FUTURE CIRCULAR COLLIDER

The FCC-eh Detector

A. Polini (INFN Bologna)

on behalf of the LHeC Study Group

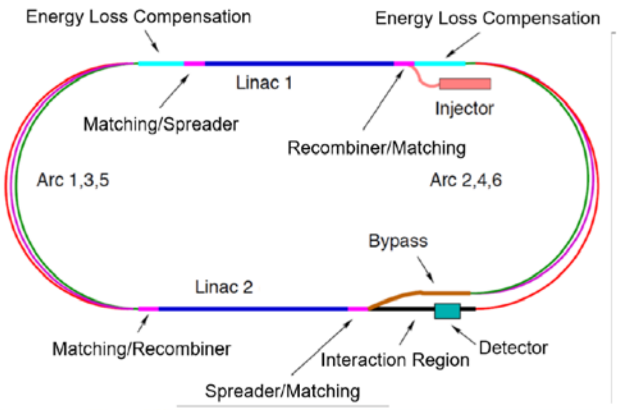
30th June 2021

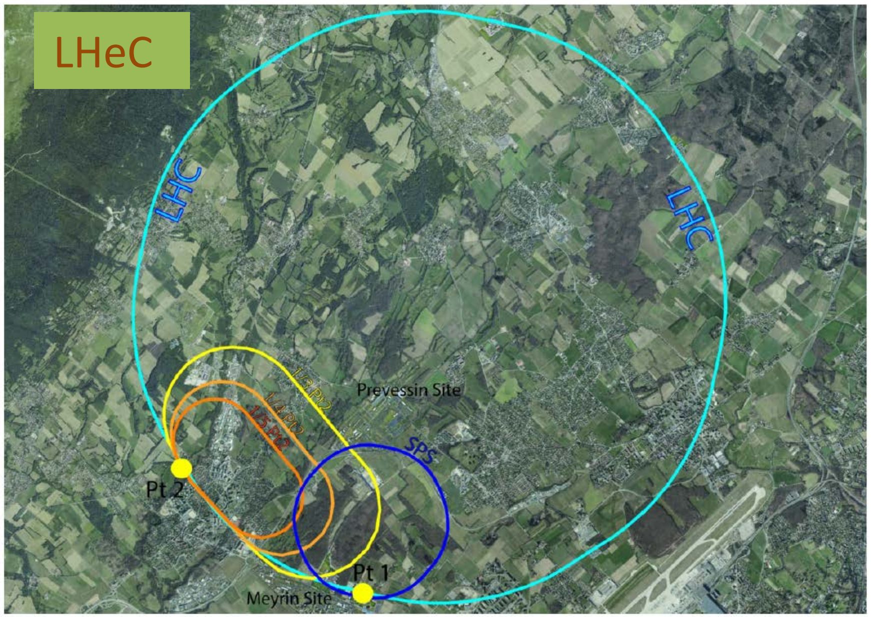
Outline:

- Introduction
  - Physics Requirements
  - Accelerator and
  - Interaction Region
- Detector and its subcomponents
- Future and Outlook

The LHeC and FCC-eh accelerators

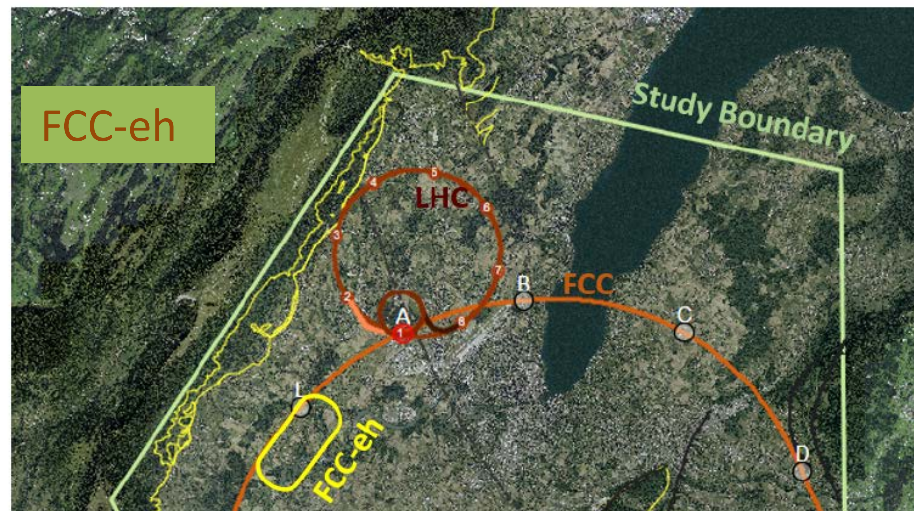
- Electrons from dedicated Energy Recovery Linac (ERL)
- Hadrons from LHC/FCC rings





50 GeV(e) × 7 TeV (p) 2.76 TeV/nucl. (A)

- $\sqrt{s} = 1.18\ (p)$ or $= 0.74\ (\mathrm{A})$ TeV
- $10^{33} - 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Electrons via 3-track ERL
  ~1/4 of LHC circumference

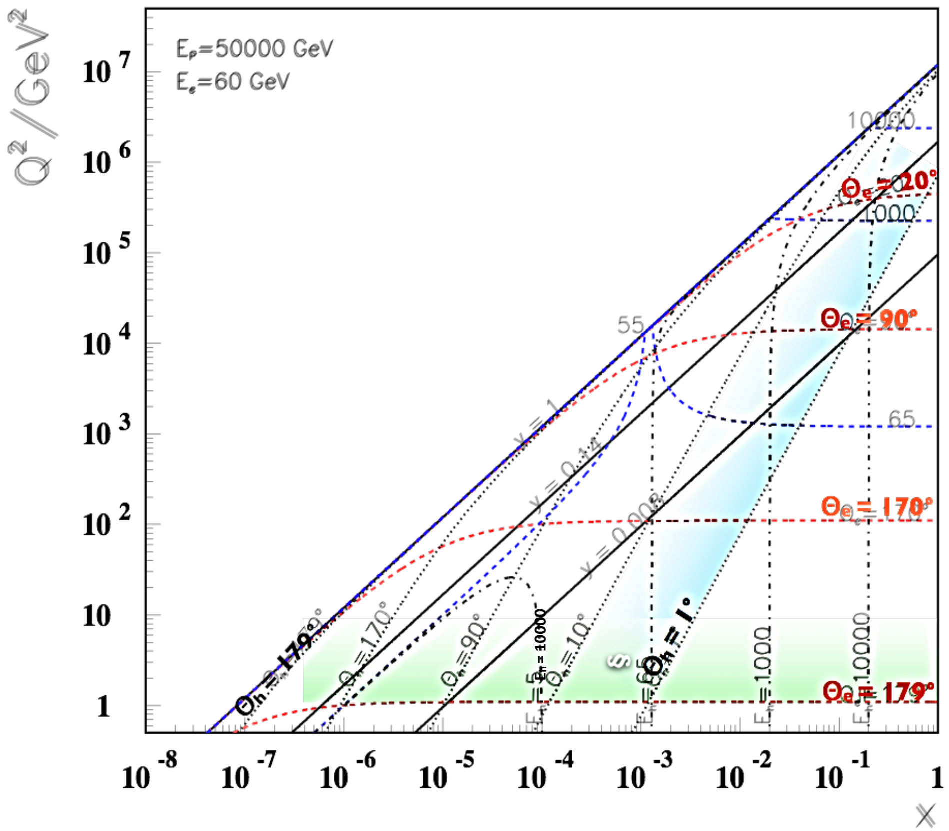


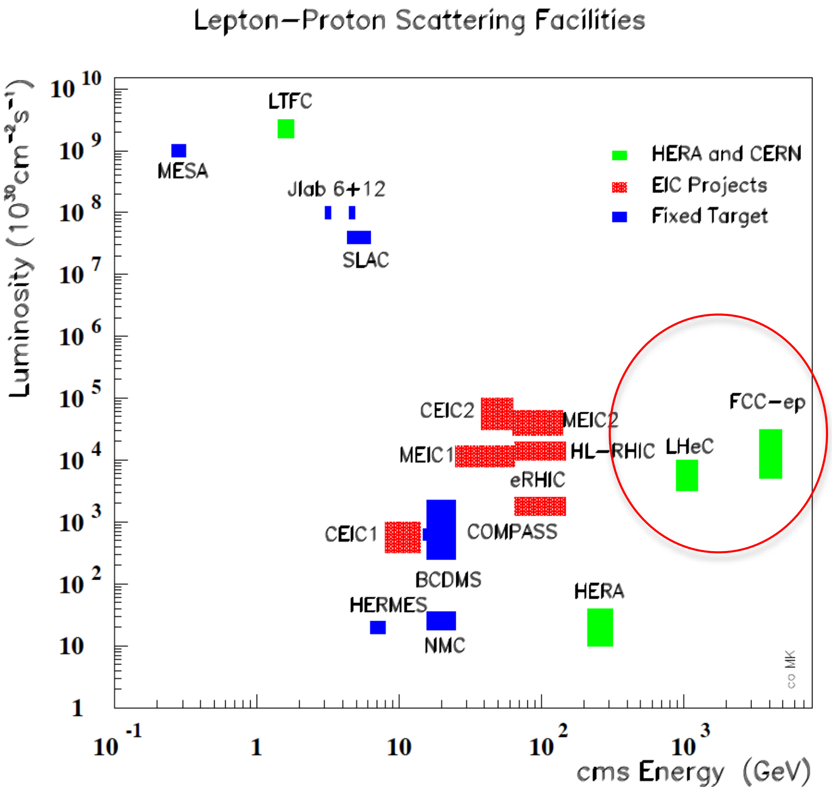
60 GeV(e) × 20 – 50 TeV (p)
7.9 – 19.7 TeV/nucl. (A)

- $\sqrt{s} = 2.2 - 3.5\ (p)$ or $1.4 - 2.2\ (\mathrm{A})$ TeV
- $10^{34}\ \mathrm{cm^{-2}s^{-1}}$

LHeC FCC-eh Context

Latest and most promising idea to take lepton-hadron physics to the TeV centre-of-mass scale … at high luminosity

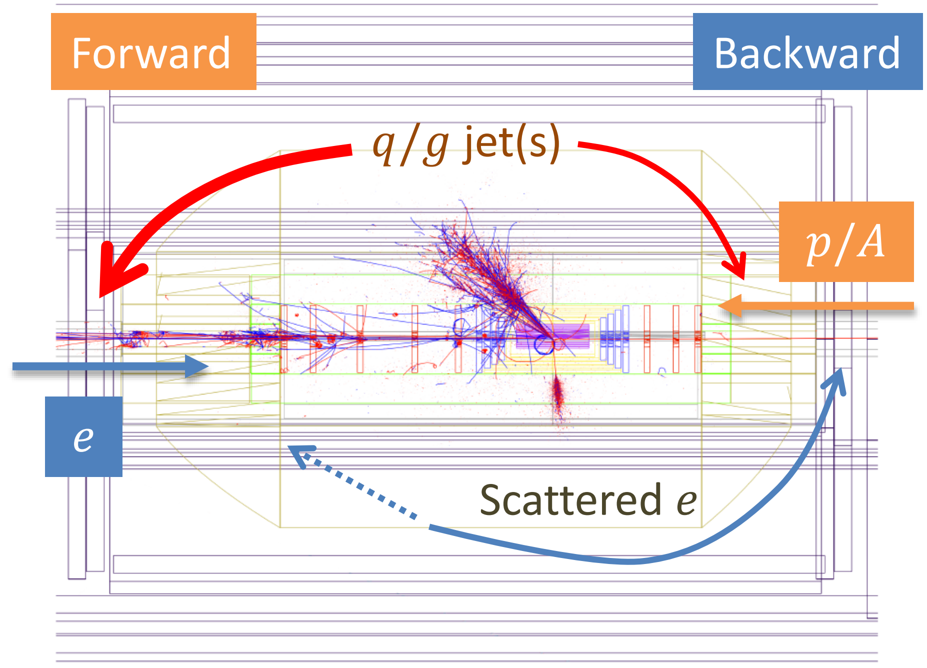




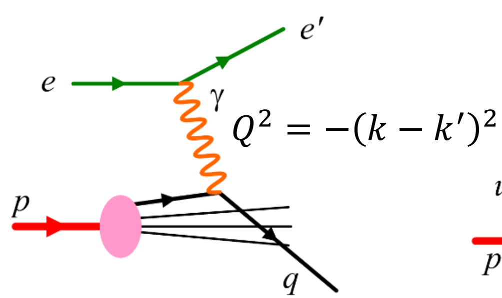
Designed to exploit intense hadron beams in the high luminosity phase of LHC running from mid 2020s

Processes & Challenges at LHeC/FCC-eh

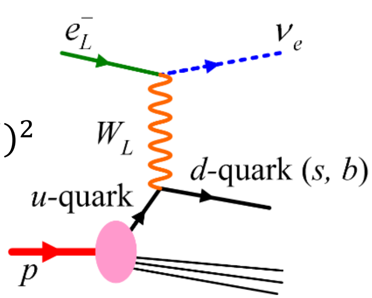
- Neutral current (NC) $ep \to eX$
  - Scattered electron (e) towards small angle (< 179°) to access low-Q^2 events
  - Hadron (X) forward-going jets from high-x events AND from QCD radiation
  - Flavour tagging for decomposing parton-density functions
- Charged current (CC) $ep \to \nu X$
  - missing p_T : need hermetic detector* small beam holes (<1°) + good calorimeter energy resolution



A NC (leptoquark) event at LHeC



NC

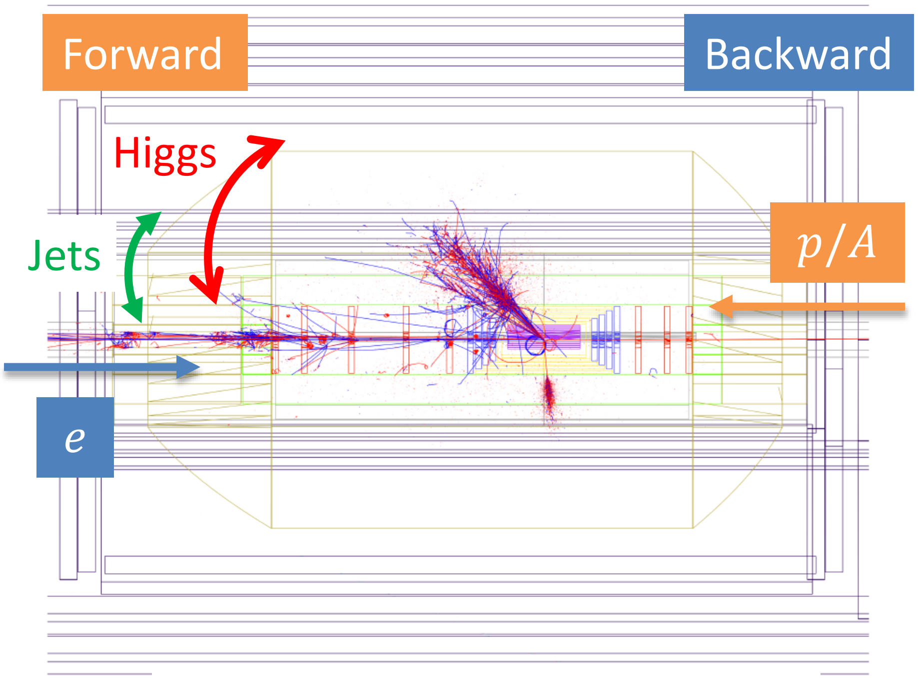


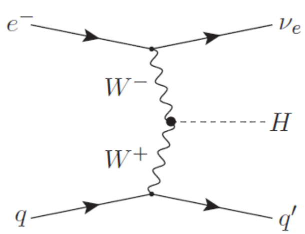
CC

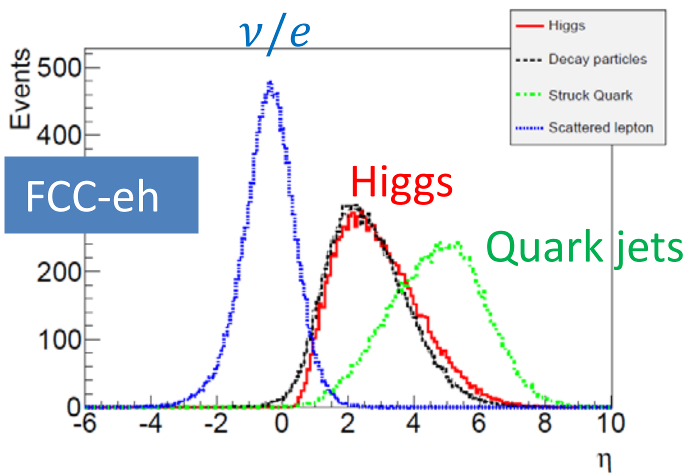
* also important for cross-calibration

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 $\gamma p \to X$
- BSM physics

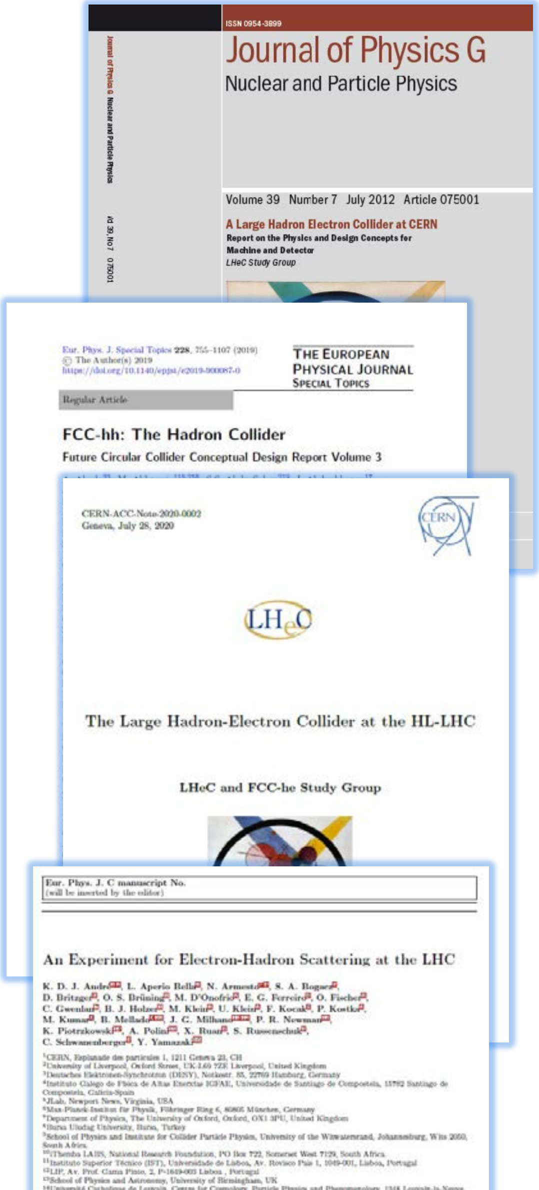




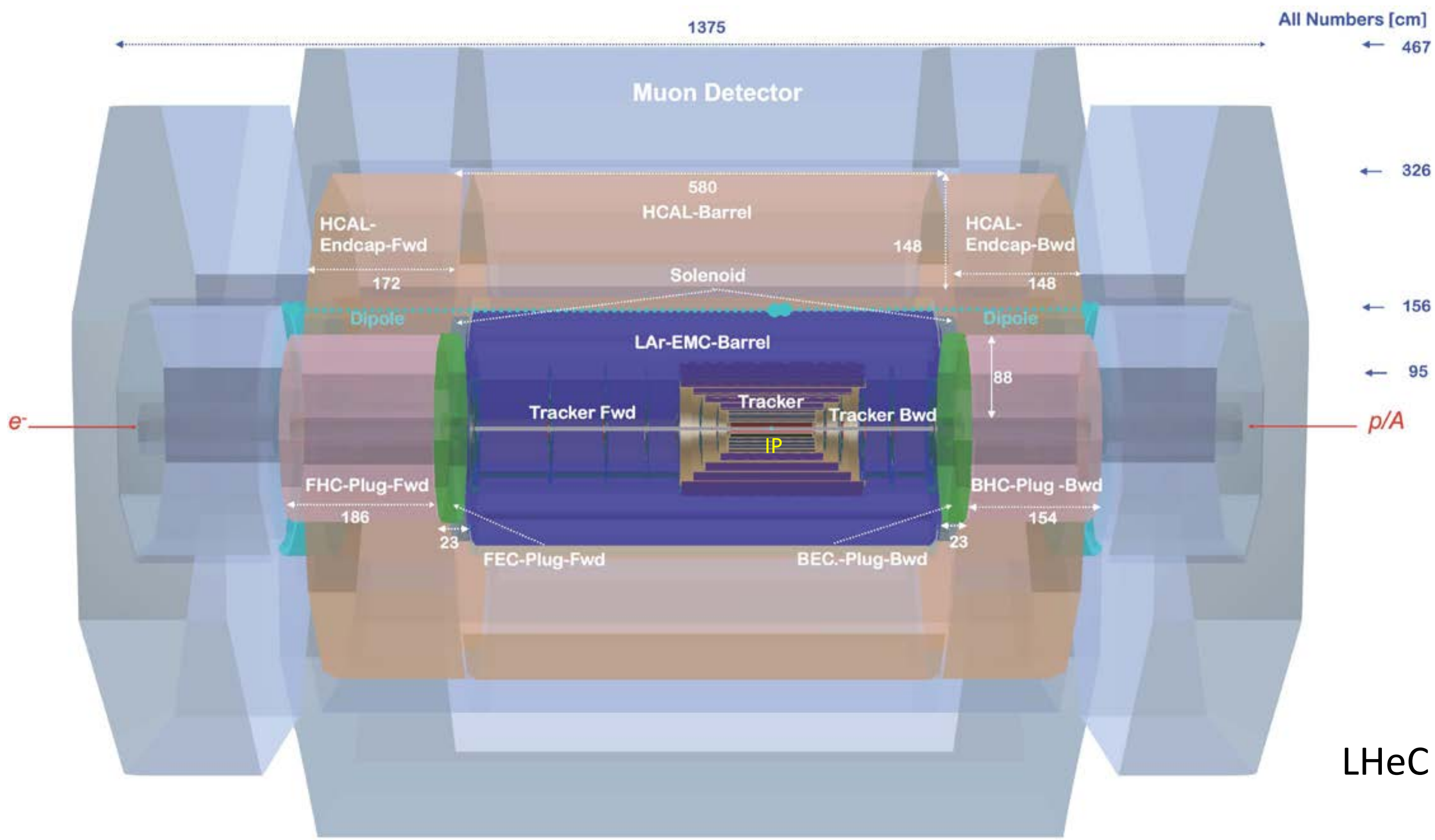


Detector Milestones and References

- LHeC CDR 2012:
  - LHeC Study Group, 2012 J. Phys. G: Nucl. Part. Phys. 39 075001
  - 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:
  - https://arxiv.org/abs/2007.14491
  - 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



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

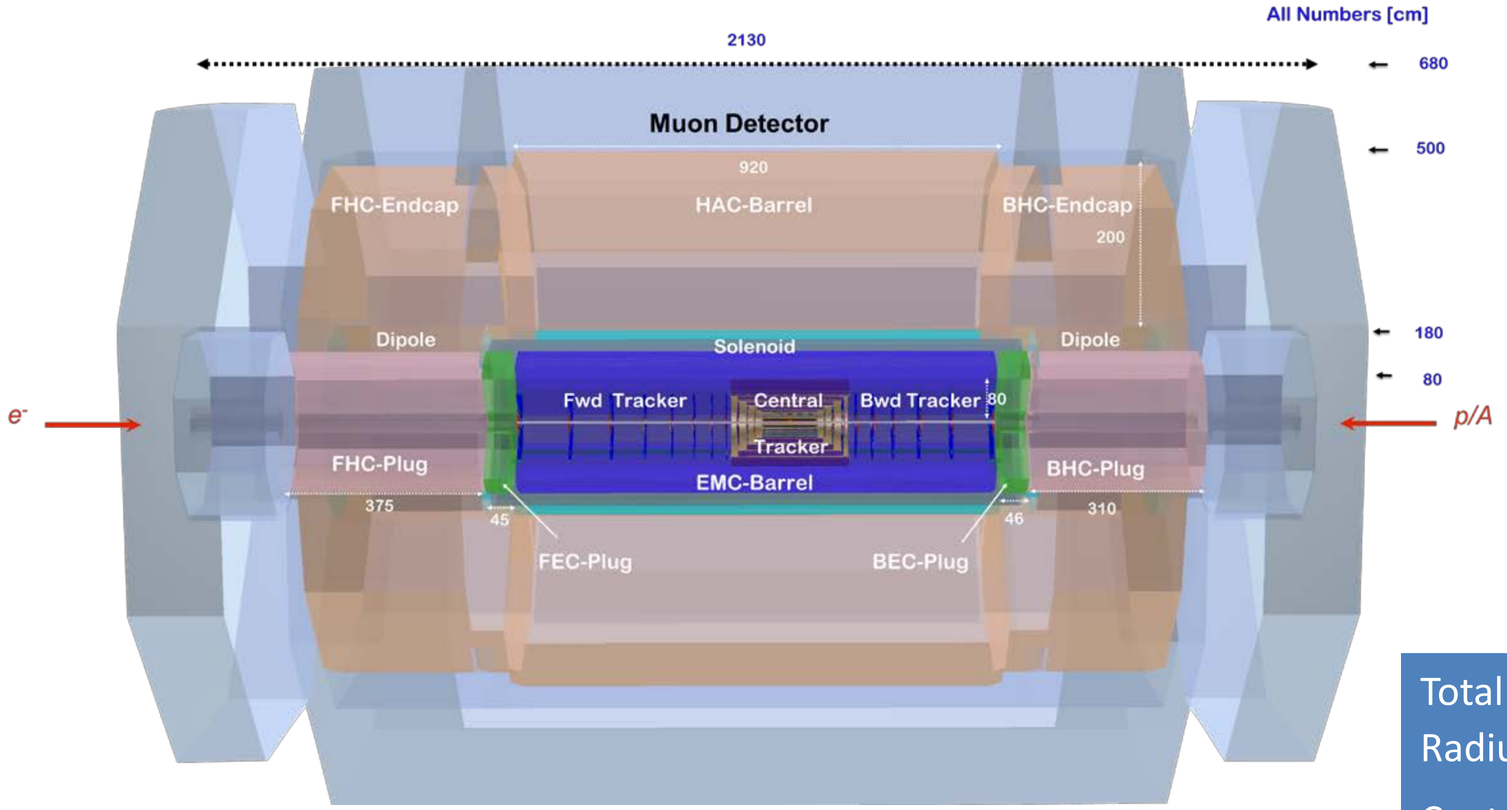
LHeC Offshell-2021 Version

- 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

- 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/γ)

* more options also considered

Detector design for FCC-eh



TheFCC-eh detector

similar size as CMS

Total length 13 → 20 m
Radius 4.8 → 6.8m

Central tracker
also with (tilted) wheels

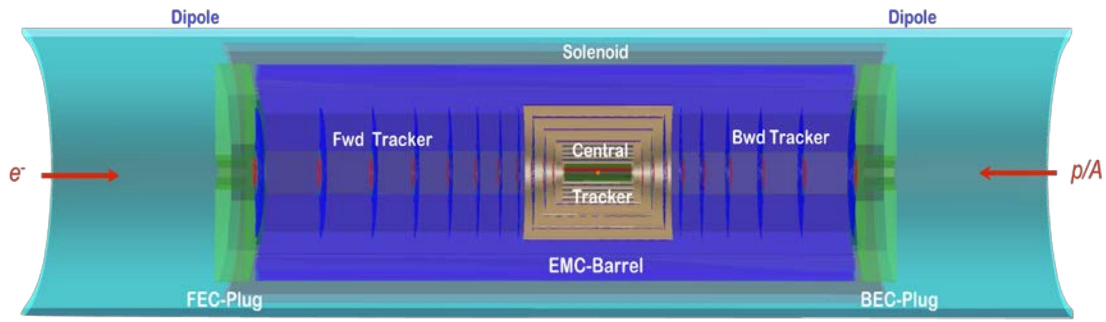
Fwd tracker 4 → 8 disks
Bwd 2 → 6 disks

HadCal:
12-15 interaction lengths

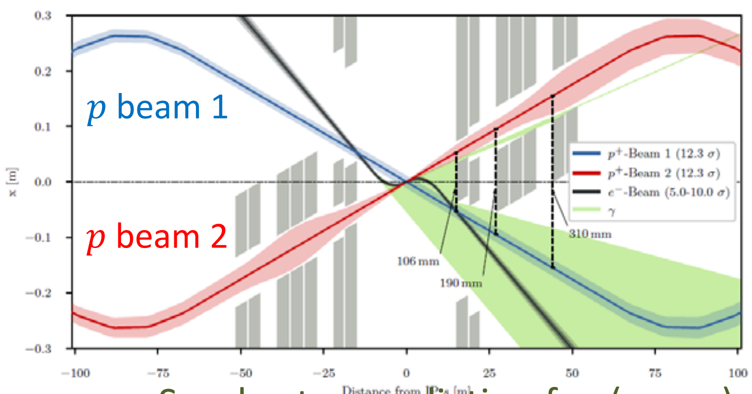
- Proton 20 and 50 TeV, electron 60 GeV
- Design for LHeC with extended volume / layers will serve also for FCC-eh
  - **Forward/Central: scales in $\sim \log E_{had}$ for calo**
  - Backward 50 or 60 GeV: similar to LHeC

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

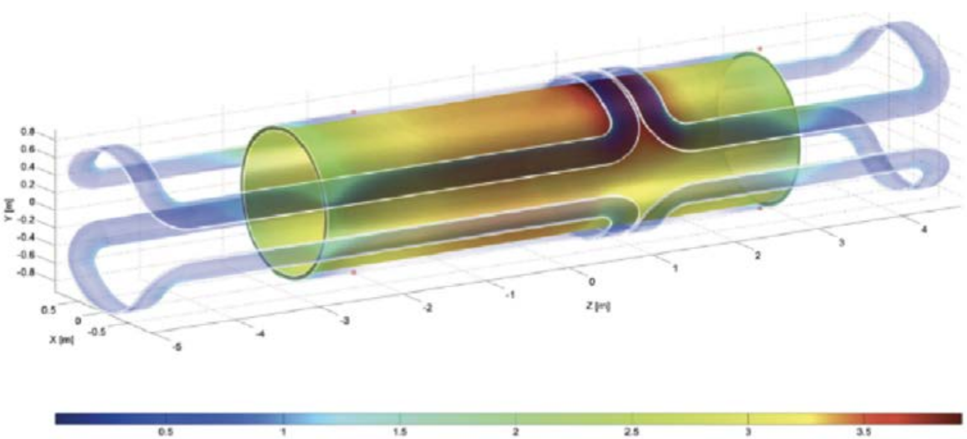


New re-designed, optimised LHeC IR in CDR 2020



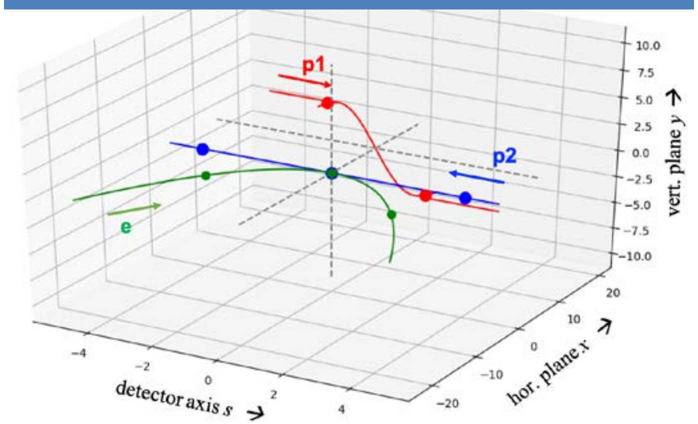
Synchrotron radiation fan (green)

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



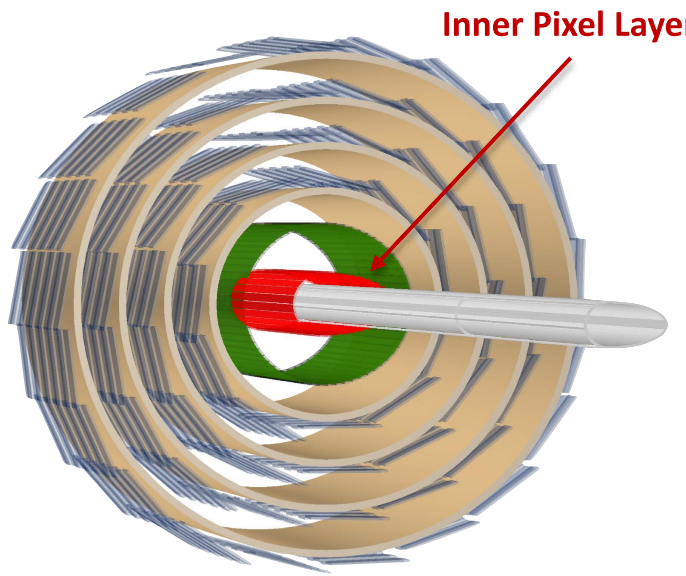
New FCC-eh IP (offshell paper)

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 $2 \times 10^{15}\ 1\text{MeV}\ n_{eq}/\text{cm}^2$ (cf. HL-LHC fluence $\gtrsim 10^{16}$)
- 5-8 layers for $-3.5 < \eta < 4$ ≥ 2 hits for $-4.2 < \eta < 5$

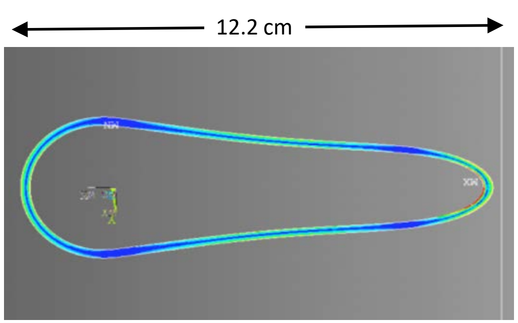


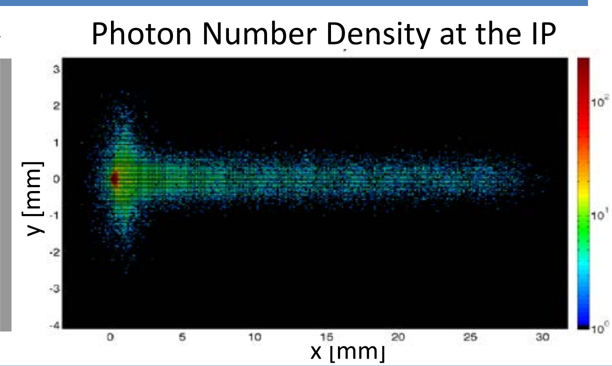
Pitch (μm)	$r\phi$	z
pixel	25	50
macro pixel	100	400
strip	100	10-50 mm

⇨ Need updated description of the IR, the e⁻ synchr. rad., masks and absorbers etc.

Circular/elliptical thin beam pipe to accommodate the outgoing synchrotron radiation fan:

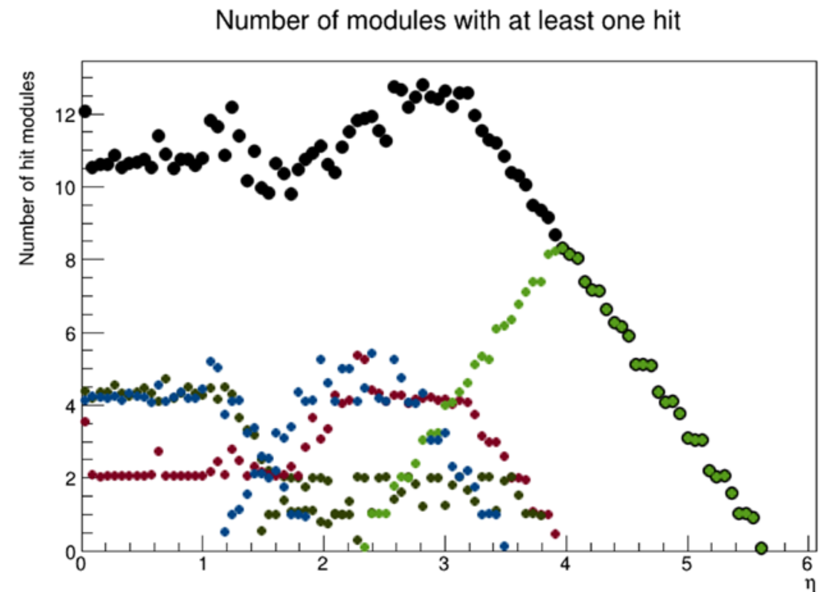
- Specs & Studies from LHeC CDR: Beryllium 2.5-3 mm thickness
- Circular(x)=2.2cm; Elliptical(-x)=-10., y=2.2cm

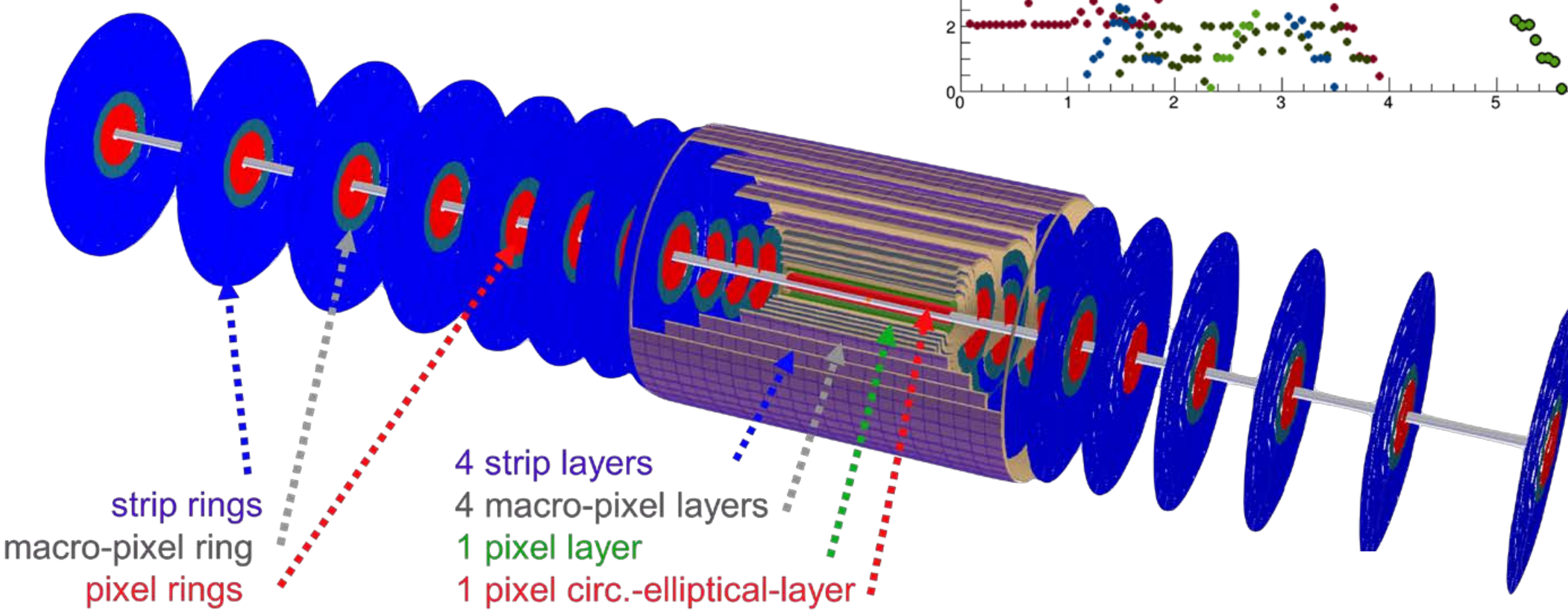




Silicon Tracker

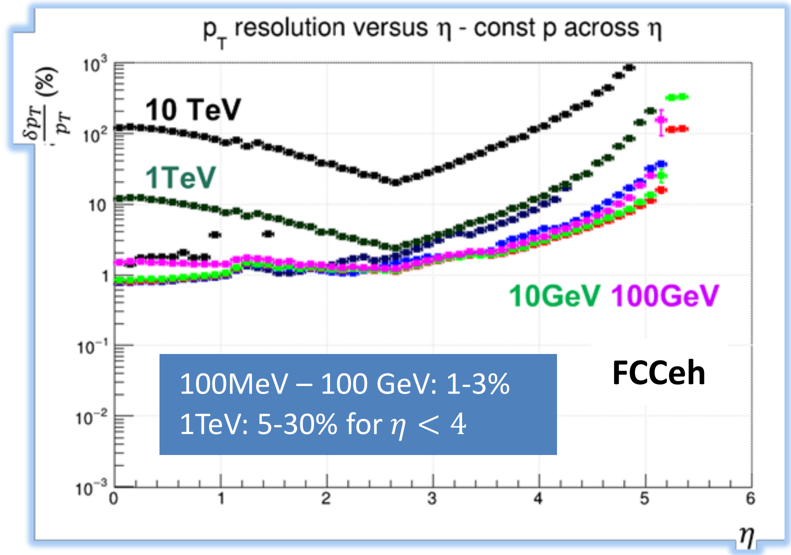
- Very preliminary design:
  - FCC-eh tracker: extend LHeC silicon tracker towards larger η
  - The chosen technology would allow for precise and redundant track measurements
  - Overall length 9.2 m, Radius 84 cm
  - 11 Forward wheels, 9 backwards

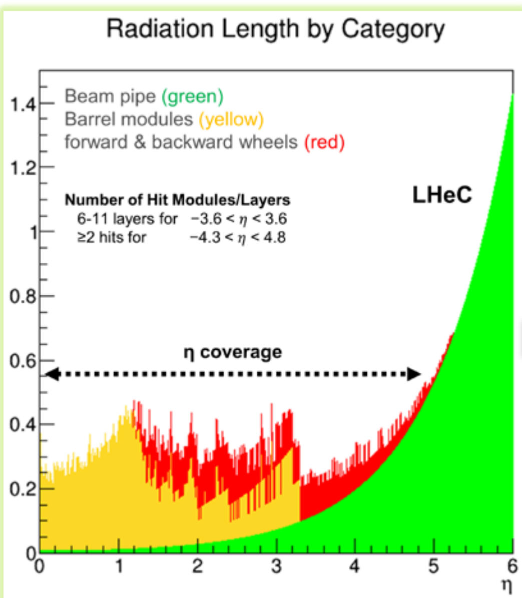


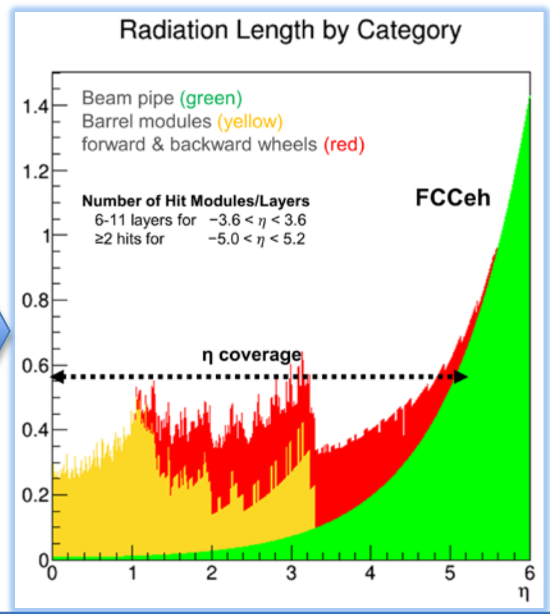


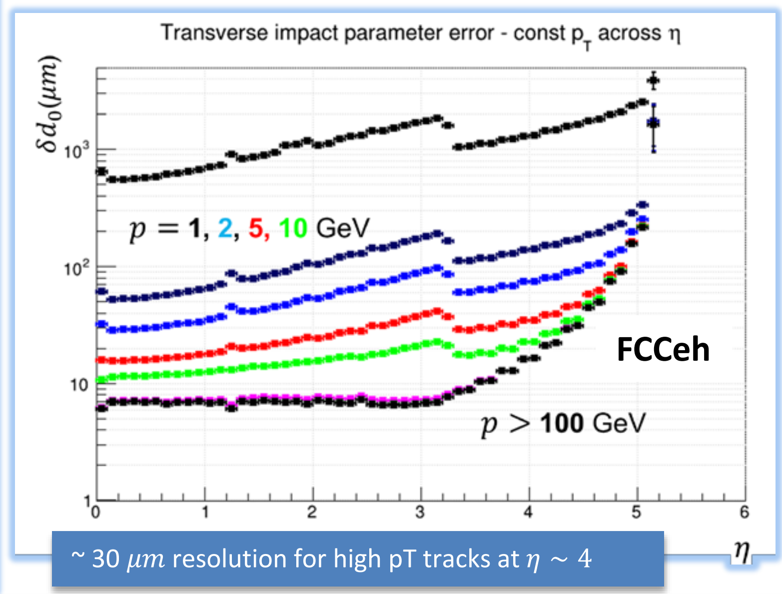
Silicon Tracker Performance

- Recent technologies allow for lightweight design:
- At large η 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



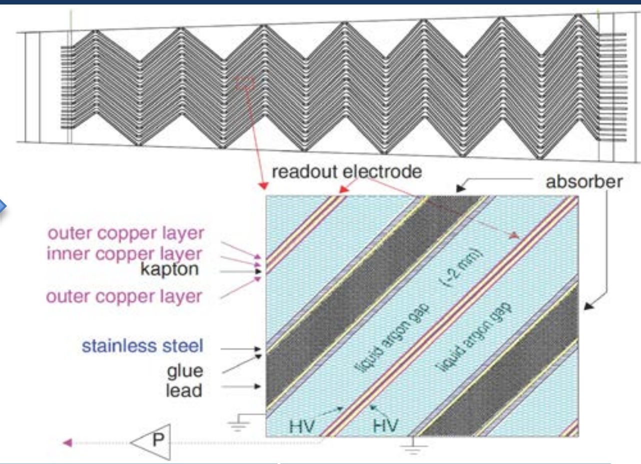




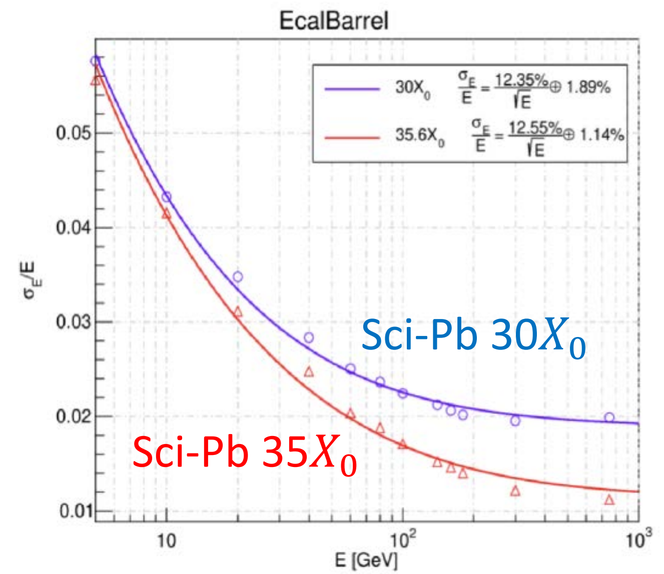


Calorimetry

- 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



LAr ($\sim 25X_0$)	$8.47/\sqrt{E} \oplus 0.32\%$
Sci-Pb ($30X_0$)	$12.55/\sqrt{E} \oplus 1.89\%$



Baseline configuration		η coverage	angular coverage
EM barrel	LAr	$-2.3 < \eta < 2.8$	$6.6^\circ - 168.9^\circ$
Had barrel+Ecap	Sci-Fe	(~ behind EM barrel)	
EM+Had forward	Si-W	$2.8 < \eta < 5.5$	$0.48^\circ -$
EM+Had backward	Si-Pb	$-2.3 < \eta < -4.8$	-179.1°

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 Λ_I for 7 → 20 → 50 TeV steps
  - 9.6 →12.7 Λ_I (forward endcap) for 7 → 20 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

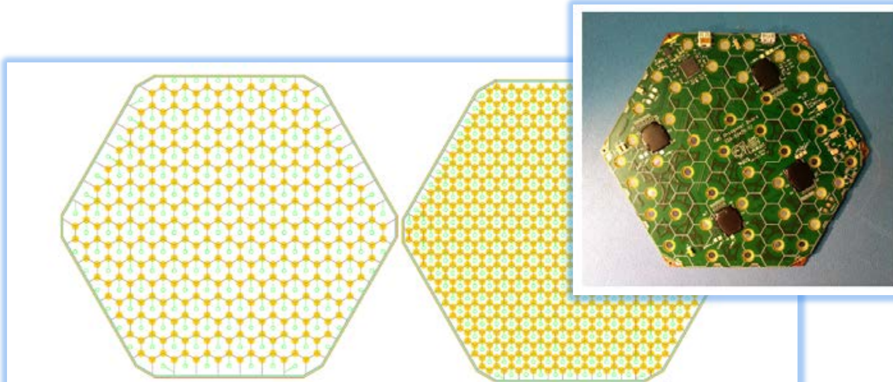


Figure 2.4: Drawing of hexagonal 8″ silicon wafers, with layout of large, 1.18 cm^2, sensor cells (left), and small, 0.52 cm^2, cells (right).

CMS HGCAL 6-inch module
cell size 1.18/0.52 cm^2 (from TDR)

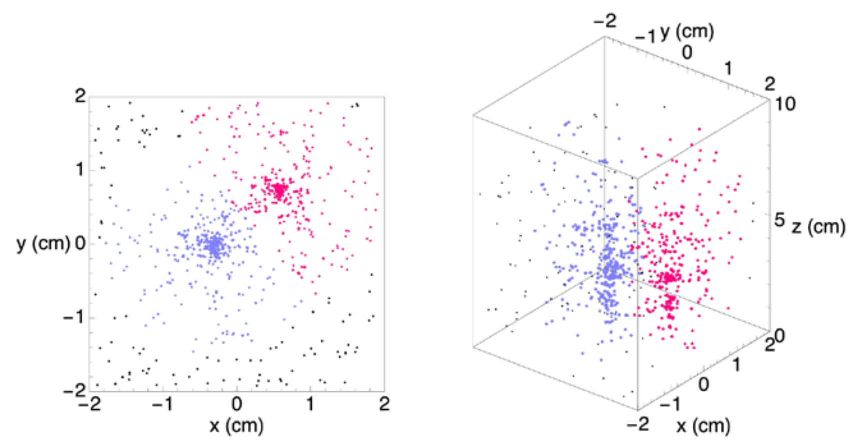
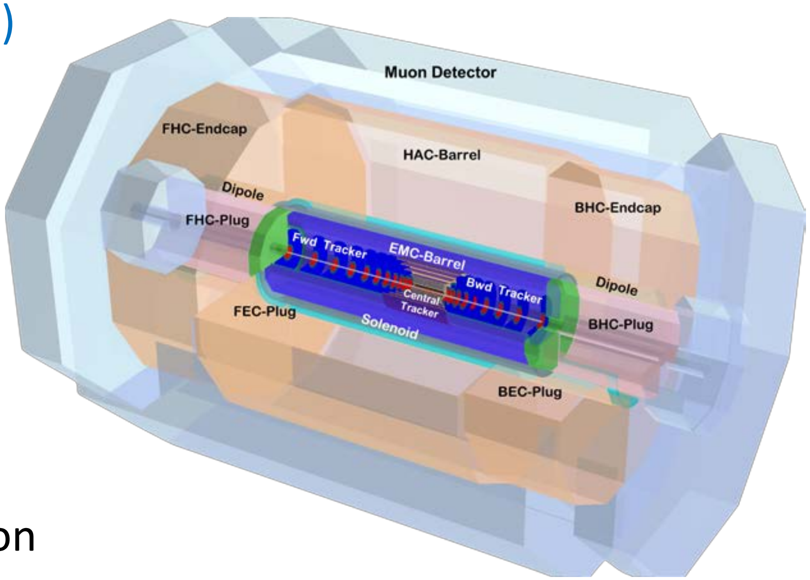


Fig. 54: Different projections of a single-event measurement (hit pixels) of two electrons of $E = 5.4$ GeV from a test beam in the pixel prototype. The left panel shows the transverse distribution summing longitudinally over all layers, the right panel shows a side view of the same event. The hits that are within 15 mm of either of the two shower centers are colored in blue and red; the black points indicate hits that are further from the shower center.

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

Muon System

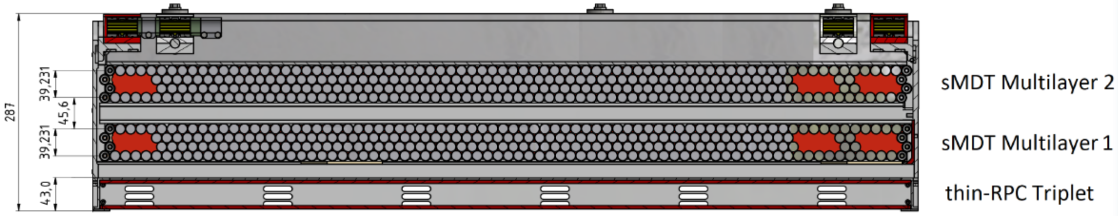
- Muons: Higgs, HFL, LFv etc. (tag/trigger/tracking)
- Baseline: no dedicated magnetic field (solenoid return thru iron only)
  - Momentum by central tracker
  - Good tagging + fast trigger
  - 2 Stations, each with 3 layers
- HL-LHC technology serves for that
  - Very thin RPC (1mm gas gap) for higher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

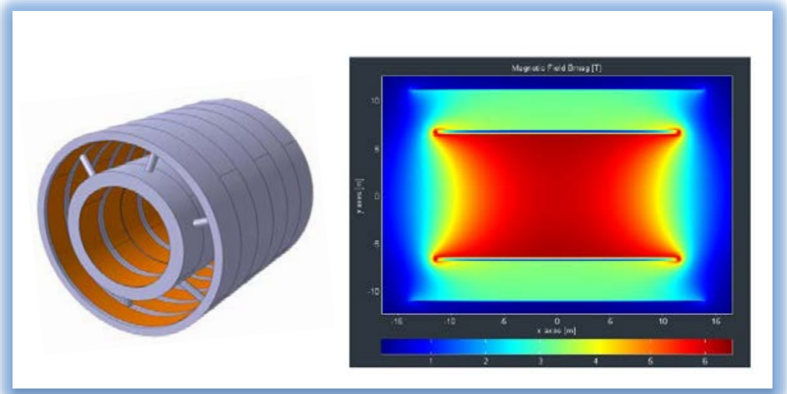


Some Specifications:
- Total area ~ 400 m^2
- Single unit detect: 2-5 m^2
- Max.rate: 3 kHz/cm^2
- Rad. Hard.: 0.3 C/cm^2
- Time res.: ~0.4 ns
- Spatial res.: 1mm (RPC); 80 µm (MDT single tube)

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.

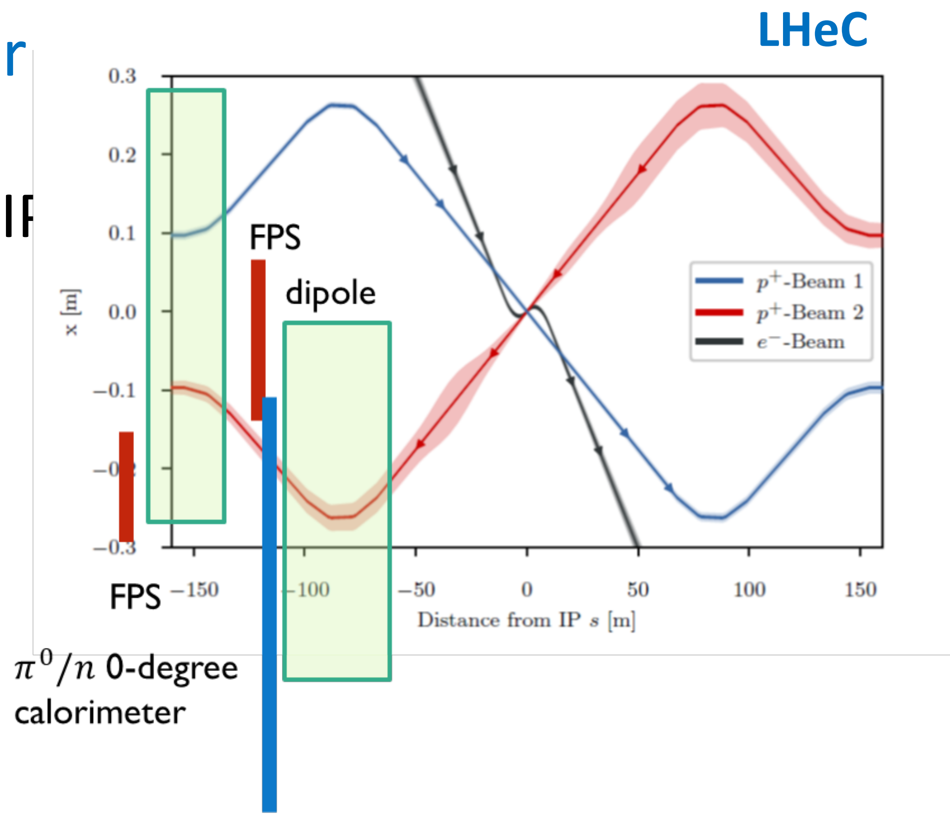
LHeC Adaption from ATLAS Phase-I RPC-MDT assembly





Around zero-degrees

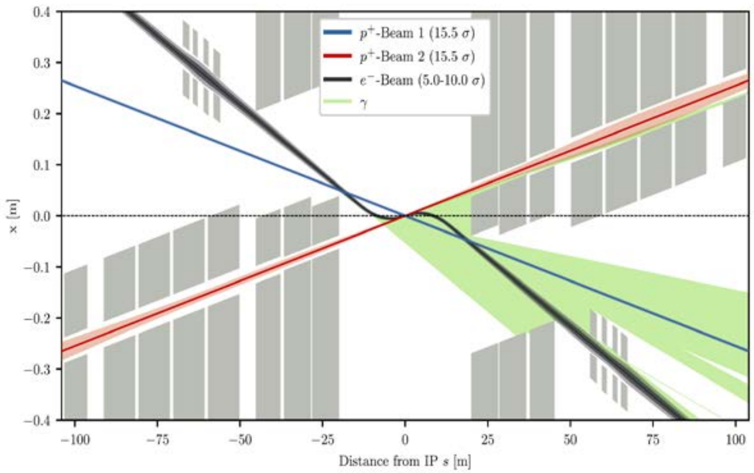
- Forward Proton spectrometer
  - following the LHC design apart from stations close to IP
- New IP design allows to place a ZDC
  - Transverse size $\pm$30 cm shower leak moderate
  - Aperture ~ 0.35 mrad or 2.4 GeV in p_T
- Technology candidate: Si-W
  - Need < 1mm resolution for p_T resolution $\ll$ 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

FCC-he



➡ 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!