Physics and design of the eh detector

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aaaa (remote presentation)
This talk

• $ep/eA$ physics, collision kinematics and detector requirements
  – for DIS and for Higgs / EW / Top / BSM physics

• Detector for FCC-eh: extension from LHeC baseline detector
  – IP and Magnet
  – Central tracker and beam pipe
  – (Calorimetry, Muon System, Forward/backward detectors, LHeC version, in backup)

• Challenges and possible improvements for FCC-eh
The LHeC and FCC-eh accelerators

- Electrons from dedicated Energy Recovery Linac (ERL)
- Hadrons from LHC/FCC rings

LHeC baseline:
50 GeV(e) × 7 TeV (p) 2.76 TeV/nucl. (A)
- \( \sqrt{s} = 1.18 \) (p) or = 0.74 (A) TeV
- \( 10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
- Electrons via 3-track ERL
  ~1/4 of LHC circumference

60 GeV(e) × 20 - 50 TeV (p)
7.9 - 19.7 TeV/nucl. (A)
- \( \sqrt{s} = 2.2 - 3.5 \) (p) or 1.4 - 2.2 (A) TeV
- \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
High-energy $ep/eA$ collisions

- Structure of nucleon and nuclei through DIS
- Higgs couplings
- Precision EW and QCD physics
- BSM physics
  - Leptoquarks, heavy neutrinos, ...

All measured with small pile-up and well-controlled detector

  - redundant kinematics from $e$ and jet: also for calibration

\[ Q^2 = -(k - k')^2 \]
**DIS kinematic plane and event topology**

\[ Q^2 = -(k - k')^2 = -q^2 \]

\[ x = \frac{Q^2}{p \cdot q}, \quad y = \frac{p \cdot q}{p \cdot k} \]

\[ s_{xy} = Q^2 \]

- **Assymmetric energy flow**
  - particles go to incoming proton direction (forward), \( e \) to backward
- But they go to **everywhere** in practice, especially in small angles

**QCD radiation between scattered parton and proton remnant**
Processes & Challenges (1): Neutral Current (NC) $ep \rightarrow eX$

**low-$x$ / low-$Q^2$ events**
- Scattered electron ($e$) towards small angle ($< 179^\circ$)
- Hadrons ($X$) go to forward (low-$y$) OR backward (high-$y$)
- High-$y$ = small energy $e$ to be distinguished with $\pi^\pm/\pi^0$ from photoproduction events $\gamma p \rightarrow X$
- $b/c$ tagging for decomposing pdf beyond $\eta = 3$

**high-$x$ / high-$Q^2$ events**
- Electrons almost everywhere
- Very high-energy jets ($O(\text{TeV})$) also everywhere, especially in forward

- **Hermetic and thick EM and Hadron calorimetry**
  - Fine granularity for $e/\pi$ separation (esp. backward = $e$ direction)
- **Fine-pitch + small $X_0$ tracking for vertexing**
  - For heavy-flavour tagging (esp. forward)

An NC (leptoquark) event at LHeC
Processes & Challenges (2): Charged Current (CC) $ep \rightarrow \nu X$

- Final state: a jet (like high-$x$ / high-$Q^2$ NC), but w/o scattered $e$
  - Kinematics should be reconstructed only from the hadronic system angle and missing $p_T$
- This also helps for:
  - QCD studies with jets
    - including photoproduction ($e \rightarrow e'\gamma$, $\gamma p \rightarrow X$)
  - detector cross-calibration using NC DIS:
    - two energies and angles ($e$ and hadronic system): over-constrained

- Hermeticity (esp. forward)
- good HadCal resolution ($e/h$ etc.)
  - tracking should help (particle flow algorithm)
Processes & Challenges (3) Higgs / EW / top / BSM

- Higgs
  - Thru WW fusion in CC or ZZ in NC:
    - need to detect forward “VBF jet”
  - Precise coupling to $b\bar{b}, c\bar{c}$, and $\tau\tau$:
    - Need very good flavour tagging in forward direction
    - Jet resolution for mass reconstruction
- EW and top physics
  - similar mass range:
    - similar requirement for flavour and jets
- BSM physics
  - high-mass $\rightarrow$ large-$x$ events

![Diagram of Higgs processes](image)

**generic detector for high-$Q^2$ NC/CC should also serve for these processes**
Machine-detector interface: IP and magnets (from LHeC)

- Dipole magnet integrated in the detector to bend electron beam
  - Beam-2 p and e brought in head-on collisions
  - Beam-1 in a different plane
- Detector needs to be away and shielded from the synchrotron radiation fan

LHeC: New IR design for both $e\bar{h}$ and $h\bar{h}$ collisions at IR2

courtesy Daniel Hanstock from his master thesis
The baseline LHeC detector

Covering from 1 to 179 degrees

- All-silicon tracker with extended forward wheels
  - Covering wide $\eta$ with small $X_0$

- EM calorimeter
  - LAr (barrel) or Si-Pb / Si-W
  - Fine segment EM calo

- Solenoid and dipole

- HCAL
  - Fe/Pb-sci. or Si-W
  - Si-W (endcap forw.)
  - Good resolution for HCAL
  - Rad-hard for very forward Calo

- Muon system
  - Embedded in return yoke

+ Forward/backward detectors along beamline

Aiming for compact, modular and very hermetic detector
Fulfilling the requirements
Detector design for FCC-eh – extension of the LHeC detector

- Proton 20 and 50 TeV, electron 60 GeV
  - Almost no change in low-mass event properties (e.g. Higgs) while new high-mass objects would be detected in very forward rapidities.

- Design for LHeC with extended volume / layers will serve also for FCC-eh
  - Forward/Central: scales in $\sim \log E_{\text{had}}$ for calo

The Low-E FCC-eh detector similar size to CMS

Total length 13.3 → 20.4m
Radius 4.9 → 7.2m
Central tracker also with (possibly tilted) wheels
Fwd tracker 4 → 8 disks
Bwd 2 → 6 disks
HadCal:
12-15 interaction lengths

Most demanding: forward detectors
Central tracker extension for FCC-eh

- More layers in Forward / Backward
  - 6m (LHeC) to 9.2m in length, rapidity coverage 5.3 → 5.6
  - # of forward disk: 4 → 7 or 8
- Planar (cost) and inclined (performance) options being considered
  - Inclined option: < 10% of $X_0$ achieved all over
- Area of rapid development: the final design would be further optimised

<table>
<thead>
<tr>
<th>Pitch (μm)</th>
<th>$r \phi$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>macro pixel</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>strip</td>
<td>100</td>
<td>10-50mm</td>
</tr>
</tbody>
</table>
Barrel sensors and beampipe (version LHeC)

- Elliptical beampipe to accommodate synchrotron radiation fan
- Innermost layers are bent (developed for ALICE)

Efforts from DRDS 8.3 (ultra-light stable high precision mechanics, Machine-detector interfaces) should be pursued
Detector challenges for FCC-eh

Officially the detector is thought to be relatively "easy"

- cross section 1/1000 of $pp$ collisions: radiation ~ lower by $>2$ digits
- almost no pile-up

But there are many points of improving, worth joint efforts with ee/hh teams

- New development on mechanics & MDI
- Better resolution for jets by barrel Calo: CC precision
- Imaging calorimeter for backward ($e/\pi$ separation), **forward (energy flow for $\eta > 3$)**
- Targeting track resolution at 5$\mu$m or better, also in as forward region as much
- Tracker closer to the beam pipe, with secondary vacuum vessel
- Rad-hard technology for very forward detectors e.g. Zero-degree Calo (50 TeV neutrons)
- **...**
hh collisions at the FCC-eh IP

• The eh detector is optimised for precision measurement
• low-pileup $pp$ collisions for precision SM physics at the FCC-eh IP may perform better
  – with higher acceptance to lower $p_T$ (moderate B field)
  – with high-$\eta$ detectors chosen for precision rather than radiation
  – ... and detectors will be better calibrated through DIS events

• Physics from pp at the FCC-eh detector
  – QCD measurements with calibrated detector are interesting
  – EW and top measurements: maybe not much items left after FCC-ee and eh runs?
    There may well be benefits in $ep$: to be studied.
Summary

• A short review on DIS kinematics and detector challenges for FCC-eh
  – Most requirements quite similar to that for LHeC
  – Forward detectors are more demanding

• A version of the FCC-eh baseline detector
  – extension of the LHeC detector, which performs well also for FCC-eh

• The detector does not have to be ready today
  – more ambitious options for precision
    e.g. E resolution, calorimeter imaging, low-$X_0$ tracker, timing and PID ...
  – and with less impact to environment: reduced cost, power consumption ...
BACKUP
Detector design studies for LHeC and FCC-eh

- Detector designs for future highest-energy \( ep/eA \) colliders
  - for FCC-eh detector in FCC CDR vol. 3 [EPJ Special Topics 228, 755-1107(2019)](https://doi.org/10.1051/epjst/e2019228_755)
  - Accelerator design optimisation (ERL 60 → 50 GeV, higher lumi etc.)
  - Physics (e.g. Higgs), technology advancement + variation
  - Low-E FCC-eh detector design also presented
- OFFSHELL-2021 – The virtual HEP conference on Run4@LHC
  - Accepted as a contribution with a reviewed paper, published in EPJC [Eur.Phys.J.C 82 (2022) 1, 40](https://doi.org/10.1140/epjc/s10052-022-10114-5)
  - Extension to \( hh \) collisions discussed
- Further development in IP design in 2021/2022 for concurrent \( eh/hh \) operation
LHeC Calorimeters

Complete coverage to ± 5 in (pseudo)rapidity


Forward Region: dense, high energy jets of few TeV

H → bb and other reactions demand resolution of HFS

Backward Region: in DIS only deposits of E < E_e

Barrel Calorimeters

<table>
<thead>
<tr>
<th>Calo (LHeC)</th>
<th>EMC</th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readout, Absorber</td>
<td>Sci,Pb</td>
<td>Sci,Fe</td>
</tr>
<tr>
<td>Layers</td>
<td>38</td>
<td>58</td>
</tr>
<tr>
<td>Integral Absorber Thickness [cm]</td>
<td>16.7</td>
<td>134.0</td>
</tr>
<tr>
<td>$\eta_{\text{max}}, \eta_{\text{min}}$</td>
<td>2.4, -1.9</td>
<td>1.9, 1.0</td>
</tr>
<tr>
<td>$\sigma_E/E = a/\sqrt{E} + b$ [%]</td>
<td>12.4/1.9</td>
<td>46.5/3.8</td>
</tr>
<tr>
<td>$\Lambda_I / X_0$</td>
<td>30.2</td>
<td>8.2</td>
</tr>
<tr>
<td>Total area Sci [m²]</td>
<td>1174</td>
<td>1403</td>
</tr>
</tbody>
</table>

Forward/Backward Calorimeters

<table>
<thead>
<tr>
<th>Calo (LHeC)</th>
<th>FHC Plug Fwd</th>
<th>FEC Plug Fwd</th>
<th>BEC Plug Bwd</th>
<th>BHC Plug Bwd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readout, Absorber</td>
<td>Si,W</td>
<td>Si,W</td>
<td>Si,Pb</td>
<td>Si,Cu</td>
</tr>
<tr>
<td>Layers</td>
<td>300</td>
<td>49</td>
<td>49</td>
<td>137.5</td>
</tr>
<tr>
<td>Integral Absorber Thickness [cm]</td>
<td>156.0</td>
<td>17.0</td>
<td>17.1</td>
<td>14.4</td>
</tr>
<tr>
<td>$\eta_{\text{max}}, \eta_{\text{min}}$</td>
<td>5.5, 1.9</td>
<td>5.1, 2.0</td>
<td>-4.5, -4.5</td>
<td>-4.5, -5.0</td>
</tr>
<tr>
<td>$\sigma_E/E = a/\sqrt{E} + b$ [%]</td>
<td>51.8/5.4</td>
<td>17.8/1.4</td>
<td>28.9/7.9</td>
<td>14.4/2.8</td>
</tr>
<tr>
<td>$\Lambda_I / X_0$</td>
<td>$\Lambda_I = 9.6$</td>
<td>$X_0 = 48.8$</td>
<td>$X_0 = 30.9$</td>
<td>$\Lambda_I = 9.2$</td>
</tr>
<tr>
<td>Total area Si [m²]</td>
<td>1354</td>
<td>187</td>
<td>187</td>
<td>745</td>
</tr>
</tbody>
</table>

Radiation environment

• The luminosity: similar to LHC ($O(10^{34}\ \text{cm}^{-2}\text{s}^{-1})$)

• Total cross section: < 1/200

→ Expected # of interactions / second: 1/1000 of the LHC pp

  – # of pileups per bunch $\langle \mu \rangle \approx 0.1$
    
    No need for pile-up correction
    
    Can use PFA and calorimeter variables
    
    without correction (e.g. missing $p_T$, rapidity gap...)

  – # of integrated dose in forward region $\ll 10^{14}\ 1\text{MeV}\ n_{eq}$

• LHeC detector technology is based on HL-LHC upgrade, but

  – that developed for less severe environment (e.g. ILC) is also applicable

  – More aggressive options for performance and price can be used
    
    e.g. very thin Si detector with integrated readout
Central tracker: performance

• Possible further improvements
  – backward beam pipe with smaller diameter (SR fan thinner there)
  – innermost layer in vacuum?

Yellow: barrel sensors
Red: disk sensors
Green: beampipe

Small material budget for entire coverage!

Radiation Length by Category

\( \frac{10 \text{ GeV}}{10 \text{ TeV}} \)

\( \frac{100 \text{ MeV}}{100 \text{ GeV}}: 1\%-3\% \)

\( \frac{1 \text{ TeV}}{10 \text{ TeV}}: 5\%-30\% \)

for \( \eta < 4 \)

\( \delta_{pT} (\%) \)

\( \delta_{d_0} (\text{um}) \)

\( p = 1, 2, 5, 10 \text{ GeV} \)

\( p > 100 \text{ GeV} \)

\( \eta \)

\( \frac{100 \text{ MeV}}{100 \text{ GeV}} \) resolution

\( \frac{1 \text{ TeV}}{10 \text{ TeV}} \) resolution

\( \sim 30 \mu m \) resolution for high momentum tracks at \( \eta \sim 4 \)
Calorimetry

- High-performance barrel ($|\eta| < 2.8$)
  - Baseline: LAr EM inside solenoid with shared cryostat
  - R&D ongoing to make the barrel layer thinner, also cryostat (goal: a few % of $X_0$)
  - Plastic scintillator for good e/h for HadCal
- Fine-segmented plugs with compact shower with Si sensor
  - technology developed for ILC / FCC-ee
- "warm" option
  - Sci-Pb $\rightarrow$ modular (easy install inside the L3 magnet)
  - Comparable performance: LAr still advantageous for resolution, segmentation, radiation stability

<table>
<thead>
<tr>
<th>Baseline configuration</th>
<th>$\eta$ coverage</th>
<th>angular coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM barrel + small $\eta$ endcap</td>
<td>LAr $-2.3 &lt; \eta &lt; 2.8$</td>
<td>$6.6^\circ - 168.9^\circ$</td>
</tr>
<tr>
<td>Had barrel+Ecap</td>
<td>Sci-Fe (- behind EM barrel)</td>
<td></td>
</tr>
<tr>
<td>EM+Had very forward</td>
<td>Si-W $2.8 &lt; \eta &lt; 5.5$</td>
<td>$0.48^\circ - $</td>
</tr>
<tr>
<td>EM+Had very backward</td>
<td>Si-Pb $-2.3 &lt; \eta &lt; -4.8$</td>
<td>$-179.1^\circ$</td>
</tr>
</tbody>
</table>

LAr ($\sim 25X_0$) $8.47/\sqrt{E} \oplus 0.32\%$

Sci-Pb ($30X_0$) $12.55/\sqrt{E} \oplus 1.89\%$
Calorimeter extension for HE-LHeC / FCC-eh

- Solenoid and dipole outside barrel EM calorimeter, similarly as LHeC
- Endcap plugs should be thicker by order of a few $\Lambda_I$ for $7 \rightarrow 20 \rightarrow 50$ TeV steps
  - $9.6 \rightarrow 12.7 \Lambda_I$ (forward endcap) for $7 \rightarrow 20$ TeV
- Challenging: shower separation in very forward rapidity regions

ALICE FoCal pixel ALPIDE (MAPS) test beam data (from FoCAL TDR CERN-LHCC-2020-009)
Muon system

• Baseline: no dedicated magnetic field (solenoid return thru iron only)
  – Momentum by central tracker
  – Good tagging + fast trigger
  – 3-stations, each with ≥ double layer

• HL-LHC technology serves for that
  – Very thin RPC (1mm gas gap) for higher rate capability and timing (<1ns)
  – sMDT: $\phi = 1.5$ cm drift tubes for precise position measurement

• Possible extensions
  – Dedicated forward toroid or outer solenoid
Around zero-degrees

- Backward $e$ tagger + photon tagger
  - for photoproduction and luminosity ($ep \rightarrow e\gamma$)
- Forward Proton spectrometer following the LHC design apart from stations close to IP
- IP design ($eh$-only scheme 2020) allows to place a ZDC
  - Transvers size $\pm 30$ cm: shower leak moderate
  - Aperture very big: 0.35 mrad or 2.4 GeV in $p_T$
- ZDC Technology candidate: Si-W
  - Need $< 1$mm resolution for $p_T$ resolution $\ll 100$ MeV for 7 TeV neutron i.e. very fine segmentation (e.g. ALICE FoCal)
  - Radiation dose: $O(10\text{MGy})$ or more
    - Much less than LHC, possibility to use silicon

\[ \pi^0/n \text{ 0-degree calorimeter} \]
LHeC – HE-LHeC – FCC-eh

HE-LHeC still fits inside the L3 magnet!
Running the LHeC detector for $hh$ collisions

The LHeC detector is very similar to:

- the general purpose LHC detectors
  - covering beyond $|\eta| < 5$
  - even more if symmetrised
- ... and the proposed ALICE3 detector
  - the tracker under similar concept
  - even more if adding outer subsystems
  - TOF also desired for LHeC

from https://indico.cern.ch/event/1063724/, talk “ALICE 3 overview” by M. van Leeuwen
The symmetrised LHeC

- Barrel tracker enlarged (already in baseline LHeC detector)
- Bonus: more acceptance to small angle for electron
  - for low-$Q^2$ / low-$x$