A 5th Element for the LHC

An ep/ea collider experiment at the energy frontier. “Electrons to the LHC”.

Introduction
Accelerator
Detector
Project
Recognition

Max Klein
For the LHeC/FCCeh Study Group

Illustrations and Remarks at
DIS2018, Kobe, 20.04.2018
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS

CDHS

CERN-EP/89-07
January 17th, 1989

CERN-EP/89-103
15 August 1989
Physics with Energy Frontier DIS

Raison(s) d’etre of the LHeC

- Cleanest High Resolution Microscope: QCD Discovery
- Empowering the LHC Search Programme
- Transformation of LHC into high precision Higgs facility
- Discovery (top, H, heavy ν’s..)
- Beyond the Standard Model

A Unique Nuclear Physics Facility
.. and yet, ep is usually treated like the early Cinderella

- Needs radiant appearance (lumi, physics, technology), readiness to work, a bit of luck +
LHC Physics

Superb LHC performance, reliable detectors and great experimental art

- 2000 LHC papers published (ATLAS 100/year). No BSM Physics observed
- Discovery of the Higgs Boson (Mass to $W, Z, \text{fermions} + \text{portal to BSM}??)
- Surprisingly high precision (e.g. ATLAS $W$ mass to $19 \text{MeV} \rightarrow 0.02\%$)

- The LHC exploits large majority of HEP physicists, ATLAS: $\sim 900$ on upgrade

LHC may now be expected to operate until 2040. How can we sustain its success?
Accelerator

Very detailed design in the CDR 2012

Update since then: rise of luminosity to pursue Higgs and BSM physics
Detailed simulation, ATS optics, simultaneous ep-pp operation. Dedicated?

Update of the IR $\rightarrow$ to conclude for Orsay workshop

Choice of frequency (801.58 MHz, cavity)

ERL demonstrator and technology development facility (PERLE).
Present default configuration, 60 GeV, 3 passes, 802 MHz, synchronous ep+pp, $L_{ep}=10^{34}$
you never walk alone
Chapter 9 of CDR

9 System Design
9.1 Magnets for the Interaction Region
9.1.1 Introduction
9.1.2 Magnets for the ring-ring option
9.1.3 Magnets for the linac-ring option
9.2 Accelerator Magnets
9.2.1 Dipole Magnets
9.2.2 BINP Model
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9.3 Ring-Ring RF Design
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9.3.2 Cavities and klystrons
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9.8 Cryogenics
9.8.1 Ring-Ring Cryogenics Design
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9.9 Beam Dumps and Injection Regions
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9.9.5 Absorber for 140 GeV Linac-Ring option
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9.9.7 Beam line dump for ERL Linac-Ring option
9.9.8 Absorber for ERL Linac-Ring option

Components and Cryogenics

<table>
<thead>
<tr>
<th></th>
<th>Ring</th>
<th>Linac</th>
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<tr>
<td>magnets</td>
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<tr>
<td>number of dipoles</td>
<td>3080</td>
<td>3504</td>
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<td>dipole field [T]</td>
<td>0.013 – 0.076</td>
<td>0.046 – 0.264</td>
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<td>number of quadrupoles</td>
<td>968</td>
<td>1514</td>
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<td>RF and cryogenics</td>
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<tr>
<td>number of cavities</td>
<td>112</td>
<td>960</td>
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<td>gradient [MV/m]</td>
<td>11.9</td>
<td>20</td>
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<td>linac grid power [MW]</td>
<td>–</td>
<td>24</td>
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<td>synchrotron loss compensation [MW]</td>
<td>49</td>
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<td>cavity voltage [MV]</td>
<td>5</td>
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<td>cavity R/Q [Ω]</td>
<td>114</td>
<td>285</td>
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<td>cavity Q₀</td>
<td>5.4@4.2 K</td>
<td>300@2 K</td>
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<tr>
<td>cooling power [kW]</td>
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</table>

Need to develop LHeC cavity (cryo-module) [2013]

systems will consist of a complex task. Further cavities and cryomodules will require a limited R&D program. From this we expect improved quality factors with respect to today's state of the art. The cryogenics of the L-R version consists of a formidable engineering challenge, however, it is feasible and, CERN disposes of the respective know-how.
# Luminosity for LHeC, HE-LHeC and FCC-ep

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
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<tr>
<td>$E_p$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>12.5</td>
<td>50</td>
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<tr>
<td>$E_e$ [GeV]</td>
<td>60</td>
<td>60</td>
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<td>60</td>
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<td>$\sqrt{s}$ [TeV]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.7</td>
<td>3.5</td>
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<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>2.5</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma \epsilon_p$ [$\mu$m]</td>
<td>3.7</td>
<td>2</td>
<td>2.5</td>
<td>2.2</td>
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<tr>
<td>Electrons per bunch [10^9]</td>
<td>1</td>
<td>2.3</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Electron current [mA]</td>
<td>6.4</td>
<td>15</td>
<td>20</td>
<td>20</td>
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<tr>
<td>IP beta function $\beta^*_p$ [cm]</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>15</td>
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<td>Hourglass factor $H_{geom}$</td>
<td>0.9</td>
<td>0.9</td>
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<td>Pinch factor $H_{b-b}$</td>
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<td>Proton filling $H_{coll}$</td>
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<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Luminosity [$10^{33}$cm^{-2}s^{-1}]</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>15</td>
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</tbody>
</table>

Contains update on eA: 6 $10^{32}$ in e-Pb for LHeC.
Interaction Region

Serve 3 beams
Need head-on ep collisions
Magnets, Pipe, Masks, Backgrounds..

A Fast Track R&D Quadrupole Magnet Concept
R&D Proposal for a “Fast Track” High Field Nb₃Sn Actively Shielded Quadrupole
A compact structure is needed to provide Nb₃Sn coil prestress. Our preliminary modeling results are very encouraging.

Space needed for Hadron Beam, Forward Charged Particles and Neutrons (ep & e⁺A)
Again 9.3 T at coll but few gauss at e-beam!

CDR 2012
may not need half quad if L*(e) < L*(p)

IR design week in May at CERN: G Arduini, H Burkhardt, E Cruz, B Holzer, P Kostka, H ten Kate R Martin, B Parker, S Russenschuck, R Tomas with O Bruening and MK → Orsay workshop
Detector

Detailed, complete design, including taggers exists in the CDR

Update of technology – related to ILC, HL LHC developments

New tracker concept (for B tagging and displaced vtx)

Software (DD4HEP, integration into FCC detector software..)

Design will develop until it will be built..

IR being revisited

Easy: pileup 0.1, rad level: 1/100 of LHC
Challenging: synchrotron radiation and backgrounds in IR

Crucial: Modularity for fast installation. Cost+effort to stay reasonable

IF CERN/HEP decided for HE LHC: LHeC detector would be designed for 14 TeV
LHeC Detector for the HL/HE LHC

Length x Diameter: LHeC (13.3 x 9 m$^2$)  HE-LHC (15.6 x 10.4)  FCCeh (19 x 12)
ATLAS (45 x 25)  CMS (21 x 15):  [LHeC < CMS, FCC-eh ~ CMS size]

If CERN decides that the HE LHC comes, the LHeC detector should anticipate that
Hadronic Tile Calorimeter

Outside Coil: flux return
Modular. ATLAS experience.

Combined GEANT4 Calorimeter Simulation
$H \rightarrow bb$ in LHeC Detector
### Dimensions and Multitudes - LHeC

#### Tracker

<table>
<thead>
<tr>
<th>Tracker</th>
<th>FST pix</th>
<th>FST strix</th>
<th>CFT pix</th>
<th>CPT pix</th>
<th>CST strix</th>
<th>CBT pix</th>
<th>BST strix</th>
<th>BST pix</th>
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<td>#Wheels</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>3</td>
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<td>#Rings/Wheel</td>
<td>2&lt;sub&gt;inner&lt;/sub&gt;</td>
<td>3&lt;sub&gt;outer&lt;/sub&gt;</td>
<td>3/4</td>
<td>-</td>
<td>-</td>
<td>3/4</td>
<td>3&lt;sub&gt;outer&lt;/sub&gt;</td>
<td>2&lt;sub&gt;inner&lt;/sub&gt;</td>
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<tr>
<td>#Layers</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>$\theta_{min/max}$ $[^{0}]$</td>
<td>0.7</td>
<td>3.8</td>
<td>3.0</td>
<td>5.1</td>
<td>24/155</td>
<td>177.8</td>
<td>173.1</td>
<td>178.7</td>
</tr>
<tr>
<td>$\eta_{max/min}$</td>
<td>5.1</td>
<td>3.4</td>
<td>3.6</td>
<td>$\pm 3.1$</td>
<td>$\pm 1.4$</td>
<td>-3.6</td>
<td>-2.8</td>
<td>-4.5</td>
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<tr>
<td>Si&lt;sub&gt;pix/strix&lt;/sub&gt; $[m^2]$</td>
<td>6.9</td>
<td>9.5</td>
<td>2.8</td>
<td>5.4</td>
<td>33.7</td>
<td>2.8</td>
<td>5.7</td>
<td>4.1</td>
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<td>Sum-Si $[m^2]$</td>
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</table>

70.9 double layers taken into account

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#### Calo

<table>
<thead>
<tr>
<th>Calo</th>
<th>FHC&lt;sub&gt;SiW&lt;/sub&gt;</th>
<th>FEC&lt;sub&gt;SiW&lt;/sub&gt;</th>
<th>EMC&lt;sub&gt;SciPb/LAr&lt;/sub&gt;</th>
<th>HAC&lt;sub&gt;SciFe&lt;/sub&gt;</th>
<th>BEC&lt;sub&gt;SiPb&lt;/sub&gt;</th>
<th>BHC&lt;sub&gt;SciFe&lt;/sub&gt;</th>
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<tr>
<td>$\theta_{min/max}$ $[^{0}]$</td>
<td>0.61</td>
<td>0.68</td>
<td>8/166</td>
<td>14.2/160</td>
<td>178.7</td>
<td>178.9</td>
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<tr>
<td>$\eta_{max/min}$</td>
<td>5.2</td>
<td>5.1</td>
<td>2.7/-2.1</td>
<td>2.1/-1.7</td>
<td>-4.5</td>
<td>-4.7</td>
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<tr>
<td>Volume $[m^3]$</td>
<td>6.7</td>
<td>1.6</td>
<td>15.1</td>
<td>165</td>
<td>1.6</td>
<td>5.8</td>
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<tr>
<td>Sum-Si $[m^2]$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>197.4</td>
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**Goal:** Feasibility study, acceptance + calibration + sensitivity to match to eh physics
Such as: forward tracking, high resolution of hadronic final state, HQ vertexing...
Latest status provided in talk by Peter Kostka at FCC week Amsterdam

A future collaboration will change such a design certainly but it should be feasible
**LHeC (CDR) Solenoid 3.5 T, 2.24 m OD, 7.1 m L**

It will look like...........a stretched and squeezed ATLAS solenoid,

2 T scaled up to 3.5T (2 layer coil, slightly less free bore but a bit longer)

Relatively small bore but long, and efficient coil with 1.8 m free bore, 7.1 m long

- \( \approx 11 \text{ km Al stabilized NbTi/Cu superconductor for 10 kA} \)
- \( \approx 80 \text{ MJ stored energy and } \approx 24 \text{ t mass including cryostat} \)

No specific R&D needed, except detailed analysis of the dipole load case

- Design concept: minimum cost, R&D and risk, relies on present technology for detectors magnets
- **3.5 T Solenoid & 2 Dipoles** in same cryostat around EMC, Muon tagging chambers in outer layer
- Solenoid and dipoles have a common support cylinder in a single cryostat; free bore of 1.8 m; extending along the detector with a length of 10 m.
Installation Study
to fit into LHC shutdown needs
directed to IP2
Andrea Gaddi et al

Detector fits in L3 magnet support

Modular structure

**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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<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>BARREL MUON CHAMBERS</td>
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<td>ENDCAPS MUON CHAMBERS</td>
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<td>TRACKER &amp; CALORIMETER PLUGS</td>
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<td>BEAMPIPE &amp; MACHINE</td>
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Project Issues

PERLE

Cost-Energy-Civil Engineering

Transition of $O(10)$ years from HL-HE [?] LHC

Milestones – then and next

Integration into FCC Study [includes HE LHC]

Recognition
Powerful ERL for Experiments at Orsay

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

Max Klein Kobe 17.4.18
Why PERLE [as seen from LHeC]?

FUNDAMENTAL MOTIVATION:

- Validation of key LHeC Design Choices
- Build up **expertise** in the design and operation for a facility with a fundamentally new operation mode:
  - ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)
- Proof validity of fundamental **design** choices:
  - Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  - Implications of high current operation (2 * 3 * [6mA – 25mA] ⇒ 30-150mA!!)
- Verify and test machine and operation **tolerances** before designing a large scale facility
  - Tolerances in terms of field quality of the arc magnets and cavity alignment
  - Required RF phase stability (RF power) and LLRF requirements
  - Halo and beam loss tolerances

PERLE Collaboration meeting in Daresbury: 15-16 January 2018

Oliver Brüning, CERN
First 802 MHz Cavity Produced with Superb Performance

TDR by mid 2019 (town meeting of the European PP community)
BINP, CERN, Daresbury, Liverpool, Jlab, Orsay (IPN+LAL) – open for further participation

Technical developments accompanying ERL development (e.g. Jlab’s 7 GeV ERL synrad test)

PERLE operational in the early twenties - in time for LHeC in LS4 (2030)

Thank you and many congratulations
First 802 MHz Cavity Produced with Superb Performance

TDR by mid 2019 (town meeting of the European PP community)
BINP, CERN, Daresbury, Liverpool, Jlab, Orsay (IPN+LAL) – open for further participation

Technical developments accompanying ERL development (e.g. Jlab’s 7 GeV ERL synrad test)

PERLE operational in the early twenties - in time for LHeC in LS4 (2030)
Tunnels: Triple Arc and LINACs

Preliminary [1 or 2?]
CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich. Detailed estimate of cost and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

**More studies will be needed** for
- Integration with all services
- (EL,CV, transport, survey etc).
- Geology
- Understanding vibration risks
- Environmental impact assessment

Tunnel connection in IP2
Location, Footprint, Use of the Electron Racetrack

e beam external to LHC. Location suitable for both HL and HE LHC.

Energy – Cost – Physics – Footprint are being reinvestigated for EU strategy
Further use of ERL in between HL and HE LHC

Reconfiguring LHeC → SAPPHiRE

LHeC-ERL

SAPPHiRE*

γγ Higgs factory

*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons
'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

F. Zimmermann at LHeC WS 9/17

LHeC: perfect FCC-ee injector!

10 GeV cw linac

3 or 4 loops

e+ target at ~9 GeV

e+ damping ring

e+ source

LHeC-FEL

up to 60 GeV,
~25 mA,
1 MeV photons?

3-15x higher beam energy
(10-200x higher γ energies),
300-600x higher current

XFEL: 20 GeV e, 0.03 mA, 24 keV photons. LCLSII: 4 GeV e, 0.06 mA, 5 keV photons
Recognition and Outlook

Theorists

Past

Future
LHeC had enjoyed strong attention and support of theory community: van Neerven, Altarelli Lipatov, Tung … to a new generation of impressive theorists who recently strengthens ep
Determination of SM Higgs Couplings, **HL-LHC** and **LHeC → LHC**

The addition of ep to pp (LHeC to LHC (HL,HE) and FCC-eh to FCC-pp) transforms these machines into precision Higgs facilities. **Vital complementarity with e⁺e⁻ (JdB Amsterdam)**

Note that the HL LHC prospects are being updated (HL/HE LHC Physics workshop).

**ttH at LHeC to 15%**
new physics can manifest indirectly as modifications to “known” physics
The LHeC has been a large community effort involving many of us. It is there to proceed.
An electron–proton collider could bridge the gap between the LHC and its successor

Frédéric Bordry, CERN’s director for accelerators and technology. The project needs more support from the particle-physics community, he notes. “The next European strategy for particle physics will be very important for the LHeC.” The strategy recommendations are slated to come out in 2020, and decisions may be delayed beyond that.

Toni Feder

MAY 2017 | PHYSICS TODAY 31
Time to unite pp with ep and ee

Josh Rudermann, FCC week Amsterdam
Time to unite pp with ep and ee
DIS and pp at CERN some 30-40 years ago

UA1

"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…

UA2

Pierre Darriulat

Charged Currents

BEBC, CDHS(W), CHARM, CHORUS

Neutral Currents

BCDMS, EMC, SMC, COMPASS
“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
The LHeC is not the first racetrack of the world. It can be built and will lead to fundamental progress in particle physics and technology in our lifetimes, the elder ones included.
An early racetrack embedded in the Vatican (XV century)

Seguìl tuo corso, e lascia dir el genti (Dante, KM)... and success to the EICs. Thanks Yuji+
HL LHC offers unique opportunity for ep and eA detector in the 30ies

O Bruening, F Bordry
Physics Considerations on the Choice of $E_e$

**SM Higgs Couplings**

$H \to bb$ (cc): 0.5 (4)% coupling uncertainty, for $1ab^{-1}$, 60 GeV, polarised

This becomes 2(15)% for $0.5ab^{-1}$ and 30 GeV: Under these conditions one looses high H precision and the ep portal to new physics potential and the neutral current Higgs programme disappears

**New Higgs+top Physics**

**Heavy new objects**: Htt coupling: 17 $\to$ 31 % for $60 \to 40$ GeV (M Kumar)

Discovery potential for anomalous tqH: 0.5 – 3.2 -22% precision for $60 \to 50 \to 40$ GeV (H Sun). At 40 GeV the discovery potential is gone.

**Longitudinal Structure Function – THE path to saturation**

Low x physics: Saturation requires 1% measurement of $F_L$. That needs $y=0.9=1-E'/E_e$. HERA: big complication: $E'$ at high $y$ too small for precision (eID, background, charge symmetry): needs $\sim$twice $E_e$ to be safe.

→ 50 GeV the programme stands, 40 GeV it looses BSM, t, 30 GeV: precision gone
→ Keep the electron energy as high as it can be afforded, and not lower than 50 GeV