Future Precision PDF Physics with ep/A

1. ep/A with the LHC
2. Higgs in ep
3. PDFs Beyond this Presentation
4. How Precise – a New Detector
5. Nine Quark Distributions
6. The Gluon Density (hi+lo x)
7. $\alpha_s$
8. Nuclear PDFs
9. Project Prospects
10. Remarks

Max Klein
University of Liverpool
for the LHeC Study Group

For references, please consult
lhec.web.cern.ch
LHeC CDR
arXiv:1206.2913

Precise Experiments for Precise Theory, Quy Nhon, Rencontre du Vietnam, 27th of September 2016
Intensity and Energy Frontier of Future DIS

From CERN Courier
MK, H.Schopper
June 2014

With input from
A.Hutton, R.Ent,
F.Maas, T.Rosner

Max Klein, Vietnam, 27.9.16
Intensity and Energy Frontier of Future DIS

Lepton–Proton Scattering Facilities

From CERN Courier
MK, H.Schopper
June 2014

With input from
A.Hutton, R.Ent,
F.Maas, T.Rosner

Max Klein, Vietnam, 27.9.16
1. ep/A with the LHC


LHeC: 60 GeV off 7 TeV, L(ep) = $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (1000 x HERA) in synchronous ep+pp operation

Non default: An expensive generalisation to achieve $E_e = 500 \text{ GeV}$ or more

Polarized source

Dump
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>
A Baseline for the FCC-he

Oliver Brüning¹ Max Klein¹,², Daniel Schulte¹, Frank Zimmermann¹
¹ CERN, ² University of Liverpool
March 3rd, 2016

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>$E_e$ [GeV]</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\sqrt{s}$ [TeV]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.9</td>
<td>3.5</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>protons per bunch [$10^{11}$]</td>
<td>1.7</td>
<td>2.2</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>$\epsilon_p$ [$\mu$m]</td>
<td>3.7</td>
<td>2</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>electrons per bunch [$10^9$]</td>
<td>1</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>electron current [mA]</td>
<td>6.4</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>IP beta function $\beta^*_p$ [cm]</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>hourglass factor</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>pinch factor</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>luminosity [$10^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>1.3</td>
<td>10.1</td>
<td>15.1</td>
<td>9.2</td>
</tr>
</tbody>
</table>

May count on $1ab^{-1}$ in 10 years of OP, 1000xHERA in ep with HL LHC, with HE-LHC and with FCC_eh

work in progress (also eA)

Max Klein, Vietnam, 27.9.16
Realization of the LHeC

Physics and cost will determine footprint
2. **SM Higgs in ep → ν/e H X**

\[ \sigma(e^-p) = 200 \text{ fb}^{-1} \]

at LHeC, pol. CC
Higgs in ep

\[ e^{-} p \rightarrow W^{\pm} Z^{\mp} H^{+} b, c, \tau^{\pm}, \ldots \]

ep \rightarrow vHX, H \rightarrow cc

ep \rightarrow vHX, H \rightarrow bb

H \rightarrow bb \text{ cut based: 1\% coupling error}

H \rightarrow cc \text{ BDT based: 6\% coupling error}

To study: WW, \tau\tau, Higgs width in NC..

ep complements Higgs in pp, also with N^3LO PDFs and strong coupling to 0.1\%
Further Recent Studies on Higgs in ep

**BSM Higgs with LHeC**

Invisible Higgs Decay at the LHeC

Yi-Lei Tang,1, * Chen Zhang,2, † and Shou-hua Zhu1,2,3, ‡

*arXiv:1508.01095, 2015*

H-HH with FCC-he (√s=3.5 TeV vs 0.3 at FCC-ee)

Our study clearly justifies a luminosity upgrade to 1 ab⁻¹ for the LHeC to become a Higgs boson factory [46] and demonstrates its huge potential on study of exotic Higgs decays. Besides the invisible Higgs decay, the LHeC is suited to the study of those exotic Higgs decays which suffer from large backgrounds, trigger or p_T threshold problem at the (HL-)LHC such as h → 4b, h → 2b2τ, h → 4j, h → b̄b + E_T [73], h → γ + E_T, h → Z + E_T [74]. Work on these directions is in progress [75].

---

Probing anomalous couplings using di-Higgs production in electron-proton collisions

Mukesh Kumar,1, * Xifeng Ruan,2, † Rashidul Islam,3, ‡ Alan S. Cornell,1, § Max Klein,4, * Uta Klein,4, ** and Bruce Mellado2, ††


Higgs cross section at FCC-ep is O(1pb) [4x FCCee] → striking potential being studied
The Phenomenological Higgs Landscape (Revisited)

Future ep colliders could make important contribution to Higgs physics!

- Mass
- Width (via VV scattering)
- Spin-Parity
- Coupling
  - hVV, hff
  - 3h, 4h, hhVV
  - FCNC coupling

- Exotic Higgs Decay
  - h to invisible
  - h to 4b
  - ...
  - Reducing PDF & Alpha_s uncertainties in Higgs measurements

See talk given by Voica Radescu


See also:
M. Kumar et al., 1509.04016
U. Klein, talk given at LHeC Workshop 2015

Chen Zhan 12.4.16 (talk at annual FCC week 2016, Rome)
In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

**Specifics of the linear SM EFT.**

Four fermion operators with leptons and quark fields:

<table>
<thead>
<tr>
<th>8 : (LL)(LL)</th>
<th>8 : (RR)(RR)</th>
<th>8 : (LL)(RR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{eL}$</td>
<td>$(\bar{\ell}<em>e \gamma</em>\mu L)(\bar{\ell}_e \gamma^\mu l_1)$</td>
<td>$(\bar{e}<em>L \gamma</em>\mu e_r)(\bar{e}_L \gamma^\mu e_r)$</td>
</tr>
<tr>
<td>$Q_{q_L}$</td>
<td>$(\bar{q}<em>{\nu} \gamma</em>\mu q_r)(\bar{q}_{\nu} \gamma^\mu q_l)$</td>
<td>$(\bar{u}<em>r \gamma</em>\mu u_r)(\bar{u}_r \gamma^\mu u_r)$</td>
</tr>
<tr>
<td>$Q_{q_R}$</td>
<td>$(\bar{q}<em>L \gamma</em>\mu \tau^f \tau^f q_r)(\bar{q}_L \gamma^\mu \tau^f \tau^f q_l)$</td>
<td>$(\bar{u}<em>r \gamma</em>\mu \tau^f \tau^f u_r)(\bar{u}_r \gamma^\mu \tau^f \tau^f u_r)$</td>
</tr>
<tr>
<td>$Q_{q_{Rq}}$</td>
<td>$(\bar{u}<em>r \gamma</em>\mu \tau^f \tau^f q_r)(\bar{d}_r \gamma^\mu \tau^f \tau^f d_r)$</td>
<td>$(\bar{e}<em>L \gamma</em>\mu \tau^f \tau^f q_r)(\bar{\ell}_L \gamma^\mu \tau^f \tau^f \ell_r)$</td>
</tr>
</tbody>
</table>

Number of 4 fermion parameters with lepton-quark: $13 n_g^4$ or 1053 of 2499
3. PDFs in ep/n - beyond this presentation

Generalised Parton Distributions [DVCS] – “proton in 3D - tomography”

Unintegrated Parton Distributions [Final State] – DGLAP/BFKL?

Diffractive Parton Distributions [Diffraction] – pomeron, confinement??

Photon Parton Distribution [Photoproduction Dijets, QQ; F_2,L] - fashionable..

Neutron Parton Distributions [Tagged en (eD) Scattering] – ignored at HERA

+ Huge extension of kinematic range and precision through energy and luminosity gains
  cf CDR for initial studies [arXiv:1206.2913]

+ Note that ALL of these areas are at their infancy, just discovered/opened with HERA, also LHC

+ Complementarity here with EIC: lower energy, larger x, but more ions and proton polarisation
4. A New Detector and its Simulation

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

Present dimensions: LxD = 14x9 m² [CMS 21 x 15 m², ATLAS 45 x 25 m²]

Taggers at -62 m (e), 100 m (γ, LR), -22.4 m (γ, RR), +100 m (n), +420 m (p)
Simulation and LHeC PDF Set

Numerical program to simulate NC and CC cross sections
(based on J.Blümlein and MK, PHE 90-19, benchmarked with H1 Monte Carlo Simulation)

<table>
<thead>
<tr>
<th>source of uncertainty</th>
<th>error on the source or cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>scattered electron energy scale $\Delta E'_e/E'_e$</td>
<td>0.1 %</td>
</tr>
<tr>
<td>scattered electron polar angle</td>
<td>0.1 mrad</td>
</tr>
<tr>
<td>hadronic energy scale $\Delta E_h/E_h$</td>
<td>0.5 %</td>
</tr>
<tr>
<td>calorimeter noise (only $y &lt; 0.01$)</td>
<td>1-3 %</td>
</tr>
<tr>
<td>radiative corrections</td>
<td>0.5%</td>
</tr>
<tr>
<td>photoproduction background (only $y &gt; 0.5$)</td>
<td>1%</td>
</tr>
<tr>
<td>global efficiency error</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

**Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – based on typical best values achieved by H1**

- Statistical: it ranges from 0.1% (low $Q^2$) to ~10% for $x=0.7$ in CC
- Uncorrelated systematic: 0.7 %
- Correlated systematic: typically 1-3% (for CC high $x$ up to 9%)

50fb$^{-1}$

PDF set like HERAPDF available at LHAPDF

MK + Voica Radescu
PDF set update to come
5. Nine Quark Distributions (and \(xg\))

\[ u_v, d_v, \bar{u}, \bar{d}, s, \bar{s}, c, b, t \]

Various important features of the NC and CC and \(F_L\) and HQ Structure Function DIS Data:

- high precision (e-h redundancy, clean final state, no pile-up..)
- high statistics (1000 times HERA) – much increased precision at high \(x\), recall: \(xq_v \sim (1-x)^3\)
- much extended kinematic range: at high \(Q^2 < 1\) TeV\(^2\): CC becomes precise, unlike at HERA
- charged current: hugely important for: Higgs, strange, top and flavour separation
- low \(x \sim 1/s\) : DGLAP may fail, long expected BFKL? \(xg\) damping “saturation”
- beam spot extension \(\sim 7\mu m\) in \(x\) and \(y\). with modern Silicon trackers \(\rightarrow\) precision HQdfs
- ...

Theory: clean, light cone. In 10 years time: provide \(N^3LO\) PDFs - for precision Higgs at LHC

Phenomenology: no more symmetry assumptions, HQ known, no HT, no nuclear corrections, parameterisation uncertainties ‘gone’, model errors also (mc, \(\alpha_s\), ...)
Valence quarks

High x crucial for HL LHC searches
Related to DrellYan, W mass etc
d/u → 1 a classic question, still there

up

down
Valence quarks

High $x$ crucial for HL LHC searches
Related to DrellYan, $W$ mass etc
$d/u \to 1$ a classic question, still there

**up**

**down**

---

Max Klein, Vietnam, 27.9.16
$e^+ p + p p$ and free fit to $\bar{u}, \bar{d}, s$

HERA: assume $u_{\overline{u}} = d_{\overline{d}}$ and no sensitivity to $s$. LHC ($W, Z$) helps. LHeC provides independent determination.

MK, V. Radescu at 2014 LHeC Workshop, Chavannes, January 2014
Strange Quark Distribution from LHeC

First $(x, Q^2)$ measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4} \ldots 0.05$

$Q^2 = 100 - 10^5 \text{ GeV}^2$

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter
$F_2^{\text{charm}}$ and $F_2^{\text{beauty}}$ from LHeC

Hugely extended range and much improved precision ($\delta M_c = 50$ HERA $\rightarrow 3$ MeV) will pin down heavy quark behaviour at and far away from thresholds, crucial for precision t,H..

In MSSM, Higgs is produced dominantly via $b\bar{b} \rightarrow H$ (Pumplin et al), but where is the MSSM..
6. Gluon Density

Gluon distribution at $Q^2 = 1.9 \text{ GeV}^2$

- Gluon prior to LHC data (2011)
- Gluon with (first) LHC data (2015) used by CT14, NNPDF, MMHT

High $x$

cf talks by Ringaile Plakacyte, Pavel Nadolsky, Sasha Glazov at this conference

Max Klein, Vietnam, 27.9.16
Gluon from the LHeC

Figure 3.19: Relative uncertainty of the gluon distribution at $Q^2 = 1.9 \text{ GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic $x$, right: linear $x$. 

From the LHeC Conceptual Design Report
Gluon (gg) Luminosity

Present status

Crucial for SUSY searches/limits
Similarly: Drell-Yan qq luminosity
Cf Jan Kretzschmar and Sasha Glazov

Max Klein, Vietnam, 27.9.16
Low x

$x_g$ for $x < 10^{-4}$ not known, it is not unknown above.

Low x evolution law unlikely linear DGLAP

HERA: where is BFKL?

Needs precision $F_2$ and $F_L$ in extended x range

Search for Saturation requires $x_g$ to be large and $\alpha_s$ to be small $\rightarrow$ $Q^2$ ought to be $> 10$ GeV$^2$

Affects pp rates because $x=M/V(s) \exp(\pm y)$
Low x Gluon

Fix the gluon at low x by the derivative of $F_2$ and precision $F_L$ data $\rightarrow$ deviations from DGLAP?

cf CDR
7. Strong Coupling Constant

- $\alpha_s$ least known of coupling constants  
  Grand Unification predictions need smaller $\delta\alpha_s$

- Is $\alpha_s$(DIS) lower than world average (?)

- LHeC: per mille - independent of BCDMS!

- High precision from inclusive data – $\alpha_s$(jets)??

- Challenge lattice QCD [cf L Del Debbio, this conf]

LHeC simulation, NC+CC inclusive, total exp error
The exp. error on the Higgs cross section calculated with LHeC PDF is 0.3% → sensitive to mass
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 …
Nuclear Parton Distributions

Nuclear Parton Distributions with the LHeC
MK, POETIC 2015, EPJ Web Conf. 112 (2016) 03002
Collaboration with H.Paukuunen, N.Armesto, V.Radescu

nPDFs are in infant state, resembles

Max Klein, Vietnam, 27.9.16
Proton PDFs before HERA

BCDMS muon-proton, also -carbon

Gluon density in 1989

CDHS neutrino-iron scattering

Sea, valence and xg in 1989
Future Nuclear PDFs

From an eA collider one can determine nuclear PDFs in a novel, the classic way. Currently: use some proton PDF base and fit a parameterised shadowing term $R$. Then: use the NC and CC eA cross sections directions and get $R$ as p/N PDFs.

Gluon density uncertainty in eA

Charm density in nuclei

$1 \text{fb}^{-1}$ of sole eA isoscalar data fitted

Impact parameter measurement in eA

LHeC  eA: 60 GeV x 2.75 TeV

Max Klein, Vietnam, 27.9.16
FCC-he, LHeC, EIC eA Colliders

Extension of kinematic range in IA by many orders of magnitude will change QCD view on nuclear structure and parton dynamics

May lead to genuine surprises...

- No saturation of $x_g (x,Q^2)$?
- Small fraction of diffraction?
- Broken isospin invariance?
- Flavour dependent shadowing?

Relates to LHC Heavy Ion Physics
- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

Max Klein nPDFs with LHeC 10.9.2015 POETIC a PARIS

Max Klein, Vietnam, 27.9.16
9. Remarks on the LHeC Project Status

**LHeC**: CDR in 2012 (300 authors, 600 pages). 2014+16: CERN Mandate to continue the study:

**DG: Mandate to the International Advisory Committee 2015-2018**

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.

Chair: Herwig Schopper

**Two major next goals:**

- Design and build an LHeC ERL demonstrator (10mA, 3 turn, 802 MHz)
- Update of the CDR by 2018: LHC physics, $10^{34}$ lumi, detector and accelerator updates

**FCC-eh**: Utilize the LHeC design study to describe baseline ep/A option.

Emphasis: 3 TeV physics, IR and Detector: synchronous ep-pp operation.

Open to other configurations and new physics developments (750..)
Organisation*)

International Advisory Committee

“..Direction for ep/A both at LHC+FCC”

Sergio Bertolucci (CERN/Bologna)  
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)  

Coordination Group

Accelerator+Detector+Physics

Nestor Armesto  
Oliver Brüning – Co-Chair  
Stefano Forte  
Andrea Gaddi  
Erk Jensen  
Max Klein – Co-Chair  
Peter Kostka  
Bruce Mellado  
Paul Newman  
Daniel Schulte  
Frank Zimmermann

5(11) are members of the FCC coordination team

OB+MK: FCC-eh responsibilities  
MDO: physics co-convenor

Working Groups

PDFs, QCD
Fred Olness,  
Voica Radescu  
Higgs
Uta Klein,  
Masahiro Kuze  
BSM
Georges Azuelos,  
Monica D’Onofrio  
Top
Olaf Behnke,  
Christian Schwanenberger  
eA Physics
Nestor Armesto  
Small x
Paul Newman,  
Anna Stasto  
Detector
Alessandro Polini  
Peter Kostka

IAC being renewed by new DG
We lost Guido Altarelli.

*)August 2016
ERL Testfacility

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

$E_e = 200 \ (400) \ \text{MeV}$ with 1(2) module which houses four 5-cell cavities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles per arc</td>
<td>3/4</td>
</tr>
<tr>
<td>Dipole length</td>
<td>50 cm</td>
</tr>
<tr>
<td>Max B Field</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Quadrupoles per arc</td>
<td>5</td>
</tr>
<tr>
<td>Quadrupoles in straight lines</td>
<td>4</td>
</tr>
<tr>
<td>Dipoles in Spreader/Combiner</td>
<td>1-3</td>
</tr>
<tr>
<td>Quads in Spreader/Combiner</td>
<td>3</td>
</tr>
<tr>
<td>Dipoles for Injection-Extraction</td>
<td>6</td>
</tr>
</tbody>
</table>

“PERLE” CDR to be published, ICFA Beam Newsletter 68 (2016)

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (LAL/INP),+

Technical Design as next goal
802 MHz cavity soon produced

Footprint: 14x4m$^2$
802 MHz Cavity Parameters

design to also test FCC-ee

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity type</td>
<td></td>
<td>LHeC prototype (2016)</td>
<td>LHeC study (2015)</td>
<td>LHeC Ver. 1</td>
<td>LHeC Ver. 2</td>
</tr>
<tr>
<td>frequency</td>
<td>MHz</td>
<td>801.58</td>
<td>802</td>
<td>802</td>
<td>801.58</td>
</tr>
<tr>
<td>number of cells</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$L_{active}$</td>
<td>mm</td>
<td>917.91</td>
<td>922.31</td>
<td>922.14</td>
<td>935</td>
</tr>
<tr>
<td>$R/Q = V_{eff}^2/(\omega*W)$</td>
<td>$\Omega$</td>
<td>523.7</td>
<td>580.1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>$R/Q/cell$</td>
<td>$\Omega$</td>
<td>104.7</td>
<td>116.0</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>$G$</td>
<td>$\Omega$</td>
<td>274.6</td>
<td>273.2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$R/Q\cdot G/cell$</td>
<td></td>
<td>28765</td>
<td>31702</td>
<td>3</td>
<td>44</td>
</tr>
<tr>
<td>Eq. Diameter</td>
<td>mm</td>
<td>327.95</td>
<td>323.12</td>
<td>323.12</td>
<td>323.12</td>
</tr>
<tr>
<td>Iris Diameter</td>
<td>mm</td>
<td>130</td>
<td>115</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>mm</td>
<td>130</td>
<td>140</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Eq./Iris ratio</td>
<td></td>
<td>2.52</td>
<td>2.81</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Wall angle (mid-cell)</td>
<td>deg</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$ (mid-cell)</td>
<td></td>
<td>2.26</td>
<td>2.07</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$ (mid-cell)</td>
<td>mT/(MV/m)</td>
<td>4.20</td>
<td>4.00</td>
<td>4.00</td>
<td>4.77</td>
</tr>
<tr>
<td>$k_{cc}$</td>
<td>%</td>
<td>3.22</td>
<td>2.14</td>
<td>2.14</td>
<td>4.47</td>
</tr>
<tr>
<td>$N^2/k_{cc}$</td>
<td></td>
<td>7.78</td>
<td>11.71</td>
<td>11.71</td>
<td>5.59</td>
</tr>
<tr>
<td>cutoff $TE_{11}$</td>
<td>GHz</td>
<td>1.35</td>
<td>1.26</td>
<td>1.53</td>
<td>1.17</td>
</tr>
<tr>
<td>cutoff $TM_{01}$</td>
<td>GHz</td>
<td>1.77</td>
<td>1.64</td>
<td>2.00</td>
<td>1.53</td>
</tr>
</tbody>
</table>

F. Marhauser, B. Rimmer, J. Henry (Jlab) + R. Calaga, E. Jensen, K. Schirm et al. (CERN) [4.8.16]
FCC-he Civil Engineering

FCC-he Point H

FCC Long Straight Section H

Tunnel Geology
- Molasse rock (sandstone)

Construction
- Tunnel Boring Machine (TBM) in straight sections
- Roadheader in arcs

Civil Engineering challenges
- Low geological risk
- Interaction with main FCC tunnel(s)

CE: favoured eh site is point H
Vatican XV Century - a racetrack must be embedded in something bigger to make sense
10. Concluding Remarks
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. The contribution of the LHeC to that can not be overestimated.
Summary

High precision in pp matters.

It may be achieved with an electron beam upgrade of the LHC, following the luminosity upgrade.

That “delivers” PDFs to $N^3\text{LO}$, an order of magnitude more precise than so far and free of most of the current complications.

This provides the world with the cleanest microscope it can build, and it further exploits the LHC, transforming it to a precision Higgs facility and leading to BSM.

The novel electron ERL will be an ideal complement also of the HE LHC and later the FCC.

DIS needs to be kept to be an integral part of HEP at TeV scales. There is a way forward.
“The future belongs to those who believe in the beauty of their dreams.”

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015
can one build a 2 km long linac?

it has been done before
Can CERN host pp and DIS at once?
.. in the 80ies it successfully did

Charged Currents

BEBC, \textbf{CDHS(W)}, CHARM, CHORUS

Neutral Currents

\textbf{BCDMS}, EMC, SMC, COMPASS

"We have two tasks: kill Weinberg Salam, kill QCD"
Carlo Rubbia: 1978 BCDMS meeting at Dubna.
The failure to fulfill his task made Carlo famous…

UA1

Pierre Darriulat
now in Vietnam

UA2
Many thanks to the LHeC/FCC-eh collaborators, the IAC, to CERN and our labs
backup
## Installation Study

Detector fits in L3 magnet support

### 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>
</tr>
</thead>
<tbody>
<tr>
<td>DETECTOR CONTRUCTION ON SITE TO START BEFORE LHC LONG SHUT-DOWN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC LONG SHUTDOWN START (T0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COIL COMMISSIONING ON SURFACE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACTUAL DETECTOR DISMANTLING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PREPARATION FOR LOWERING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOWERING TO CAVERN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCAL MODULES &amp; CRYOSTAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CABLES &amp; SERVICES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BARREL MUON CHAMBERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENDCAPS MUON CHAMBERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRACKER &amp; CALORIMETER Plugs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEAMPIPE &amp; MACHINE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DETECTOR CHECK-OUT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC LONG SHUTDOWN END (T0+24m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First FCC-eh Simulations

FCC-he

50 TeV p vs 60 GeV e^- 
H → bb
<table>
<thead>
<tr>
<th>item</th>
<th>HKN07</th>
<th>EPS09</th>
<th>DSSZ</th>
<th>nCTEQ</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order pQCD</td>
<td>LO &amp; NLO</td>
<td>LO &amp; NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NNLO</td>
</tr>
<tr>
<td>NC e+A / e+d DIS</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>NC</td>
</tr>
<tr>
<td>Drell-Yan II in p+A / p+d</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>--</td>
</tr>
<tr>
<td>RHIC pions in d+Au / p+p</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>--</td>
</tr>
<tr>
<td>Neutrino-nucleus DIS</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td>CC</td>
</tr>
<tr>
<td>√Q² cut in DIS</td>
<td>1 GeV</td>
<td>1.3 GeV</td>
<td>1 GeV</td>
<td>2 GeV</td>
<td>free</td>
</tr>
<tr>
<td># of data points</td>
<td>1241</td>
<td>929</td>
<td>1579</td>
<td>740</td>
<td>many</td>
</tr>
<tr>
<td>Free parameters</td>
<td>12</td>
<td>15</td>
<td>25</td>
<td>17</td>
<td>O(20)</td>
</tr>
<tr>
<td>Error sets available</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>(y)</td>
</tr>
<tr>
<td>Error tolerance Δχ²</td>
<td>13.7</td>
<td>50</td>
<td>30</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Baseline</td>
<td>MRST98</td>
<td>CTEQ6.1</td>
<td>MSTW08</td>
<td>CTEQ6M?</td>
<td>None – or ep+eD+eA</td>
</tr>
<tr>
<td>Heavy quark treatment</td>
<td>ZM_VFNS</td>
<td>ZM_VFNS</td>
<td>GM_VFNS</td>
<td>GM_VFNS</td>
<td>s,c,b data</td>
</tr>
</tbody>
</table>
# Electron-Hadron Scattering at the Energy Frontier –
A Higgs Physics Facility Resolving the Substructure of Matter

Draft Table of Contents (9. June 2016)

1. Introduction: The LHC, Modern Particle Physics and the Rôle of ep/eA
2. Physics: QCD/PDFs, Higgs, top, BSM, small x, eA at the LHeC; key items at 1.9/3.4 TeV
3. ERL electron beam: Design, Components, Injector, Dump, Civil Engineering ..
4. LHeC Performance: Collider Parameters, Luminosity, Joint Operation, Infrastructure..
5. Detector: Machine Interface (IR), Design and Performance, Components, Software
6. Installation of the Machine and Detector
7. Summary

Appendix:
- Status of the LHeC Demonstrator and ERL Developments
- Cost-Energy Relation and Cost Estimate for LHeC
- Detector Cost Estimate
- Extensions into the HE LHC Phase
- Electron-Hadron Scattering with the FCC (link to FCC CDR)

LHeC CDR update because:
- Lumi * 10
- LHC results
- Technology progress

Open for any participation

Update of the LHeC CDR*) and input to EU Particle and Nuclear Physics Strategy

*) arXiv:1206.2913

Interaction Regions for ep with Synchronous pp Operation

Likely one IR.
Matching e and p beams
Limit synchrotron radiation
Design of inner magnets
Beam-beam effects ....

Tentative: $\epsilon_p=2\mu\text{m}$, $\beta^*=20\text{cm} \rightarrow \sigma_p=3\mu\text{m} \approx \sigma_e$ matched! $\epsilon_e=5\mu\text{m}$ ....

LHeC (CDR)
60 GeV * 7 TeV

FCC-he (ERL)
60 GeV * 50 TeV
LHeC Detector baseline design.
LHeC/FCC-he Civil Engineering

LHC Point 8 & FCC Long Straight Section L
Further Study

TO BE STUDIED

8 fold way .. for serving LHC+FCC
Top Quark Electro-Weak Interactions

precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations): top quark expected to be most sensitive to BSM physics, due to large mass

- high precision measurements of $V_{tb}$ and search for anomalous $W_{tb}$ couplings
- measurement of top isospin and search for anomalous $t\bar{t}Z$ couplings (e.g. EDM, MDM)
- direct measurement of top quark charge and search for anomalous $t\bar{t}\gamma$ couplings (e.g. EDM, MDM)
- sensitive search for FCNC couplings will constrain BSM models that predict FCNC (e.g. SUSY, little Higgs, technicolour)
BDT Results Higgs→cc

For analysis and variables, c.f. U Klein LHeC Workshop

NEW: Using $R = 0.5$ anti-kt jets and ATLAS IBL vertex resolution (5 μm)

→ Hcc candidates increased by factor 3.5 w.r.t. anti-kt $R=0.9$ jets

1000 fb$^{-1}$
All backgrounds assumed to 2%, i.e.
14000 Hbb evts.
→ $\kappa(\text{Hbb}) \sim 1\%$

BDT cut >0.2: Hcc Signal events: 474
S/VS+B=12.8  → $\kappa(\text{Hcc}) = 5\%$ for 1000 fb$^{-1}$

Clear potential to access the Higgs to charm decay channel at the LHeC.
The electron beam upgrade has a place in between the recently endorsed luminosity and the not unlikely energy upgrade of the LHC. It builds on the biggest investment particle physics ever enjoyed and helps sustaining its future with a seminal physics programme [SM+BSM].

It provides a new, independent energy and intensity frontier collider configuration which fits to the needs of both particles and nuclear physics and its collaborating communities.

That may be realised, with the required courage and realism, bridging well to future, expensive ee and pp machines which it complements too.

The DIS environment of the LHeC is extremely precise which gives theory a variety of fundamental new tasks and the experimentalists a novel GPD.

Thank you.

Many thanks to CERN’s directors, the IAC, the FCC team and the ep/h community engaged
PDF precision matters at the LHC

Cf also talks by Jan Kretzschmar and Sasha Glazov and others