The FCC-eh Detector

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on behalf of the LHeC Study Group

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Outline:

• Introduction
  • Physics Requirements
  • Accelerator and
  • Interaction Region
• Detector and its subcomponents
• Future and Outlook
The LHeC and FCC-eh accelerators

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

LHeC baseline:
- $50 \text{ GeV(e)} \times 7 \text{ TeV (p)}$ 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
- $\sim1/4$ of LHC circumference

FCC-eh:
- $60 \text{ GeV(e)} \times 20 - 50 \text{ TeV (p)}$
- $7.9 - 19.7 \text{ TeV/nucl. (A)}$
- $\sqrt{s} = 2.2 - 3.5 (p)$ or $1.4 - 2.2 (A)$ TeV
- $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Latest and most promising idea to take lepton-hadron physics to the TeV centre-of-mass scale ... at high luminosity

Designed to exploit intense hadron beams in the high luminosity phase of LHC running from mid 2020s
Processes & Challenges at LHeC/FCC-eh

- **Neutral current (NC) \( ep \rightarrow eX \)**
  - Scattered electron \( (e) \) towards small angle (< 179°) to access low-\( Q^2 \) events
  - Hadron \( (X) \) forward-going jets from high-\( x \) events AND from QCD radiation
  - Flavour tagging for decomposing parton-density functions

- **Charged current (CC) \( ep \rightarrow \nu X \)**
  - missing \( p_T \) : need hermetic detector*
  - small beam holes (<1°) + good calorimeter energy resolution

* also important for cross-calibration

A NC (leptoquark) event at LHeC
Processes & Challenges at LHeC/FCC-eh

- **Higgs couplings**
  - Thru WW fusion in CC: forward “VBF jet”
  - Precise coupling to $b\bar{b}$, $c\bar{c}$, and $\tau\tau$:
    - Flavour tagging in forward direction
    - Jet resolution for mass reconstruction

- **EW and top physics**

- **QCD studies (soft and hard)**
  - Also photoproduction $\gamma p \rightarrow X$

- **BSM physics**
Detector Milestones and References

• LHeC CDR 2012:
  – 630 Pages, detailed detector studies and baseline designs

• FCC-eh detector in FCC CDR vol. 3
  – EPJ Special Topics 228, 755–1107(2019)

• CDR update in 2020:
  – Accelerator design optimisation: ERL 60 → 50 GeV, higher luminosity, etc.
  – Physics (e.g. Higgs) updates, technology advancement + variations
  – Low-E FCC-eh detector design also presented

• Offshell-2021 Conference:
  – 06-09 July + paper to EPJ-C
The LHeC Detector

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• Based on LHC experience and HL-LHC upgrade,

• Main Differences:
  – No pile-up (max 0.1) + much less radiation \( O(1/1000) \)
  – Technology developed for elsewhere (e.g. ILC, etc.) may also be applicable

• Aims for compact, modular but very hermetic detector. Coverage from 1 to 179 degrees

LHeC Offshell-2021 Version

Asymmetric detector design: higher energy flow in the forward direction; 7TeV \( p \) vs 50-60 GeV \( e^- \)

Main Components:
  – High acceptance Silicon Tracking System
  – Detector and Steering Magnets
  – Liquid Argon Electromagnetic Calorimeter*
  – Iron-Scintillator Hadronic Calorimeter
  – Forward Backward Calorimeters: Si/W Si/Cu...
  – Muon System, Forward (p/n) /Bwd Taggers (e/\gamma)

* more options also considered
The FCC-eh detector
similar size as CMS

- Proton 20 and 50 TeV, electron 60 GeV
- Design for LHeC with extended volume / layers will serve also for FCC-eh
  - **Forward/Central**: scales in $\sim \log E_{\text{had}}$ for calo
  - Backward 50 or 60 GeV: similar to LHeC

Total length 13 $\rightarrow$ 20 m
Radius 4.8 $\rightarrow$ 6.8 m
Central tracker also with (tilted) wheels
Fwd tracker 4 $\rightarrow$ 8 disks
Bwd 2 $\rightarrow$ 6 disks
HadCal: 12-15 interaction lengths
Interaction Region and B Field

- **Dipole magnet** integrated in the detector to bend electron beam
  - Beam-2 $p$ and $e$ brought in head-on collisions
  - Beam-1 traversing unaffected

- **Updated Field values:**
  - 3 Tesla (solenoid); 0.15 Tesla (dipole)

New re-designed, optimised LHeC IR in CDR 2020

Synchrotron radiation fan (green)

New FCC-eh IP (offshell paper)

*Same Vertex for ep/eA or hh*
Central Tracker & Beam Pipe

- Det. technology advanced since 2012 CDR
- Option: Low-material tracker by DMAPS
  - CMOS sensors (HV-CMOS for this update)
    Readout electronics integrated
- Very thin: 0.1mm for pixel, 0.2mm for strips
  - Small material budget for forward/backward
- Rad hard up to $2 \times 10^{15}$ 1MeV $n_{eq}/cm^2$
  (cf. HL-LHC fluence $\geq 10^{16}$)
- 5-8 layers for $-3.5 < \eta < 4$
  $\geq 2$ hits for $-4.2 < \eta < 5$

Need updated description of the IR, the $e^{-}$ synchr. rad., masks and absorbers etc.

### Pitch (μm)

<table>
<thead>
<tr>
<th></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>10-50 mm</td>
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Circular/elliptical thin beam pipe to accommodate the outgoing synchrotron radiation fan:

- Specs & Studies from LHeC CDR: Beryllium 2.5-3 mm thickness
- Circular($x$)=2.2cm; Elliptical(-$x$)=-10., $y$=2.2cm

Photon Number Density at the IP

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Silicon Tracker

- Very preliminary design:
  - FCC-eh tracker: extend LHeC silicon tracker towards larger $\eta$
  - The chosen technology would allow for precise and redundant track measurements
  - Overall length 9.2 m, Radius 84 cm
  - 11 Forward wheels, 9 backwards

Number of modules with at least one hit

4 strip layers
4 macro-pixel layers
1 pixel layer
1 pixel circ.-elliptical-layer
Silicon Tracker Performance

• Recent technologies allow for lightweight design:

• At large $\eta$ dead material from beampipe and low B field

• Possible further improvements:
  – Thinner backward beam pipe in diameter (SR fan thinner there)
  – OR: Si tracker in second order vacuum - to be evaluated

100MeV – 100 GeV: 1-3%
1TeV: 5-30% for $\eta < 4$

~ 30 $\mu$m resolution for high pT tracks at $\eta \sim 4$
Calorimetry

- High-performance barrel calorimeter
  - Baseline: Liquid Argon EMC, accordion structure (ATLAS like)
  - inside the solenoid with shared cryostat
  - "warm" option:
    - Sci-Pb: no need for cryostat → modular
    - Comparable performance: LAr still advantageous for resolution, segmentation, radiation stability

- Fine-segmented plugs with compact shower (allow for particle flow)
  - technology developed for ILC

<table>
<thead>
<tr>
<th>Baseline configuration</th>
<th>$\eta$ coverage</th>
<th>angular coverage</th>
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<tbody>
<tr>
<td>EM barrel</td>
<td>LAr</td>
<td>$-2.3 &lt; \eta &lt; 2.8$</td>
</tr>
<tr>
<td>Had barrel+Ecap</td>
<td>Sci-Fe</td>
<td>(~ behind EM barrel)</td>
</tr>
<tr>
<td>EM+Had forward</td>
<td>Si-W</td>
<td>$2.8 &lt; \eta &lt; 5.5$</td>
</tr>
<tr>
<td>EM+Had backward</td>
<td>Si-Pb</td>
<td>$-2.3 &lt; \eta &lt; -4.8$</td>
</tr>
</tbody>
</table>
Calorimeter extension for 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 $7 \rightarrow 20 \rightarrow 50 \text{ TeV}$ steps
  - $9.6 \rightarrow 12.7 \Lambda_I$ (forward endcap) for $7 \rightarrow 20 \text{ TeV}$
  - More details in 2020 CDR
- Challenging: shower separation in very forward rapidity regions
- HCAL Barrel region: standard design Iron-Scintillator tiles providing also return flux for Solenoid field

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

- Muons: Higgs, HFL, LFv etc. (tag/trigger/tracking)
- Baseline: no dedicated magnetic field (solenoid return thru iron only)
  - Momentum by central tracker
  - Good tagging + fast trigger
  - 2 Stations, each with 3 layers
- HL-LHC technology serves for that
  - Very thin RPC (1mm gas gap) for higher rate capability and timing (<1ns)
  - sMDT: $\phi = 1.5\text{cm}$ drift tubes for precise position measurement
- Possible extensions:
  - Dedicated forward toroid or outer solenoid

Some Specifications:
- Total area ~ 400 m$^2$
- Single unit detect: 2-5 m$^2$
- Max. rate: 3 kHz/cm$^2$
- Rad. Hard.: 0.3 C/cm$^2$
- Time res.: ~0.4 ns
- Spatial res.: 1 mm (RPC);
  80 µm (MDT single tube)

Magnets options/extensions:
- Use twin solenoid option as proposed for other experiments.
- Field in the fwd/bwd region to allow for tracking would required a dipole field at small angle or a toroidal solution
- To be investigated.

LHeC Adaption from ATLAS Phase-I RPC-MDT assembly
Around zero-degrees

- **Forward Proton spectrometer**
  - following the LHC design apart from stations close to IP

- **New IP design allows to place a ZDC**
  - Transverse size ±30 cm shower leak moderate
  - Aperture ~ 0.35 mrad or 2.4 GeV in $p_T$

- **Technology candidate: Si-W**
  - Need < 1mm resolution for $p_T$ resolution $\ll$ 100 MeV for 7 TeV neutron i.e. very fine segmentation (e.g. ALICE FoCal)
  - Radiation dose: O(10MGy) or more
    - Much less than LHC, possibility to use silicon sensors
Considerations for FCC-eh Forward Detectors

- We believe there should be some locations to have good acceptance for forward proton spectroscopy
- Neutrons with 3x or 7x boost w.r.t. LHeC
  - Radiation almost proportionally more
  - **Need ≪ 1mm resolution for** $p_T$ **resolution below 100 MeV:** this requires very detailed shower profile measurement: need R&D
- Still aperture may be enough
  - similar IP layout as LHeC
  - may be good enough to measure heavy ion breakup
  - may have good enough energy flow measurement
- $pp$ IP similar to LHC and tight, ZDC there may again be too small

Data should definitely be useful for understanding e.g. Ultra High Energy Cosmic Ray shower

Design will follow the accelerator machine layout development

Similar discussion for backward taggers (e/γ) and their use for luminosity measurements. Detailed studies were available for LHeC in CDR-2012
Conclusions

• The LHeC and the FCC-he offer a vast, unique and complementary physics program (QCD, EW, Higgs, top, BSM) to the LHC and beyond.

• The main elements of detector design for LHeC and FCC-eh have been presented and indicate that the LHeC detector with a limited set of extensions should satisfy the performance goals for FCC-eh.

• The possibility of $hh$ collisions in the same IP opens up for unprecedented cross calibration possibilities and measurements in $hh$, $AA$ program.

• To bring the detector design to the next level a detailed description of the FCC interaction region and its machine interface will be needed.
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Thank You!