboration to study:

- **pp-collider (FCC-hh)** → defining infrastructure requirements
  - \( \sim 16 \text{ TeV} \Rightarrow 100 \text{ TeV } pp \text{ in } 100 \text{ km} \)
  - \( \sim 20 \text{ TeV} \Rightarrow 100 \text{ TeV } pp \text{ in } 80 \text{ km} \)

- **e^+e^- collider (FCC-ee)** as potential intermediate step
  - 120-350 GeV
- **p-e (FCC-he)** option

- 80-100 km infrastructure in Geneva area

**FCC:**

- **pp:** \( \sqrt{s} = 100 \text{ TeV} \)
- **PbPb:** \( \sqrt{s} = 39.4 \text{ TeV/nucleon} \)
- **pPb:** \( \sqrt{s} = 62.8 \text{ TeV/nucleon} \)
● **PERLE**: ambitious design (2×150 MeV linacs, 3 passes → 900 MeV), significant physics potential of its own (10^{40} \text{ cm}^{-2} \text{ s}^{-1} \text{ fixed target}): EW physics, proton radius, photonuclear physics, dark photons … + accelerator development, magnet test, LHeC prototype/injector.

● Conceptual Design Report by spring 2016, under consideration a low energy but high current demonstrator with 3 passes.
Contents:

1. Introduction.

2. Accelerator.

3. Detector.

4. Physics case (some highlights):
   ➜ Precision QCD.
   ➜ Top and EW.
   ➜ Higgs.
   ➜ BSM.
   ➜ Small x and eA.

5. Organisation and plans.

   CDR:1206.2913; 1211.4831; 1211.5102; Brüning & Klein,1305.2090;
   Klein & Schöpper, CERN Courier, June 2014;
   2015 LHeC Workshop http://indico.cern.ch/event/356714/.

N. Armesto, 09.01.2016. - LHeC status and plans.
Kinematics:

- Small-x demands 1 degree acceptance. This gets worse with increasing electron energy.
- Higher luminosity would benefit high-x and \( Q^2 \) studies: linked to small x via DGLAP evolution (see HERA final analysis).

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N. Armesto, 09.01.2016. - LHeC status and plans: 3. Detector.
- Taggers at -62m (e), 100m (γ, LR), +100m (n), +420m (p).
- Present size < 14m x 9m (CMS 21m x 15m, ATLAS 45m x 25m).
- Developed in DD4HEP.
LHeC detector:

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---

Path of services for all tracking. The detector services (shown in dark orange) shall be integrated into support structures whenever possible. Optimum of costs and detector acceptance. Design of services and infrastructure crucial for material budget.

---

N. Armesto, 09.01.2016. - LHeC status and plans: 3. Detector.

R), +100m (n), +420m (p).
S 21m x 15m, ATLAS 45m x 25m.
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N. Armesto, 09.01.2016. - LHeC status and plans: 3. Detector.
**LHeC detector:**

**LHeC INSTALLATION SCHEDULE**

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
<th>Q6</th>
<th>Q7</th>
<th>Q8</th>
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<tbody>
<tr>
<td>DETECTOR CONSTRUCTION ON Site START BEFORE LHC LONG SHUTDOWN</td>
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<tr>
<td>LHC LONG SHUTDOWN START (T0)</td>
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<td>COIL COMMISSIONING ON SURFACE</td>
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<td>ACTUAL DETECTOR DISMANTLING</td>
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<td>PREPARATION FOR LOWERING</td>
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<td>LOWERING TO CAVERN</td>
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<td>HCAL MODULES &amp; CRYOSTAT</td>
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<td>CABLES &amp; SERVICES</td>
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<td>BARREL MUON CHAMBERS</td>
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<td>ENDCAPS MUON CHAMBERS</td>
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<tr>
<td>TRACKER &amp; CALORIMETER PLUGS</td>
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<td>BEAM PIPE &amp; MACHINE</td>
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<tr>
<td>DETECTOR CHECK-OUT</td>
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<tr>
<td>LHC LONG SHUTDOWN END (T0+24m)</td>
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</tbody>
</table>

- **Control Plane Tracker - CPT**
  - Inner R = 4.51 cm
  - Max Inner R = 17.13 cm
  - Z = 255 cm

- **Central Silicon Tracker - CST**
  - 5 double-layers
    - 1st layer: R = 23.5 cm
    - 2nd layer: R = 50.5 cm
    - 3rd layer: R = 64.7 cm
    - 4th layer: R = 64.7 cm
    - 5th layer: R = 64.7 cm

- **Backward Silicon Tracker - BST**
  - 5 double-layers p/A site
    - Min Inner R = 4.3 cm
    - Max Inner R = 16.2 cm
    - Max Outer R = 48.1 cm
    - Z = 67, 87, 142, 236, 202, 332, 372 cm

Path of services for all tracking. The detector services (shown in dark orange) shall be integrated into support structures whenever possible. Optimum of costs and detector acceptance. Design of services and infrastructure crucial for material budget.

N. Armesto, 09.01.2016. - LHeC status and plans: 3. Detector.
• Size scales ~2 in forward, ~1.3 in backward.
• Preliminary version, size and cost of huge magnets (H→μμ) are the limiting factors.
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• Preliminary version, size and cost of huge magnets (H→μμ) are the limiting factors.
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   - Higgs.
   - BSM.
   - Small $x$ and $eA$.

5. Organisation and plans.

Summary:

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

Summary:

LHeC Experiment:
- L1

HERA Experiments:
- H1 and ZEUS

Fixed Target Experiments:
- NMC
- BCDMS
- E665
- SLAC

- Large x Gluon
- RPV SUSY, LQ Substructure
- High Precision QCD & El.weak Physics
- Higgs Boson
- Nuclear Structure
- High Density Matter
- QGPlasma

PDFs:

proton PDFs, today

- need to know PDFs much better than today, for:
  - nucleon structure; q-g dynamics; Higgs; BSM searches;
  - future colliders, FCC-hh; and development of QCD

- LHC will provide further constraints, but cannot resolve precisely (shown are latest global PDFs, also including available LHC data)

C. Gwenlan, PDFs and QCD at the LHeC
**PDFs:**

**FCC-eh:** $E_p = 50 \text{ TeV}, E_e = 100 \text{ GeV}$  
NC and CC: $e-p$, $P = 80\%$, 1000 fb$^{-1}$  
stat: 0.1 – 30%, uncor: 0.7%, syst: 1 – 5%  
coverage down to $x = 2 \times 10^{-7}$, up to $Q^2 = 10^7 \text{ GeV}^2$

- charm
- beauty
- strange
PDFs:

- Full flavour decomposition, also eD, possibility to release assumptions in fits.

\( \alpha_s: \)

- Least known of all coupling constants.
- 0.1 % requires \( N^3\text{LO}, \Delta m_c \sim 5 \text{ MeV}. \)

<table>
<thead>
<tr>
<th>Method</th>
<th>Current relative precision</th>
<th>Future relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+e^- \text{ evt shapes} )</td>
<td>expt ( \sim 1% ) (LEP) thry ( \sim 1-3% ) (NNLO+up to ( N^3\text{LL} ), n.p. signif.) [27]</td>
<td>&lt; 1% possible (ILC/TLEP) ( \sim 1% ) (control n.p. via ( Q^2)-dep.)</td>
</tr>
<tr>
<td>( e^+e^- \text{ jet rates} )</td>
<td>expt ( \sim 2% ) (LEP) thry ( \sim 1% ) (NNLO, n.p. moderate) [28]</td>
<td>&lt; 1% possible (ILC/TLEP) ( \sim 0.5% ) (NLL missing)</td>
</tr>
<tr>
<td>precision EW</td>
<td>expt ( \sim 3% ) (( R_Z ), LEP) thry ( \sim 0.5% ) (( N^3\text{LO} ), n.p. small) [9, 29]</td>
<td>0.1% (TLEP [10]), 0.5% (ILC [11]) ( \sim 0.3% ) (( N^4\text{LO} ) feasible, ( \sim 10 \text{ yrs} ))</td>
</tr>
<tr>
<td>( \tau \text{ decays} )</td>
<td>expt ( \sim 0.5% ) (LEP, B-factors) thry ( \sim 2% ) (( N^3\text{LO} ), n.p. small) [8]</td>
<td>&lt; 0.2% possible (ILC/TLEP) ( \sim 1% ) (( N^4\text{LO} ) feasible, ( \sim 10 \text{ yrs} ))</td>
</tr>
<tr>
<td>( ep \text{ colliders} )</td>
<td>( \sim 1-2% ) (pdf fit dependent) (mostly theory, NNLO) [30, 31], [32, 33]</td>
<td>0.1% (LHeC + HERA [23]) ( \sim 0.5% ) (at least ( N^3\text{LO} ) required)</td>
</tr>
<tr>
<td>hadron colliders</td>
<td>( \sim 4% ) (Tev. jets), ( \sim 3% ) (LHC ( t\bar{t} )) (NLO jets, NNLO ( t\bar{t} ), gluon uncert.) [17, 21, 34]</td>
<td>&lt; 1% challenging (NNLO jets imminent [22])</td>
</tr>
<tr>
<td>lattice</td>
<td>( \sim 0.5% ) (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]</td>
<td>( \sim 0.3% ) ( \sim 5 \text{ yrs [38]} )</td>
</tr>
</tbody>
</table>
Least known of all coupling constants.

0.1% requires $\alpha_s^3\text{LO}$, $\Delta m_c \sim 5\text{ MeV}$.

$\alpha_s$:

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

0.3% precision from LHeC

M Klein, V Radescu

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

Expected 0.1% precision when combined with HERA

Top and EW physics:
High precision measurements of V_{tb}

LHeC, 100 fb^{-1}
1.000 \pm 0.005 (expected)

Top and EW physics:

\[ \sin^2 \theta_W \]

- Sensitivity from:
  - \( A_{LR} \) at high \( Q^2 \)
  - \( \sigma_{NC}/\sigma_{CC} \) at lower \( Q^2 \)
Higgs at the LHeC:

- **(VBF)** cross section comparable to that at the ILC, clear separation of WWH and ZZH.

- No pileup (0.1 at $10^{34}$), S/B~1.
Higgs at the LHeC:

- 
  - **Higgs in $e^-p$**
  - *Polarisation*
  - *Luminosity [ab$^{-1}$]*
  - *Cross Section [fb]*

<table>
<thead>
<tr>
<th>Decay</th>
<th>BrFraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>0.577</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>0.029</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>0.063</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>0.0002</td>
</tr>
<tr>
<td>$H \rightarrow 4l$</td>
<td>0.0011</td>
</tr>
<tr>
<td>$H \rightarrow 2l2\nu$</td>
<td>0.0106</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>0.086</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>0.215</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>0.0264</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.0022</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

- 
  - $\sqrt{s} = 14$ TeV
  - $Ldt = 300$ fb$^{-1}$
  - $Ldt = 3000$ fb$^{-1}$

- **BR$_{t,u}=0$**
- Work in progress
  - Br: $b$ 59% c 3%

- **$\ell^+\ell^-$**
  - $e^+e^-$
  - $\mu^+\mu^-$

- **No pileup (0.1 at $10^{34}$)**
- $S/B \sim 1$.
Higgs at the LHeC:

- **FCC-he:**
  - $HH \rightarrow 4b$'s,
  - $\sigma \sim 0.01-0.04$ fb.

1509.04016
Higgs at the HL-LHC:

- $\alpha_s$ and PDFs dominate the uncertainties on the cross section e.g. $\Delta \alpha_s = 0.005$ means 10% for the cross section.
- Sensitivity to the Higgs mass cannot be achieved due to these reasons.

- The LHeC would turn HL-LHC into a precision Higgs machine.
FCNC: new physics models (SUSY, TC, little H, ED, …) predict BR=O(10^{-5}) accessible @ LHeC.

Present LHC constraints on scale of qqll CI: 15 – 26 TeV (40 @14 TeV).
- LHeC $F_2$ and $F_L$ data will have discriminatory power on models.
Small-x: inclusive

- NLO DGLAP cannot simultaneously accommodate LHeC $F_2$ and $F_L$ pseudodata if saturation effects included according to current models. Two observables required ($F_2 - F_{2c}$).

- LHeC F$^2$ and F$^L$ data will have discriminatory power on models.
Small-$x$: diffractive

- Large increase in the $M^2$, $x_P= (M^2 - t + Q^2)/(W^2 + Q^2)$, $\beta = x/ x_P$ region studied.
- Possibility to combine LRG and LPS.
- Elastic J/Ψ production appears as a candidate to signal saturation effects at work!!!

Linear, sensitivity to \((xg)^2\).
Small-x: diffractive

Linear, sensitivity to \((xg)^2\).

\[ E_e = 50 \text{ GeV}, \text{1}\text{o acceptance, } L=2 \text{ fb}^{-1} \]

\[ \gamma p \to J/\psi + p \]

LHeC central values from extrapolating HERA data:
\[ \sigma (\gamma p) = (2.96 \text{ nb})(W/\text{GeV})^{0.721} \]

\[ W_{\text{max}} = \sqrt{s} = \sqrt{LHeC E_e} \text{ at the LHeC with } E_e = 7 \text{ TeV.} \]
DVCS:

- Exclusive processes give information about GPDs, whose Fourier transform gives a transverse scan of the hadron: DVCS sensitive to the singlet.
- Sensitive to dynamics e.g. non-linear effects.

Note the huge $Q^2$!!!
• Large impact on nPDFs, possible to make a Pb fit without proton PDFs!!!
• Large room for improvements: NC+CC at several energies, flavour decomposition,…
- Large impact on nPDFs, possible to make a Pb fit without proton PDFs!!

- Large room for improvements: NC+CC at several energies, flavour decomposition,…
Large impact on nPDFs, possible to make a Pb fit without proton PDFs!!!

Large room for improvements: NC+CC at several energies, flavour decomposition, …

M. Klein at POETIC6
eA: diffractive

- Elastic VM: saturation, nGPDs.

\[ \gamma(A) \rightarrow J/\Psi A \]

\[ t=0, \quad Q^2 = 0 \]

\[ \frac{1}{A^2} \frac{d\sigma}{dt} \left( \mu^2/\text{GeV}^2 \right) \]

Saturation effects

\[ W \quad (\text{GeV}) \]

\[ 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \]

\[ 10^{-10} \quad 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0} \]

\[ 0 \quad 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \quad 0.1 \quad 0.12 \quad 0.14 \quad 0.16 \quad 0.18 \]

\[ Q^2 = 0 \]

\[ W = 400 \text{ GeV} \]

\[ \text{with breakup} \]

\[ \text{Lead} \]

\[ \text{proton} \]

\[ \text{Calcium} \]

\[ \text{Lead} \]

\[ \text{nosat} \]

\[ \text{b-Sat} \]

\[ \text{b-NonSat} \]
The LHeC:

The LHeC:

Coordination Group
Gianluigi Arduini
Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Gaddi
Erk Jensen
Max Klein
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

Physics Groups + Convenors
PDFs, QCD Fred Olness, Voica Radescu
Higgs Uta Klein, Masahiro Khuze
BSM Georges Azuelos, Monica D’Onofrio
Top Olaf Behnke, Christian Schwanenberger
Nuclei Nestor Armesto
Small x Paul Newman, Anna Stasto

Referees for Design Report

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)
Tentative plans:

International Advisory Committee + Mandate

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.

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, plus
Oliver Brüning  Max Klein ex officio

Max Klein ICFA Beijing 10/2014
Tentative plans:

- Update of the CDR for 2017, ready for the next European Strategy of Particle Physics in 2018:
  - Update of physics case in view of LHC findings.
  - ERL test facility.
  - Accelerator: IR.
  - Detector.

- Ongoing discussions with the new CERN management. Next workshop: around September 2016.

- Any decision pending on LHC findings in Run II.

- In current schedule, LHC expected to operate until ~ 2037.
Summarising:

- PDFs for $h h$, $\alpha_s$, turn the HL-LHC into precision
- Direct BSM searches
- Higgs factory
- Non-linear domain of QCD, physics relevant for HI

http://cern.ch/lhec

N. Armesto, 09.01.2016. - LHeC status and plans.
Many thanks to:
- Anna, Hannu, Max, Paul,…
- The organisers for the invitation.
- You all for your attention!!!

Non-linear domain of QCD, physics relevant for HI

Direct BSM searches

Higgs factory

Summarising:

PDFs for $h h$, $\alpha_s$, turn the HL-LHC into precision

http://cern.ch/lhec
Backup:
FCC:

Future Circular Collider Study - SCOPE CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

• $pp$-collider ($FCC-hh$) → defining infrastructure requirements
  ~16 T ⇒ 100 TeV $pp$ in 100 km
  ~20 T ⇒ 100 TeV $pp$ in 80 km

• $e^+e^-$ collider ($FCC-ee$) as potential intermediate step
  120-350 GeV
• $p-e$ ($FCC-he$) option
• 80-100 km infrastructure in Geneva area
Forming an international collaboration to study:

- **pp-collider (FCC-hh)**
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- **e^+e^- collider (FCC-ee)** as potential intermediate step
  \[120-350 \text{ GeV}\]

- **p-e (FCC-he)** option

- 80-100 km infrastructure in Geneva area

**FCC:**

- **pp:** \(\sqrt{s} = 100 \text{ TeV}\)
- **PbPb:** \(\sqrt{s} = 39.4 \text{ TeV/nucleon}\)
- **pPb:** \(\sqrt{s} = 62.8 \text{ TeV/nucleon}\)
FCC:

93 km option (Lebrun in Washington DC)
FCC:

100 km option (Lebrun in Washington DC)
LHC vs. LHeC:

pp@LHC

ep@LHeC

pPb@LHC

ePb@LHeC

LHC vs. LHeC:

- **Ultra-peripheral QQ**: LHC Y (|y| < 2.5) and LHC J/Ψ (|y| < 2.5)
- **PbPb@LHC**
- **Ep@LHeC**

**Nuclear DIS & DY data:**
- NMC (DIS)
- SLAC-E139 (DIS)
- FNAL-E665 (DIS)
- EMC (DIS)
- FNAL-E772 (DY)

**Present nuclear DIS and Drell-Yan in p+A**

- **PbPb@LHC**
- **Ep@LHeC**

**Fixed Target Experiments:**
- Fixed Target Experiments:
  - NMC
  - E665
  - EMC

**Present** DIS+DY

**nuclear DIS - \( F_{2}^{p,A} (x, Q^{2}) \):**

- **Proposed facilities:**
- **LHeC**
- **Fixed Target data:**
  - NMC
  - E665
  - EMC

**Q^{2} (GeV^{2})**

<table>
<thead>
<tr>
<th>x</th>
<th>10^{-7}</th>
<th>10^{-6}</th>
<th>10^{-5}</th>
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</tbody>
</table>

**Q^{2}_{sat,Pb}(x):**

- **PbPb@LHC**
- **Ep@LHeC**

**N. Armesto, 09.01.2016. - LHeC status and plans: 4. Physics case.**
LHC vs. LHeC:

- The LHeC will explore a region overlapping with the LHC:
  - in a cleaner experimental setup;
  - on firmer theoretical grounds.
PDFs with LHC:

S. Forte at ECFA, Nov. 2015

HERA AND LHC DATA:
WHAT IS THE RELATIVE IMPACT?

- OVERALL MEASURE OF IMPACT:
  \( \varphi \rightarrow \text{FIT UNCERTAINTY/DATA UNCERTAINTY} \)
- HERA-II IMPACT SIZABLE
- IMPACT OF LHC DATA MODERATE BUT VISIBLE
- IMPACT OF CMS OR ATLAS COMPARABLE TO (MODERATE) IMPACT OF NON-LHC, NON-HERA DATA

<table>
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</table>

PDFs with LHC:

S. Forte at ECFA, Nov. 2015

PDFS AT LHC RUN II

- Data at higher CM energy & info on correlation to low energy → extended kinematic coverage & reduced systematics
- Expect reduction in model dependence
- Moderate reduction in uncertainty

Very difficult to reduce uncertainties below 3-4% level at a hadron collider

(PDF4LHC: 1507.00556)
Diffraction in ep and shadowing:

- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the ‘benchmark’ for new effects.
Diffraction in ep and shadowing:

- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the ‘benchmark’ for new effects.
Diffractive dijets:

- Diffractive dijet and open heavy flavour production offer large possibilities for:
  - Checking factorization in hard diffraction.
  - Constraining DPDFs.

- Large yields up to large $p_T^{\text{jet}}$.

- Direct and resolved contributions: photon PDFs.
• Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
• At the LHeC it could be studied far from the kinematical limits.

\[ C(\phi_{12}) = \frac{1}{d\sigma(\gamma^* N \rightarrow h_1 h_2 + X)} \frac{d\sigma}{dz_{h_1}} \frac{d\sigma}{dz_{h_2}} d\phi_{12} \]

\[ p_{T,\text{lead}} > 3 \text{ GeV} \]
\[ p_{T,\text{ass}} > 2 \text{ GeV} \]
\[ z_{\text{lead}} = z_{\text{ass}} = 0.3 \]
\[ y = 0.7 \]
\[ Q^2 = 4 \text{ GeV}^2 \]

Albacete-Marquet '10
Dijet azimuthal decorrelation:

- Studying **dijet azimuthal decorrelation** or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:
  - $k_T$-ordered: DGLAP.
  - $k_T$-disordered: BFKL.
  - Saturation?
- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.
Forward jets:

- Studying dijet azimuthal decorrelation or forward jets ($p_T \sim Q$) would allow to understand the mechanism of radiation:
  - $k_T$-ordered: DGLAP.
  - $k_T$-disordered: BFKL.
  - Saturation?

- Further imposing a rapidity gap (diffractive jets) would be most interesting: perturbatively controllable observable.
Jets:

- Jets: large $E_T$ even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.

Radiation and hadronization:

- **LHeC**: dynamics of QCD radiation and hadronization.
- **Low energy**: hadronization inside $\rightarrow$ formation time, (pre-)hadronic absorption,...
- **High energy**: partonic evolution altered in the nuclear medium.

$$R_A^h(z, \nu) = \frac{1}{N_A^e} \frac{dN_A^h(z, \nu)}{d\nu \, dz} \left/ \frac{1}{N_D^e} \frac{dN_D^h(z, \nu)}{d\nu \, dz} \right.$$
Radiation and hadronization:

- **LHeC**: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.
- **Low energy**: hadronization inside → formation time, (pre-)hadronic absorption,...

- **High energy**: partonic evolution altered in the nuclear medium.

\[
R^h_A(z, \nu) = \frac{1}{N^e_A} \frac{dN^h_A(z, \nu)}{d\nu \, dz} / \frac{1}{N^e_D} \frac{dN^h_B(z, \nu)}{d\nu \, dz}
\]
LHC schedule:

LHC roadmap: according to MTP 2016-2020 V1

- LS2 starting in 2019: 24 months + 3 months BC
- LS3 LHC: starting in 2024: 30 months + 3 months BC
- Injectors: in 2025: 13 months + 3 months BC

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- Run 2: 2015-2018
- LS 2: 2019

- Run 3: 2022-2024
- LS 3: 2025
- Run 4: 2026-2028

- LS 4: 2029-2030
- Run 5: 2031-2032
- LS 5: 2033-2035

Color codes:
- Green: Physics
- Red: Shutdown
- Yellow: Beam commissioning
- Blue: Technical stop

Frederick Bordry to the SPC and FC, June 2015

N. Armesto, 09.01.2016. - LHeC status and plans.
LHC schedule:

<table>
<thead>
<tr>
<th>Year</th>
<th>LS2 Starting in 2019</th>
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<th>Injectors: in 2025</th>
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LHC roadmap: according to MTP 2016-2020 V2

- LHC: starting in 2024
- Injectors: in 2025

- Phase 1: 2022-2028
  - Run 3
  - LS 3
  - Run 4

- Phase 2: 2029-2035
  - LS 4
  - Run 5

Legend:
- Green: Physics
- Red: Shutdown
- Yellow: Beam commissioning
- Blue: Technical stop

N. Armesto, 09.01.2016. - LHeC status and plans.